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A controlled stream mesocosm for tertiary treatment of sewage

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Abstract

Freshwater stream ecosystems are well known for their capabilities for "self-purification" of sewage and other wastewaters. Unfortunately, the efficiencies of treatment are low and concentrations and volumes now discharged cannot be treated by self-purification alone. This paper describes an experiment with a stream mesocosm, in central California, USA, using controlled ecosystem methodologies in the format of an algal turf scrubber (ATS™). This system was used to drive primary production and export in the mesocosm to bring secondary sewage to tertiary levels. The mesocosm consisted of a natural, mixed assemblage of attached periphyton, microalgae and bacteria which colonized an inclined floway 152 m long and 6.7 m wide, over which wastewater flowed in a series of pulses. The capacity of the wastewater flow varied between 436 and 889 m^3 per day and various operational parameters were tested. Biomass was mechanically harvested from the floway at 1- or 2-week intervals depending upon the season. This paper presents the results for nitrogen and phosphorus removal as well as that of other contaminants and productivity of the algal turf. Nitrogen and phosphorus removal from the secondary wastewater was measured twice a week during four, 8-week quarters corresponding to the solar seasons. Nitrogen and phosphorus content of the harvested solids was also measured during these periods. Based on the percentage of nutrients in the harvested solids (3.1% N and 2.1% P) and the operational productivity of 35 g dry solids m^{-2} day^{-1}, the yearly mean removal of nitrogen and phosphorus was 1.11 ± 0.48 gN m^{-2} day^{-1} and 0.73 ± 0.28 gP m^{-2} day^{-1}, respectively. Results indicate the strong potential of

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controlled stream mesocosms for the removal of nutrients and other contaminants from wastewaters to achieve tertiary levels.

Keywords: Algal Turf Scrubber; Heterogeneous community; Mesocosm; Primary production; Tertiary treatment

1. Introduction

Wastewater treatment technology has come full circle and is returning to natural ecosystems for solutions. Early treatment methods simply depended on the self-purifying mechanisms of natural waterways (lakes, rivers and streams) to adequately treat, disperse and redistribute low concentration wastes. However, both the concentration and volume of the sewage effluent now discharged is too great to be treated by natural ecosystems alone (Harlin and Darley, 1988). In the United States, dense urban populations discharge more sewage effluent to surface waters (117 million m^3 day^{-1}) than they withdraw water from them (83 million m^3 day^{-1}) (Solley et al., 1988). Municipal sewage is one of the main contributors to freshwater pollution and eutrophication (Council in Environmental Quality, 1981). More than 30% of waterways in the US show signs of eutrophication which is mostly a result of excessive phosphorus concentrations in large part derived from sewage (Hecky and Kilham, 1988). Furthermore, it is predicted that by the year 2012, there will be a need for over 4000 new or upgraded sewage treatment facilities, at the secondary level or higher (U.S. EPA, 1993).

Traditional primary and secondary treatment provide optimal conditions for microbial degradation of organic wastes to inorganic nutrients by providing extensive mixing and oxygen input. However, they have little capacity to remove the nutrients (Oswald, 1988; Metcalf and Eddy, 1991). Nutrients can be removed by physical and chemical "tertiary" processes, but these have variable efficiency, depending upon the nutrient to be removed. Since tertiary treatment requires extended residence times in expensive reactors, and in some cases uses additive chemicals, it is usually too costly to be implemented. Residues may also be left in the effluent which can lead to secondary pollution (Waldichuk, 1985; Oswald, 1988; Robinson et al., 1989; Metcalf and Eddy, 1991). Microbial tertiary treatment is extensively employed to remove dissolved nitrogen (Randall et al., 1990), but nitrification is a lengthy process, requiring neutral wastewater and has variable performance due to daily fluctuations in wastewater loading (Harremoës, 1987). Most sewage treatment promotes heterotrophic respiration without proper restoration of the nutrient levels, oxygen concentration or pH values required to prevent deterioration of receiving water ecosystems (Adey and Hackney, 1989). The use of controlled ecology, promoting the mechanisms of self-purification in natural ecosystems, can provide efficient, cost effective and environmentally sound technologies for treating wastewaters.

This study was undertaken to determine whether the Algal Turf Scrubber (ATS™), a controlled stream mesocosm, in conjunction with ultra-violet (UV) disinfection, could treat the effluent from a wastewater treatment facility. To be successful, the ATS/UV system needed to meet California regulations for river discharge and to achieve mechanical harvesting on a large scale.

1.1. Self-purification of natural water bodies

Natural self-purification results in a decline in nutrient concentrations to background or equilibrium levels downstream of the pollution source. This process, called nutrient spiraling, involves transport and cycling of metabolites from sources through various storage subsystems (Beyers and Odum. 1993). The most important subsystems involved in self-purification are physical gradient and current velocity, sediments, microbiota, and photosynthetic autotrophs. Design of controlled ecologies relies on an understanding of ecosystems, the functions of their subsystems and the relationships between subsystems (Adey, 1995a).

Physical gradient, or slope, of a stream determines the current velocity. Higher current velocity enhances algal production and respiration in stream microcosms (Beyers and Odum. 1993) and has been shown to increase uptake of phosphorus by bryophytes in the field (Meyer, 1979). The energy of the current velocity drives biological metabolism and chemical reactions, while the flowing water facilitates nutrient uptake by bringing metabolites to reaction sites and carrying away waste. High current velocity and turbulence promote re-aeration of polluted waters through increased diffusion from the atmosphere. Current velocity also determines the ability of the water to hold and transport suspended solids. Sediments and organic particulates are deposited or trapped in slow moving pools, eddies, rock crevasses and among dense stands of periphyton and macrophytes. The sediments are a limited sink and source of nutrients. Phosphorus, for example, is rapidly adsorbed from the water column by fine sediments (Meyer, 1979; Nichols, 1983) and may also be precipitated in large quantities, especially in conditions of high pH (Hemens and Mason, 1968).

