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ENVIRONMENTAL ENGINEERING AND HEALTH SCIENCES LABORATORY (EEHSL)

EEHSL REPORT NO. 96-2

Investigation and Evaluation of the Feasibility and Performance of the Algal Turf Scrubbing Process at the City of Patterson Wastewater Treatment Plant

Final Report

by

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April 1996

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April 4, 1996

Richard Purgason
Aquatic BioEnhancement Systems, Inc.
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Sugar Land, TX 77479

Dear Mr. Purgason:

Enclosed please find EEHSL Report No. 96-2 entitled "Investigation and Evaluation of the Feasibility and Performance of the Algal Turf Scrubbing Process at the City of Patterson Wastewater Treatment Plant" Final Report.

It is clear that the ATS removes significant amounts of nitrogen and phosphorus and is capable of converting ammonium to nitrate which is often regarded as beneficial in receiving waters and, of course, is easily denitrified in an anoxic environment.

Among the improvements that stand out for future work are: improved floway surfaces, lengthened floways, and improved wastewater application systems. Many other crucial experiments could be better done on smaller floways in a research setting. It is clear from our research that lengthened floways should permit greater removals of nitrogen and phosphorus and thus increase the overall percent removal of these elements.

We want to commend Rupert Craggs for his superior work and note that several Graduate Research Assistants, especially Abra Bentley and Song Ling Ng, worked long and hard to produce the many associated analytical results. We thank you for your support of this valuable research and wish you every success in the further development of the ATS technology.

Cordially yours,

William J. Oswald

William J. Oswald, P.E., Ph.D.
Professor Emeritus Public Health and
Environmental Engineering

WJO/ds

cc: Sponsored Projects Office

P.S. Please let us know your requested distribution for this report, and we will provide you with the needed copies.

Executive Summary

This summary describes the second phase of experimental work with an Algal Turf Scrubber (ATS) at Patterson, California and recommends further studies. The ATS is an invention of Dr. Walter Adey of the Smithsonian Institution, Washington D. C. and was evaluated for use in Patterson by the Applied Algae Research Group of the Environmental Engineering and Health Sciences Laboratory, University of California, Berkely under contract with Aquatic Bio Enhancement Systems, Inc.

As currently constructed at Patterson, the ATS is a two dimensional, (6.5 m x 152.4 m, 990 m^2) fixed film reactor. It is lined with black, rough heavy plastic (HDPE) and an over-lying screen, and has confining side walls. It is primarily a nutrient removal system intended to improve the quality of wastewater by growing a periphyton mat or turf (consisting of filamentous algae and symbiotic aerobic bacteria and fungi) on the surface of a gently sloped, continuously wetted floway. Nutrients for growth of the organisms are extracted from wastewater and possibly from the air in contact with the surface of the film. Sunlight is the primary source of energy for growth of the photosynthetic portion of the fixed film. Added energy for bacterial and fungal growth may be extracted from organic matter in the wastewater when present, or from new organic matter excreted by the algae. In order to maintain continuing growth the film is harvested periodically with a scrapping and dewatering apparatus designed by Rupert Craggs.

The purposes of the second phase of the experimental evaluation at Patterson were:

1) To evaluate the feasibility and performance of the ATS process applied to tertiary wastewater treatment, specifically the removal of nitrogen (especially, ammonium) and phosphorus from secondary wastewater effluent.

2) To optimize algal production by the use if screens attached to the ATS floway surface using secondary treated wastewater as a substrate.

3) To evaluate the capability of the ATS to treat wastewater with higher BOD and SS concentrations than those present in the Patterson secondary effluent.

Few problems were encountered in developing a dense "turf" covering the entire floway, and successful harvesting of the turf was attained with a new harvester. The solids accumulation means for the west and east sides of the split floway were 17.72 ± 9.76 and 18.43 ± 11.06 g m^{-2} d^{-1} (dry wt) respectively which were considerably lower than that of floway in the initial evaluation (23.75 ± 16.39 g m^{-2} d^{-1} (dry wt)). Approximately half of the dry weight was ash, including calcium carbonate and possibly calcium ammonium phosphate.

The initial hydraulic loading velocity (HLV) on the floway in Phase 2 (1.4 m d^{-1}) was excessive when comparing nutrients applied vs. nutrients removed. Decreasing the

HLV to 0.4 m d^{-1} and then 0.2 m d^{-1} resulted in an increased pH and improved phosphorus removal. It resulted in improved metal removal, although this was not studied extensively. It was noted that much of the algal turf consisted of cyanobacteria and diatoms both favoring nitrate to ammonium as their source of nitrogen. Nitrate is of course the principal form of inorganic nitrogen discharged by Patterson's extended aeration oxidation ditch. Addition of ammonium to the secondary wastewater demonstrated that it is removed by the ATS; however, much of the removal was due to nitrification to nitrite/nitrate. A materials balance appears to indicate some denitrification on the floway, perhaps indicating denitrification in an anoxic micro environment of the algal turf.

A further reduction of HLV to 0.11 m d^{-1} did not show an improvement in phosphorus removal, but this result was probably more a function of the winter climate than reduced HLV. The ATS, like all photosynthetic systems is strongly influenced by climate and can most visibly be seen by the shift in the dominant algal species during early winter. Accordingly, system designs must accommodate periods of cold weather. In comparing the HLV levels thus far explored with those for other natural systems, it appears that reductions in HLV to as low as 0.25 m d^{-1} would improve performance and remain competitive. The 0.44 m d^{-1} loading appeared give the best performance in terms of P and N removal. Accordingly these levels of HLV should be explored further before designs are finalized. We have found the ATS to evidence very little decrease in soluble effluent BOD, but the lack of soluble BOD removal is neither unexpected nor needed, since there are already many efficient BOD removal systems in use. When filamentous species were in abundance on the floway, removal of particulate BOD and suspended solids was achieved. However, the experimental duration was too short for any firm conclusions to be made regarding its economic BOD removal. Patterson's secondary effluent DO concentrations are greatly improved by the ATS. With more green algae on the floway and lower HLV, we can expect improved N removal and virtually complete P removal. The odorless nutrient removal promised by the ATS should be compared with the highly odorous processes now used that are very expensive because they require huge amounts of energy and must be enclosed to avoid odor nuisance and complaints. The ATS is odorless and requires minimal energy inputs.

It should be kept in mind that, as its name implies, the ATS is primarily a reducing system which has the potential to remove carbonates, nitrates, ammonium and phosphorus from waste streams. Removal is dependent on a number of parameters including hydraulic loading, biomass growth and attainment of a pH greater than 9.0 in the effluent. More available organic carbon than is present in the Patterson effluent may be required to produce sufficient biomass to make phosphorus and nitrogen limiting.

In the current studies the "Algal Turf Scrubber (ATS)" has been found to be capable of removal of residuals of nitrogen and phosphorus without added chemicals and with a minimum of energy expenditure. Because of this it may turn out to be a powerful tool for removal of trace amounts of phosphorus and ammonium and for nitrifying ammonium. The major applications of the ATS may then be remediation of pre eutrophic reservoirs and lakes; for polishing tertiary effluents and for algal biomass production.

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1.0 Introduction

The present study continued the investigation and evaluation of the Algal Turf Scrubber (ATS) system at the City of Patterson wastewater treatment plant. The previous evaluation (Craggs *et al.*, 1994) showed that the effluent from the ATS followed by filtration and ultraviolet (UV) disinfection should meet the current RWQCB requirements for discharge to the San Joaquin River. This initial study demonstrated the ATS technology at large-scale (990 m^2) and the ability to easily remove the accumulated solids from the floway. Moreover, the initial research at Patterson indicated the capability of the ATS system for tertiary nutrient removal from secondary wastewater. However, there were several limitations to the Phase 1 evaluation. Nutrient removal data for the ATS in its final configuration (Pond 3A - ATS - sand filters - UV) was only collected during the Fall quarter of 1994. Few measurements of the nutrient content of the ATS accumulated solids were taken so reliable mass balance calculations could not be made. It was also apparent that the concentrations of some parameters (particularly SS, BOD and ammonium) of the Patterson secondary clarified effluent were too low to show adequate removal by the ATS system. Much was learned about the operational parameters of the ATS system, although detailed evaluation of parameters such as hydraulic loading velocity only began in the Fall quarter of 1994. Other operational parameters such as floway texture and harvesting regime which may also influence nutrient removal and productivity were not investigated during Phase 1.

The second phase of research was designed to address some od the remaining questions and had the following primary objectives:

1) To evaluate the feasibility and performance of the ATS process applied to tertiary wastewater treatment, specifically the removal of nitrogen and phosphorus from secondary municiple wastewater effluent.

2) To evaluate algal production using a screen attached to the ATS floway receiving secondary treated wastewater as a substrate.

3) To evaluate the capability of the ATS to treat wastewater with higher BOD and SS concentrations than those present in the Patterson secondary clarified effluent.

Several operational parameters described below were investigated to further characterize the performance of the ATS as a tertiary wastewater treatment technology and provide basic engineering feasibility and process design information:

Maintenance of Standing Crop

A sufficient standing crop of algal biomass is required to maintain effective regrowth and treatment immediately following harvest. The operational parameters which influence the standing crop of the ATS are floway texture and harvest interval.