Bacteria, fungi and protozoa congregate around suspended or attached organic particles. These microbes breakdown organic compounds and excrete them in simpler forms for solution in the water column, adsorption in the sediments or absorption by autotrophs. When nitrogen levels are high, bacterial denitrification to the atmosphere becomes a key process. Nutrient enrichment will also increase downstream levels of autotrophic production (Marcus, 1980). The aquatic autotrophs (vascular macrophytes, green algae, diatoms and cyanobacteria) are most dependent on nutrients, light and temperature for growth and reproduction, with current velocity and substrate affecting them to a lesser degree. The change in community structure and water chemistry as nutrients spiral downstream of a pollution source is termed longitudinal succession (Beyers and Odum, 1993). This results from the different tolerances of the biota to levels of pollution and their role in natural self-purification, as the polluted water passes downstream (Hynes, 1971). Among the photosynthetic autotrophs, the diatoms and cyanobacteria are most tolerant of elevated nutrient concentrations and deoxygenation (Hynes, 1971), with green filamentous algae tending to predominate areas further from the pollution source. High levels of pollutants impair the growth of macrophyte root systems enabling benthic algae to outcompete and proliferate (Haslam, 1990). Macrophytes often dominate in high quality, low nutrient streams (Adey, 1995b). Abundant macrophytes will shade out much of the benthic algae (Sand-Jensen et al., 1983), especially where light is already limited by a dense overhead tree canopy. Aquatic autotrophs produce oxygen through photosynthesis. This helps restore DO concentrations which promotes aerobic decomposition of organic compounds by heterotrophic bacteria (Portier and Palmer, 1989). The subsequent release of carbon dioxide and nutrients promotes further autotrophic production. Nutrients are also moved through the food web as protozoans ingest bacteria and microalgae and small invertebrates prey on the microbes (Hynes, 1971). Fish feed on both algae and invertebrates and fall prey to birds and terrestrial animals. In addition, larval insects mature and depart from the aquatic environment. Nutrients are thus moved out of the aquatic system.

1.2. Algal Turf Scrubbing – an ecosystem-based treatment technology

Algal Turf Scrubbing is a novel algal wastewater treatment technology which cultures attached or benthic bacteria, microalgae and filamentous algae on an inclined floway. The Algal Turf Scrubber (ATS™) is a low-cost treatment system which is simple in design and construction. The ATS is essentially an artificial stream which has been designed and engineered to promote biological wastewater treatment using periphyton and its associated microbes. It is a controlled ecology, driving photosynthesis, its key process, to high levels and paralleling the self-purifying mechanisms of natural streams. The ATS has several advantages to micro-algal ponds in that, given adequate light much higher rates of photosynthesis and autotrophic production can be achieved (Adey et al., 1993). Harvest of production is easily affected. This allows tight control and enhancement of the export component of the ecosystem (or mesocosm).

Algal turf scrubbing has been applied as a water management technology for freshwater and marine aquaria and mesocosms and as a treatment system for maricultural, aquacultural, agricultural and industrial wastewater (Adey and Hackney, 1989; Adey and Loveland, 1991; Adey et al., 1993; Adey et al., 1996). 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). Periodic harvesting of the algal turf removes metabolites from the ecosystem, stimulates continued production and nutrient removal and controls the invertebrate populations, which graze on the turf and would otherwise reduce primary production as the system goes through succession. Harvest is achieved by stopping the flow of wastewater, draining the floway for 1 h and vacuuming the biomass from the surface. Hence, all pollutants accumulated by the algal turf are easily removed in the harvested solids. Since the solids contain a high concentration of nutrients, they can be used as fertilizing soil ammendments, as has been demonstrated in Bermudagrass and rice production (Snyder and Adey, unpubl. study), and in hydroseeding applications.

Algal turfs are heterogeneous assemblages of attached, filamentous species of algae characterized by low stature, high biomass-specific growth rate, and an ability for rapid vegetative regeneration from their basal cells despite partial removal of their thallus such as by grazing or harvest (Adey and Hackney, 1989). A number of benthic diatoms (centric, pennate, unicellular and filamentous), coccoid and filamentous cyanobacteria, and benthic filamentous green algae dominate in the turf (Adey and Hackney, 1989). A variety of bacteria, protozoans and metazoans (e.g. nematodes, small annelids and microcrustaceans) are also associated with the turf (Adey and Hackney, 1989).

2. Materials and methods

2.1. 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, USA, approximately 70 miles southeast 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. The facility has a mean hydraulic loading of 3028 m^3 day^{-1}, and the treated wastewater is presently disposed of on-site to evaporation and infiltration ponds measuring 0.21 km^2.

2.2. Patterson ATS / Stream Mesocosm

The ATS/UV treatment system built at Patterson had several components (Fig. 1): an inclined plastic-lined floway with a pneumatic wave maker, a 400 μm rotary screen strainer, a sand filtration system, an ultra-violet disinfection system, and a mechanical harvester. The Patterson ATS was the first large scale ATS to be built and the first scrubber unit that in itself could be regarded as a mesocosm. It consisted of a liner which covered laser graded soil between two precast concrete grade beams. The liner (60 mil. textured high density polyethylene landfill liner (Poly-flex Corporation, Grand Prairie, TX)) provided a surface for periphyton attachment. The grade beams provided both the vertical sides of the floway and the rails to support and distribute the weight of the mechanical harvester. To maintain the uniform current velocity down the ATS, the top half was inclined at a 0.5% slope and the bottom half at a 0.25% slope. The total change in elevation was approximately 0.61 m over the entire length.

The floway was 152.4 m long and 6.7 m wide and had a total surface area of 1021 m^2. The influent was surged over the surface of the ATS floway in thin waves. 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 l influent trough. The rotary screen strainer collected any algae that sloughed off the floway surface. The strainer was made from a coarse mesh barrel (0.76 m diameter, 1.22 m long) with a stainless steel screen

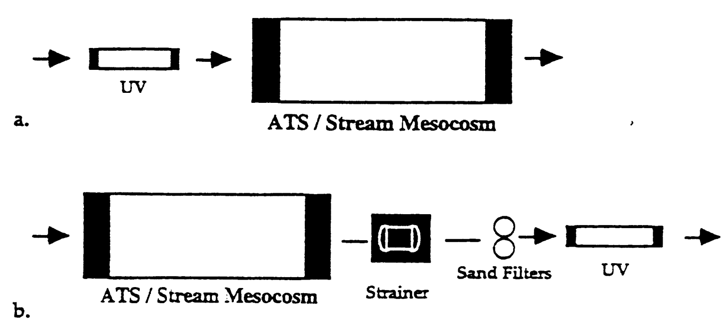

Fig. 1. Configurations of the ATS/UV wastewater treatment system.

(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 pressurized sand filters (Effco, California) were used to filter microscopic particles from the ATS effluent. Both filters had a volume of 0.3 m^3, 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 W), with seven mounts of two lamps in each trough. The lamps were enclosed within quartz shields which were cleaned periodically. The harvester removed the algal turf from the floway and transferred it to a tanker. An internal combustion gasoline engine powered the entire harvester unit including hydraulic wheel drive, an articulated vacuum nozzle, vacuum blower and transfer pump.

2.3. Sampling protocol and analytical methods

Evaluation of the ATS/Stream Mesocosm system was conducted over one year from the 30th of August 1993 to the 24th of October 1994 including a preliminary study period and four, 8-week quarters, corresponding to the solar seasons. The heterogeneous algal community of the ATS floway was examined and identified using a compound microscope. Samples were taken from eight sites along the floway on each Friday prior to harvest. Productivity (as harvested solids) was measured on Friday from composite biomass samples for both the top and bottom halves of the floway which were collected from five random 0.093 m^2 sites. The mean dry weight (105°C) of the two samples was used to calculate the mean productivity for the floway. The volatile component of the harvested solids was measured by subtracting the ash weight (550°C) from the dry weight. Harvested solids samples were collected from the top, middle and bottom of the floway for biomass analysis. Dried samples were analyzed for chemical composition (N, P, K, S, Mg, Ca, Na, Fe, Al. Mn, Cu and Zn) using standard methods by A and L laboratories in Modesto, CA.

Influent and effluent samples were taken on Wednesday and Friday for nutrient analysis and measured against deionized water blanks by standard colorimetric methods (APHA, 1992). Ammonium was measured by distillation and titration, nitrate/nitrite by cadmium reduction and total Kjeldahl nitrogen by the Kjeldahl method. Both soluble reactive phosphorus and total phosphorus were determined by the ascorbic acid method. 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 for water chemistry analysis were collected at 11:00 a.m. Each quarter included a 5-day intensive week with daily testing of all parameters, and two diurnals, during which parameters were measured at 4-h 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 from the influent and effluent of the combined ATS/mesocosm system (Fig. 1) and collected in dilute HCl acid-washed glass vials for phosphorus and high density polyethylene bottles (Nalgene) for nitrogen. Soluble reactive phosphorus samples were prefiltered through a disposable Millipore filter immediately after sampling. Samples were acidified (if required) and stored on ice or in a refrigerator until analyzed. Appropriate standards and spiked samples were analyzed to ensure adequate quality control. Preliminary samples taken between August 30th and November 21st, 1993 were analyzed by A and L laboratories in Modesto, CA.

2.4. Operation

Colonization of the mesocosm algal community was initially aided by placing screens in near-by streams and rivers. Algae attached to the screens which were then placed at the top of the mesocosm. Algae from the screens and from the upstream primary/secondary sewage system and evaporation pond colonized the mesocosm. In the last 3 weeks of the summer quarter and during the whole of the fall quarter, the mesocosm was seeded with algal biomass collected from near-by streams and harvested algae from the mesocosm. This algal "seed" was broken up and distributed down the mesocosm. 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). Hydraulic loading rate was varied from 954 m^3 day^{-1} during the winter quarter, to 1226 m^3 day^{-1} during the spring, to 889 m^3 day^{-1} during the summer and first month of fall quarter, and finally to 436 m^3 day^{-1} in the last month of the fall quarter. The hydraulic loading rate was measured using a Doppler flow meter (Dynamic fluid systems, New York, model HFM-1).