Floway texture

The texture of the floway surface seems to be of particular importance for the maintenance of algal species diversity and the promotion of algal productivity. Previous research with algal turf scrubbers used a screen on the floway surface (Adey & Goertemiller, 1987; Adey & Hackney, 1989; Adey & Loveland, 1991; Adey *et al.*, 1994). The mesh becomes impregnated with algal holdfasts and rhizoids, which are not removed during harvest (Brawley & Adey, 1981; Adey & Loveland, 1991). Algal productivity has been found to vary with the screen mesh size and color (black or white) (Adey and Hackman, 1989). Very little standing crop of algal remained on the Patterson floway (which was made from a black rough-surfaced HDPE land-fill liner), following vacuum harvest during Phase 1. The poor establishment of filamentous species on the floway may also have been due to the absence of a screen, since without the screen, filamentous species were the first to be removed by vacuum harvest. Installing a screen on the floway surface may improve the performance of the Patterson ATS. The aim of this portion of the study was to identify an economical floway surface which maintained a sufficient standing crop and algal species diversity following harvest. The susceptibility of a screen to invertebrate infestation was also taken into account during the selection experiments.

Harvest interval

A harvest interval of one week was mainly used during Phase 1. The changes in the rate of solids accumulation on the ATS resulting from the seasonal variation in solar irradiance and temperature indicate that varying the harvest interval to maintain sufficient biomass (standing crop) on the ATS floway may improve performance. The results from Phase 1 show that a harvest interval of less than one week may be appropriate during the summer months when the highest solids accumulation rate was recorded. Harvest intervals of up to one month may be required during the winter when the solids accumulation rate was at its lowest. Harvest interval studies were conducted to determine optimal harvest intervals and whether efficient treatment could be maintained and invertebrates controlled without harvesting at all.

Residence Time

Treatment by the ATS will partly be a function of the time the wastewater is in contact with the algal turf (hydraulic residence time). A simple means of optimizing treatment may be by controlling residence time. This operation control could be achieved either by altering the hydraulic loading velocity or passing the wastewater down variable lengths of floway.

Hydraulic loading

In Phase 1 it was shown that phosphorus removal could be increased by reducing the hydraulic loading velocity and thus increasing the residence time of water on the floway and the pH of the ATS effluent. Maintenance of the pH of the ATS system effluent above the level at which phosphate precipitates may provide an effective means of optimizing phosphorus removal.

Floway length

For a particular hydraulic loading, a certain length of floway will be required for efficient treatment to be achieved. Various hydraulic loading velocitys were tested and water quality profiles were taken down the length of the floway so that the relationship between hydraulic loading, floway length, solids accumulation and treatment efficiency could be investigated.

Overnight Flow

Night time release of phosphorus was observed during the diurnal testing of Phase 1. Overnight phosphorus release might be avoided by reducing overnight flow to a minimum, until the following morning when the effluent pH has risen to the threshold point at which phosphate precipitation occurs again. Several diurnal studies were conducted, some with overnight flow and others during which overnight flow was stopped, so that 24 hour treatment efficiency could be compared.

Type of Effluent

Carbon

The slight decrease in nitrogen removal efficiency at the lower hydraulic loading velocities used during Phase 1 was possibly caused by carbon limitation to algal growth. The use of an influent with higher BOD levels may improve nutrient removal by assimilation since the algal turf would be less carbon limited. BOD removal by the Patterson ATS system during Phase 1 was poor. The removal of BOD and COD by ATS/mesocosms has been previously described (Adey *et al.*, 1994), although the precise mechanisms of removal remain uncertain. Furthermore, the recirculating systems used by Adey *et al.* had different operational parameters than the linear large-scale floway at Patterson. During a portion of the current investigation, Patterson's Pond 1 settled effluent, a wastewater with higher BOD concentrations than the secondary clarified effluent was evaluated as an alternative influent for the ATS floway.

Ammonium

Algae assimilate ammonium more readily than nitrate, and ammonia may be removed by volatilization at high pH (Figure 1.1). Higher nitrogen removal by the

ATS may be achieved with an influent containing ammonium rather than nitrate as the main source of nitrogen. The Patterson secondary clarified effluent usually contained high nitrate concentrations and little or no ammonium during Phase 1. Secondary clarified effluent containing ammonium was used as the influent for the floway to evaluate ammonium removal.

2.0 Materials and Methods

2.1 Patterson Algal Turf Scrubber

The pilot ATS treatment system built at the City of Patterson's municipal wastewater treatment plant has been previously described (Craggs *et al.*, 1994). The pilot-scale ATS was 152.4 m (500 ft) long and 6.5 m (21 ft 4 in) wide, had a total surface area of 991 m^2 (10667 ft^2), and was oriented so that water flowed from north to south. To maintain the uniform flow 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 (24") over the entire length. Wooden baffles were placed on the floway surface to more evenly distribute the wastewater down its length.