3. Results

3.1. Mesocosm community

A natural assemblage of bacteria, microalgae and periphyton developed in the mesocosm. Microscopic examination of the algal community showed a significant proportion of bacterial matter and particulates. ATS algal filaments provided a large surface area to support bacterial populations and promote heterotrophic degradation of organic material. Species composition of the algal turf varied over the study period (Table 1). For much of the year the predominant algal species were cyanobacteria (*Oscillatoria* and unidentified fine filamentous species) and diatoms (*Navicula* sp., *Nitzschia* sp. and *Cyclotella* sp.). However green filamentous species (*Ulothrix* sp.,

Table 1
Dominant algal species of the ATS/mesocosm during a 1 year study at Patterson, California

Algal species	Preliminary period	Winter quarter	Spring quarter	Summer quarter W 1–5	Summer quarter W 6–8	Fall Quarter
Cyanophyceae						
Oscillatoria sp.	2	4	4	4	3	3
Unidentified fine filamentous sp.	–	–	4	4	3	3
Spirulina sp.	3	2	–	–	1	1
Anabena sp.	–	–	–	–	1	–
Bacillariophyceae						
Navicula sp.	4	4	4	4	4	4
Nitzschia sp.	4	4	2	2	2	2
Cyclotella sp.	–	–	2	3	4	4
Fragillaria sp.	–	–	–	–	–	3
Melosira sp.	–	–	–	–	–	2
Stauroneis sp.	–	1	–	–	2	2
Surirella sp.	–	1	–	–	–	–
Chlorophyceae						
Chlorella sp.	–	–	–	1	1	–
Scenedesmus sp.	1	–	–	–	1	1
Closterium sp.1	–	–	–	–	–	
Chroococcus sp.	3	1	–	–	–	–
Selenastrum sp.	–	–	–	–	–	2
Cladophora sp.	2	2	1	–	–	2
Ulothrix sp.	4	–	–	–	4	3
Stigeoclonium sp.	–	–	–	–	–	2
Spyrogyra sp.	–	–	–	–	–	4
Tribonema sp.	–	–	–	–	–	3
Rhizoclonium sp.	–	–	–	–	–	3
Hydradictyon sp.	–	–	–	–	–	2
Microspora sp.	–	1	–	–	–	–

W 1–5, weeks 1 to 5.
W 6–8, weeks 6 to 8.
1 Present; 2 few; 3 many; 4 major.

Cladophora sp. and *Microspora* sp.) which were prevalent in the mesocosm during the preliminary test period, were lost when the mesocosm dried out due to accidental power failure in October 1993. These filamentous species did not naturally reseed in the mesocosm, and were only reestablished in the last 3 weeks of the summer quarter when seeding of the mesocosm following harvest was initiated. A rapid recovery of species diversity and productivity followed a second drying out of the mesocosm in August 1994 (Fig. 2), due to weekly reseeding. Several filamentous species (*Cladophora* sp., *Ulothrix* sp., *Stigeoclonium* sp., *Spyrogyra* sp., *Tribonema* sp., and *Rhizoclonium* sp.) were prevalent during the fall quarter.

A number of invertebrate species were endemic in the stream mesocosm. Most abundant were the amphipods and midge larvae or chironomids. The grazing chironomid larvae settled on the mesocosm surface and often dislodged algal turf surrounding their

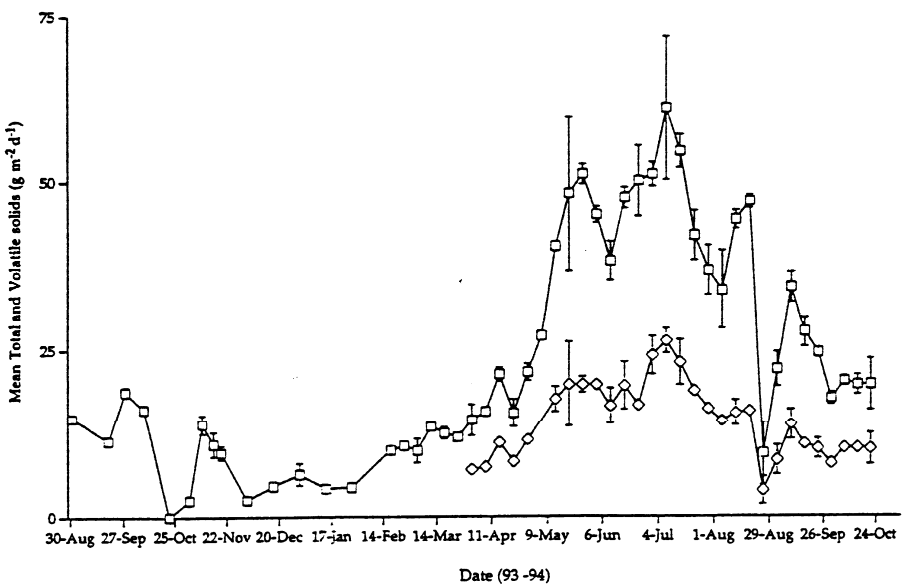

Fig. 2. Total (□) and volatile (◇) solids harvested from the ATS/mesocosm. Values are means ± S.D. of two composite samples, each from five sites.

cocoons. They were most prevalent during August 1994, when they caused algal productivity to be reduced (Fig. 2). However, drying out the mesocosm following harvest on the 26th August, successfully killed the larvae, and productivity of the mesocosm was quickly restored by seeding. Chironomids and amphipods were generally present in the system, at low to moderate levels, and were often a food source for wading birds, especially sandpipers.

Table 2
Elemental composition of ATS/mesocosm harvested solids

Element	Mean ± S.D. content ($g\ kg^{-1}$) ($n = 8$)
N	30.93 ± 2.93
P	20.72 ± 1.55
K	7.23 ± 0.94
S	3.61 ± 1.03
Mg	29.49 ± 7.50
Ca	33.69 ± 8.07
Na	3.14 ± 1.01
Fe	14.81 ± 4.83
Al	17.06 ± 4.87
Mn	0.32 ± 0.10
Cu	0.03 ± 0.02
Zn	0.17 ± 0.03

Table 3
Comparison of ATS/mesocosm fall quarter total harvested solids composition and mean weekly pH at two hydraulic loading rates

Date	Hydraulic loading (m^3 day^{-1})	Mean weekly pH	Mean ± S.D. harvested solids (g m^{-2} day^{-1})	Content (g kg^{-1})				Removal (g m^{-2} day^{-1})	
				N	P	Mg	Ca	N	P
23 Sept.	889	9.47	24.47 ± 0.20	33.70	21.23	25.13	26.70	0.82	0.52
21 Oct.	436	10.08	19.73 ± 3.80	32.17	23.37	30.80	35.90	0.63	0.46

3.2. Productivity

The productivity of the system, measured as harvested solids (algal and bacterial biomass, grazers, trapped particulates and adsorbed or precipitated compounds) varied over the year, due to changes of season and solar irradiance, and had a mean of 23.8 ± 16.4 g m^{-2} day^{-1} (dry wt.), summer maximum of 60.9 g m^{-2} day^{-1} and winter minimum of 4.2 g m^{-2} day^{-1}. The mean yearly productivity (excluding the periods of shutdown due to power failures or other factors) exceeded 35 g m^{-2} day^{-1}. The decrease of hydraulic loading rate to 436 m^3 day^{-1} in the fall quarter seemed to reduce the seasonal decline in productivity (Fig. 2).

3.3. Nutrient removal

Elemental composition of harvested solids included nutrients and a variety of heavy metals (Table 2). Analysis of N and P content in the biomass show mean concentrations of 3.1% N and 2.1% P. Based on these percentages of harvested solids and mean productivity over the one-year study, mean removal of nitrogen was 1.11 ± 0.48 g m^{-2} day^{-1} and mean removal of phosphorus was 0.73 ± 0.28 g m^{-2} day^{-1}.

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. Concentrations of phosphorus and the cations magnesium and calcium in the harvested biomass show an inverse relationship to hydraulic loading rate (Table 3). However, nitrogen content of biomass was actually reduced at the lower hydraulic loading rate (Table 3).

Yearly and fall quarter means ± S.D. of parameters measured in the ATS/mesocosm influent and effluent are shown in Tables 4 and 5. Large standard deviations of the yearly and fall data reflect the wide variations in the influent concentrations and changes in operational parameters during the evaluation period (Tables 4 and 5). However, yearly means indicate general trends of treatment by the system, which are most clearly

Table 4
Yearly means ± S.D. of parameters measured in the influent and effluent of the ATS/UV system

Parameter	Yearly mean ± S.D. ($n = 76$)	
	Influent	Effluent
Temperature (°C)	18.9 ± 5.3	24.4 ± 6.9
Dissolved oxygen (mg l^{-1})	4.8 ± 3.1	24.9 ± 4.9
pH	8.4	9.5
Alkalinity (mg l^{-1} as $CaCO_3$)	235.0 ± 34.4	210.4 ± 30.8
Hardness (mg l^{-1} as $CaCO_3$)	460.7 ± 27.0	435.0 ± 23.1
Conductivity (μS cm^{-1})	2153 ± 101	2060 ± 91
Ammonium (mg l^{-1})	3.3 ± 6.7	2.5 ± 5.6
Nitrate/nitrite (mg l^{-1})	5.0 ± 7.5	3.8 ± 5.9
Total Kjeldahl nitrogen (mg l^{-1})	5.0 ± 9.5	3.9 ± 6.0
Soluble reactive phosphorus (mg l^{-1})	2.7 ± 1.2	1.2 ± 1.0
Total phosphorus (mg l^{-1})	3.1 ± 1.0	1.7 ± 0.9

Table 5
Fall quarter means ± S.D. of parameters measured in the influent and effluent of the ATS/UV system at two hydraulic loading

Parameter	Fall quarter (889 m^3 day^{-1})		Fall quarter (436 m^3 day^{-1})	
	Mean ± S.D. ($n = 8$)		Mean ± S.D. ($n = 11$)	
	Influent	Effluent	Influent	Effluent
Temperature (°C)	23.6 ± 1.2	29.3 ± 2.1	19.0 ± 2.8	25.5 ± 3.4
Dissolved oxygen (mg l^{-1})	5.0 ± 1.3	21.1 ± 3.6	3.3 ± 1.0	23.0 ± 3.8
pH	8.1	9.3	7.7	9.8
Alkalinity (mg l^{-1} as $CaCO_3$)	245.1 ± 17.6	223.9 ± 18.2	244.8 ± 11.3	192.9 ± 14.8
Hardness (mg l^{-1} as $CaCO_3$)	480.8 ± 8.1	454.2 ± 10.4	484.1 ± 17.7	422.0 ± 20.2
Conductivity (μS cm^{-1})	2156 ± 63	2060 ± 51	2181 ± 106	2027 ± 64
Ammonium (mg l^{-1})	0.0	0.0	0.0	0.0
Nitrate/nitrite (mg l^{-1})	4.2 ± 2.6	2.2 ± 1.8	2.1 ± 2.4	0.9 ± 1.6
Total Kjeldahl nitrogen (mg l^{-1})	1.4 ± 0.2	1.4 ± 0.2	1.1 ± 0.2	1.0 ± 0.2
Soluble reactive phosphorus (mg l^{-1})	3.1 ± 0.1	0.9 ± 0.3	3.0 ± 0.5	0.4 ± 0.3
Total phosphorus (mg l^{-1})	3.5 ± 0.1	1.2 ± 0.3	3.7 ± 0.3	0.8 ± 0. < 2

seen in the fall quarter means when the complete ATS/UV system was operating. The mesocosm reduced concentrations of all nutrients in the wastewater (Tables 4 and 5). Alkalinity, conductivity and hardness of the wastewater were also reduced, while temperature, dissolved oxygen concentration (DO) and pH increased (Tables 4 and 5).

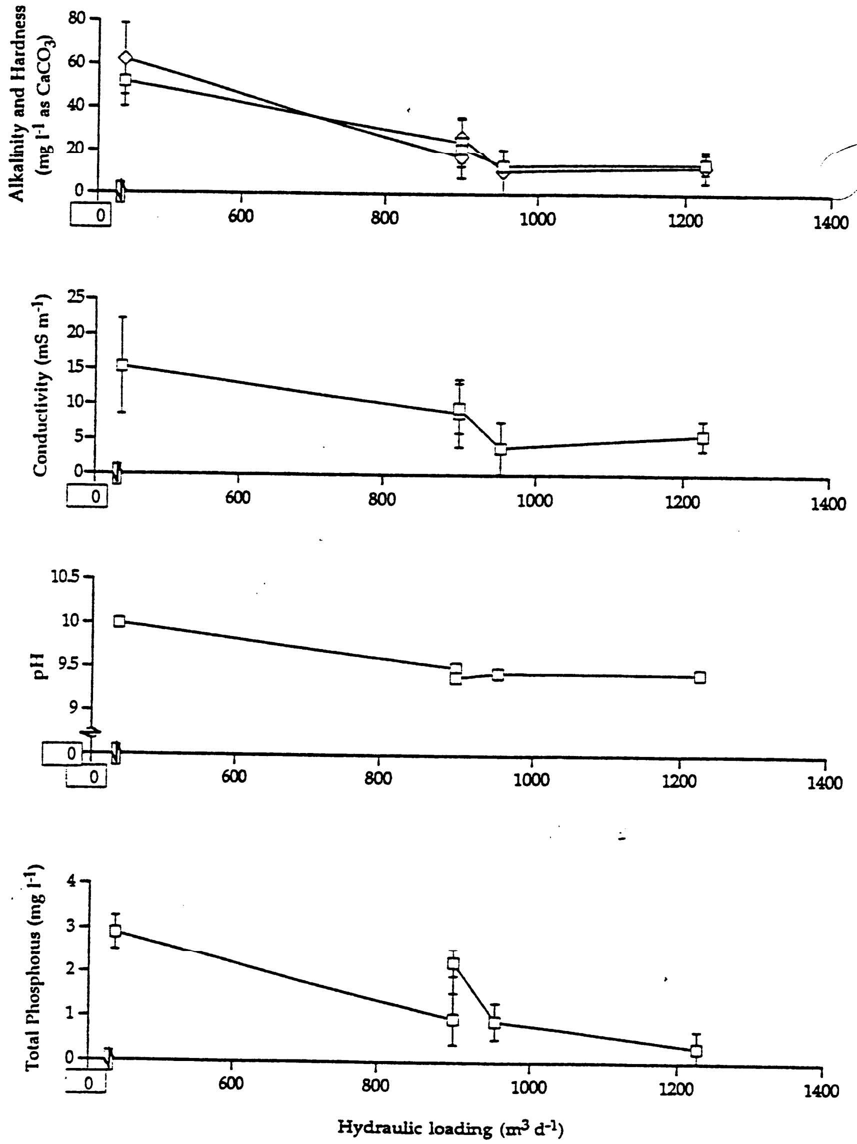

Fig. 3. Total phosphorus removal, alkalinity, conductivity and hardness reduction and effluent pH of the ATS/UV system at different hydraulic loading rates. Values are means ± S.D. ($n = 19$).

Table 6
Comparison of mean daily ammonium, nitrate/nitrite and total Kjeldahl nitrogen removal and mean daily pH values with influent concentrations at two hydraulic loading rates during the fall quarter

Date	Hydraulic loading (m^3 day^{-1})	ATS effluent mean pH	Nitrate/nitrite		Total Kjeldahl nitrogen		Total nitrogen removal (mg l^{-1})	Mass N removed (g m^{-2} day^{-1})
			Influent concentration (mg l^{-1})	Removal (mg l^{-1})	Influent concentration (mg l^{-1})	Removal (mg l^{-1})		
			Means ± S.D.	Means ± S.D.	Means ± S.D.	Means ± S.D.		
Daily means								
19–23 Sept.	889	9.5	7.7 ± 0.6	3.2 ± 1.2	1.1 ± 0.4	1.1 ± 0.1	4.4	3.9
17–21 Oct.	436	10.1	1.2 ± 0.2	1.0 ± 0.1	1.0 ± 0.1	0.8 ± 0.1	1.8	0.8
24 h means								
20–21 Sept.	889	9.3	7.8 ± 0.5	1.8 ± 1.7	1.2 ± 0.1	0.1 ± 0.2	1.9	1.6
19–20 Oct.	436	9.8	0.9 ± 0.1	0.8 ± 0.1	1.0 ± 0.1	0.2 ± 0.1	0.9	0.4

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 5). When these parameters are plotted against hydraulic loading rate for the entire year an inverse relationship can be seen (Fig. 3).

A comparison of 24-h total removal of phosphorus and mean daily removal of phosphorus, as determined by the 11:00 a.m. samples for the fall quarter, indicates that the lower hydraulic loading rate caused increased daily removal, but not increased diurnal removal (Table 6). The pH of the ATS/UV effluent showed an inverse relationship with hydraulic loading rate, indicating that pH was most likely involved in the reduction of phosphorus and cations (Fig. 3).

4. Discussion

The ATS system used in this experiment was a controlled ecology that was designed and operated to simulate the functions of a self-purifying natural stream and favour a particular biological community. The subsystems involved in water purification by ATS systems are turbulence, current velocity, water depth and the heterotrophic and autotrophic biological community. Wave action has been shown to have a major impact on primary ecosystem processes such as photosynthesis and respiration (Adey and Hackney, 1989). The ATS wave surge stimulates metabolism by reducing boundary layers and mixing the water (Adey and Hackney, 1989; Adey and Loveland, 1991). High current velocity allows increased exchange of oxygen, carbon dioxide, nutrients and wastes among the biotic community and has previously been shown to increase the productivity of ATS communities (Adey and Hackney, 1989). By contrast, in the present study reduction of current velocity in the fall quarter halted the seasonal decline in production due to the loss of solar energy (Fig. 2). At high current velocities there is a trade-off between reduced colonization but increased metabolism of established communities. The reduced hydraulic loading in the present study enables increased colonization of the floway. Algal production generally declines with increased water depth (Adey and Hackney, 1989). Vymazal (1988) found periphyton growth was much higher at shallow depth (0.06 m) than deeper (0.64 m). A 0.02–0.04 m depth of wastewater was maintained over the floway surface of the stream mesocosm which allowed optimum exposure of the autotrophs o ambient solar irradiation.

The ATS biological community consists of a heterogeneous assemblage of bacteria, phytoplankton and attached periphyton. The algal turf community probably consisted of those species most adapted to, or tolerant of, the growth conditions on the floway surface, which resembled a longitudinal successional stage of a nutrient enriched stream (Hynes, 1971; Marcus, 1980). The structure of the community was similar to that previously described for ATS (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 algal species comprising the turf can be divided into three ecological types: mat-forming species which were primarily Cyanophyta, green filamentous periphyton growing through the matted layer to produce a canopy, and diatomaceous epiphytes growing on the canopy and embedded within the mat.

Cyanobacteria are generally known to prefer nitrate as a nitrogen source (Richmond, 1983). Prevalence of nitrate in the influent wastewater used during this study may explain the dominance of *Oscillatoria* sp. and other cyanobacteria on the floway. A lack of algal spores in the Patterson treatment facility effluent, which are necessary for seeding of the floway, probably contributed to the low species diversity and reduced performance of the ATS/stream mesocosm during the first three quarters. In contrast, seeding of the floway in the sixth week of the summer quarter increased periphyton species diversity. Algal species diversity was probably maintained on previous ATS floways by recirculating spore laden water through the mesocosms (Adey and Loveland, 1991) or using influent from natural water bodies (Adey et al., 1993). Several algal genera (including *Spyrogyra, Ulothrix, Hormidium, Stigeoclonium, Oedogonium, Microspora* and *Microthamnion*) are also known for their ability to remove nitrate (Vymazal, 1988; Sladeckova et al., 1983) and many of these genera were present in the stream mesocosm (Table 1).

Harvesting kept the populations of most grazers under control. However, chironomid larvae reduced algal productivity at the end of August to the degree that it was necessary to dry out the floway. The explosive presence of chironomids seems to be only a seasonal problem (Lock et al., 1984; Davis et al., 1990b). Drying out the turf provides a simple method of control, especially when recolonization and development of the algal turf is aided by seeding from nearby streams. Within 2 weeks after drying out, the seeded floway had reached typical levels of productivity. In comparison, other screen seeded floways have required 6–12 weeks and several harvests to bring them to full production (Adey and Loveland, 1991).

4.1. Productivity

The ATS harvested solids indicate the highest productivities reported. Maximum harvested solids (total solids dry weight) observed in this study (60.9 m^{-2} day^{-1}) are much greater than previously reported productivity of periphyton water treatment systems (22 g m^{-2} day^{-1}; Davis et al., 1990b), phytoplankton growing in sewage enriched outdoor mass cultures (Oswald, 1988), and the highest values reported for macrophytes (Reddy and DeBusk, 1987). It even exceeds the maximum productivity of phytoplankton (40–50 g m^{-2} day^{-1}) measured in laboratory experiments (Spectorova et al., 1981). 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., 1990a; Adey and Loveland, 1991). Sedimentation, filtration and precipitation of inorganic particulates on the floway surface attributed to the high non-volatile component of the total solids.

Harvesting the floway has a dual role. It simulates heavy grazing of the plant community which has been shown to stimulate algal growth and nutrient removal (Sladeckova et al., 1983; Davis et al., 1990b; Adey and Loveland, 1991). It also keeps the populations of natural invertebrate grazers in check so that pollutants remain

Table 7
Comparison of mean daily phosphorus removal and mean daily pH values with influent concentration at two hydraulic loading rates during the fall quarter

Date	Hydraulic loading (m^3 day^{-1})	Mean ATS effluent pH	Total phosphorus		Mass TP removed ($g\ m^{-2}\ day^{-1}$)
			Influent concentration ($mg\ l^{-1}$)	Removal ($mg\ l^{-1}$)	
			Means ± S.D.	Means ± S.D.	
Daily means					
19–23 Sept.	889	9.47	3.40 ± 0.08	2.05 ± 0.45	1.82
17–21 Oct.	436	10.08	3.40 ± 0.05	2.65 ± 0.24	1.12
24 h means					
20–21 Sept.	889	9.27	3.35 ± 0.07	0.61 ± 1.62	0.54
19–20 Oct.	436	9.81	3.30 ± 0.07	0.58 ± 1.71	0.25

entrapped in the turf community and are not reintroduced to the water. Harvesting in this stream mesocosm also simulates the export inherent in natural streams due to organism mediated removal to the terrestrial environment and discharge at the terminus of the stream. The harvest interval should be varied with solar irradiance and time of year, to maintain sufficient biomass on the ATS floway. Results of the present study show that a harvest interval of less than one week may be appropriate when the highest productivities were recorded during the summer, while intervals of up to a month may be required during winter when productivity is at its lowest (Fig. 2).

4.2. Nutrient removal

This study demonstrates the tertiary treatment capability of an ATS configured as a controlled stream environment. Both nitrogen and phosphorus were reduced by the ATS/UV system (Table 2, Table 3, Tables 4 and 5). The nitrogen content of the total harvested solids during the fall quarter was 3.3% (Table 3). However, the calculated nitrogen concentration of the volatile solids was 7.3%, which is more typical for algal biomass (Bogan, 1961). The mass of nitrogen removed per day by the ATS based on 24-h removal during the first diurnal of the fall quarter was 1.64 $g\ m^{-2}\ day^{-1}$ (Table 7). However, the mass removed per day based on the nitrogen content of the harvested biomass for the week of the first diurnal of the fall quarter was only 0.82 $g\ m^{-2}\ day^{-1}$ (Table 3). This discrepancy of nitrogen mass balancing indicates that there was nitrogen removal by a process other than assimilation, perhaps bacterial denitrification in an anaerobic zone at the base of the mat. The decline in the percent nitrogen of the biomass with decreased hydraulic loading rate in the fall quarter (Table 3) may have been due to increased carbon deficiency of the system, which was indicated by an increase in pH of the ATS/UV effluent. Adjustments to increase the carbon supply may improve nitrogen removal by the ATS.

Periphyton may remove phosphorus from wastewaters by either filtration of particulates, adsorption, assimilation (including luxury uptake), or precipitation (Bogan, 1961;

Swift and Nicholas, 1987). Most of the total phosphorus in the Patterson treatment facility effluent was soluble reactive phosphorus, suggesting that removal was either by assimilation or precipitation. Inverse relationships between hydraulic loading and 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 hydraulic loading was reduced, hardness reductions and pH increased, as did 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 (Swift, 1981; Auer and Canale, 1982; Kesler, 1982; Davis et al., 1990a). The precipitation of phosphorus with cations (such as Ca^{2+} and Mg^{2+}) at high pH is known to begin 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 (Richmond, 1983; Fabregas et al., 1984; Soeder and Hegewald, 1988). Higher phosphorus removal (as much as 80%) at the lower hydraulic loading rate (436 m^3 day^{-1}) during the fall quarter, was measured by both biomass content and daily removal (Tables 3 and 5 and 5b), and was probably due to increased pH-mediated precipitation. Dissolution of some of this precipitate at night, when pH declined to below 8.9 accounts for the lower 24 h phosphorus removal rates (Table 6).

Maintenance of the pH of the ATS/UV system effluent above that at which precipitation occurs may provide a simple means of optimizing 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 effluent at night, or greatly reducing the hydraulic loading at night such that no water is discharged. The decrease in the mass of nitrogen and 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 7 and 6; Fig. 2). However, the ATS/UV system reduced both N and P concentrations with hydraulic loading rates which exceed rates reported for both wetland and microalgal pond treatment systems (Watson et al., 1989; Richardson et al., 1991; Oswald, 1988). In the system described here, considerably greater diurnal unit area removal rates of nitrogen and phosphorus would be achieved by operating only during daylight at higher rates of hydraulic loading.

Previous studies have shown ATS systems to remove nutrients from low levels in agricultural runoff and marine systems. In coral reef mesocosms, nitrate and nitrite levels can be maintained at levels of 0.5–1.0 μM (7–14 ppb) (Adey and Loveland, 1991). This is a level limited by nitrogen fixation by cyanobacteria. Phosphorus, not limited by atmospheric input, can be reduced below limits of detection. An experimental ATS system in Florida achieved phosphorus removal rates of 104 to 139 mg TP m^{-2} day^{-1} from agricultural run-off (Adey et al., 1993). Perhaps high levels of phosphorus could first be removed by pH-mediated precipitation, and lower concentrations could then be reduced by rapid algal growth on a second floway run in series. Combinations of floway configurations may therefore be used to meet the desired levels.

The ATS autotrophs raised the DO of the effluent to 100–300% saturation, and the odorless nutrient removal provided should be contrasted with the highly odorous bacterial tertiary treatment processes typically in use for sewage treatment. Furthermore, such processes are costly due to their high energy requirement and use of chemicals and enclosed reactors. The high oxygen levels may also contribute to the breakdown of complex organic compounds and reduction of COD (Adey et al., 1996). The filamentous algae not only provide oxygen to drive heterotrophic decomposition of organic compounds but also increase the surface area for bacteria to colonize.

In many instances, chlorination is used to disinfect partially treated municipal sewage prior to discharge. But, since chlorine residues may be toxic to aquatic life. the chlorinated effluent must be dechlorinated. Recently, chlorination has been related to the production of organic carcinogens, such as trihalomethanes in wastewaters. UV treatment is an acceptable alternative in the state of California. The short residence time (typically 20–40 min) of wastewater on the ATS floway itself permits inconsistant disinfection. However, the combination of the ATS with sand filtration and UV disinfection at Patterson enables consistantly complete removal of both fecal bacteria and viruses (Craggs et al., 1994).

Results presented in this paper indicate the potential of a controlled stream mesocosm for nutrient 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 optimization of the system for treatment of wastewaters with highly differing contaminant ratios.

5. Conclusions

The controlled use of constructed stream ecosystems, as in an ATS format, enhances and optimizes the self-purification mechanisms of natural waterways through:

1. Entrapment of organic detritus;
2. Heterotrophic breakdown of organic compounds;
3. Autotrophic assimilation, adsorption and chemical precipitation of nutrients from the water column;
4. Restoration of the DO and pH of the wastewater;
5. Assimilation, adsorption and precipitation of dissolved heavy metals;
6. Removal of pathogenic organisms when combined with UV disinfection.

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