2.2 Evaluation of Tertiary Treatment Capability and Algal Production

Evaluation of the ATS system was conducted over a eleven-month period from the 3rd of April, 1995 to the 5th of March, 1996. Performance was related to seasonal variations, such as light intensity and temperature. The ATS was operated without the sand filters and UV disinfection unit used in Phase 1 since these components were required for effluent discharge to the San Joaquin River but are not relevant to nutrient removal by the ATS floway alone. All effluent samples were filtered through a 400 μm mesh to simulate the final effluent passive screen which would remove any algae sloughing off the floway.

The ATS was initially operated with influent taken from Pond 3A (Fig. 2.1) and under similar operational parameters to those of Phase 1 so that a comparison of the data could be made. The floway was split longitudinally into two sides (west and east) to increase the data collection and provide an environmental control (one floway remained unaltered while the other was manipulated in the experiments). Background operational data for the two floways was first gathered to identify any differences between them.

2.3 Sampling and Analytical Protocol

A monitoring schedule for water chemistry, nutrient concentrations, solids accumulation and composition, the methods used, and frequency of analysis is set forth in Table 2.1. The experimental protocol was designed to allow measurement of the highest and lowest treatment efficiency of the ATS. Water quality sampling was carried out twice per week on day 1 (the day following harvest) and day 7 (typically the day of harvest) prior to harvest. Samples were collected at 12:00 noon. In addition to the twice weekly sampling, nine diurnal studies were conducted during which single samples were taken at 4-hour intervals over a 24-hour period to determine the 24 hour variation in ATS treatment performance.

Each water quality parameter was monitored from samples taken in duplicate at three sites, the influent and the west and east effluents of the split floway, except during diurnal tests when only single samples were taken (Fig. 2.2). Samples for parameters which could not be measured directly were collected in clean deionized water-rinsed high density polyethylene bottles (Nalgene). The sample bottles were rinsed twice with the sample water and then filled to the top to prevent air spaces. Samples which required acidification to a pH of below 2 for preservation were treated appropriately with concentrated H_2SO_4 (APHA, 1995). All phosphorus samples were collected in dilute HCl acid-washed glass vials. Soluble reactive phosphorus (SRP) samples were prefiltered through a disposable 0.45 μm Millipore membrane filter immediately after sampling. All samples were stored on ice or in a refrigerator until analyzed. Sample analysis was performed by the Applied Algae Research Group laboratory of Professor Oswald at the Environmental Engineering and Health Sciences Laboratory, UC Berkeley. The water quality analyses were conducted according to Standard Methods for the Analysis of Water and Wastewater, 19th Ed. (APHA, 1995). Quality control of all parameters tested was maintained by the use of blanks, standards, splits, replicates and spiked samples.

Accumulated solids (algal biomass and inorganic material) of the two sides (west and east) of the split floway were sampled prior to harvest at weekly intervals from ten randomly located 0.093 m^2 (1 ft^2) sites. Samples were analyzed for total and volatile solids and for chemical composition.

Experiments to determine the effects of the following operational parameters on treatment performance and solids accumulation of the ATS were specifically made:

1) Floway Texture

Various types of screens were compared to each other and to the floway's textured HDPE liner for their ability to accumulate solids (since both algal growth and the removal of particulates on the screen contribute to treatment of the wastewater). An initial evaluation of 11 screen types was made based on accumulated solids (Figs. 2.3 & 2.4). Sections of various screens (10' by 2') were placed at two sites on the floway (top and bottom). The screen sections were placed side by side across the width of both sides (west, D-A, east, E-A) of the split floway where flow conditions were observed to be similar (Table 2.2, Fig. 2.5). The floway surface was seeded with algae collected from near-by streams, and the algal turf was allowed to establish itself for three weeks without harvest. Accumulated solids were measured after this period and then at weekly intervals for a additional five weeks (2nd May to 27th June). Samples were taken from a 1' by 10' strip down the middle of each screen and scrapped off using a plastic shovel. The samples were air dried on a 400 μm drying screen and the solids dry weight and volatile weight was determined. Following sampling the floways were completely harvested and reseeded.

Table 2.2 Screen type and position on the two sides of the split floway

	Screen Location	
Screen Type	Top Site (W - E)	Bottom Site (W - E)
Tensar (LG400321)	TWD	-
Jason Mills (1999MF60NAT) PE	TWC	-
Naltex (191-3317-1)	TWB	BEE
Tenax (green)	TWA	BED
Tenax (grid)	TEE	-
Conwed (XN2410)	TED	BEB
Bare Liner	TEC	BEC
Conwed (XB2970)	TEB	BWB
Conwed (XN1678)	TEA	BWD
Conwed (XV1678)	-	BWC
Conwed (XB1131)	-	BWA
Jason Mills (65MF50WAT) PE	-	BEA

To provide an indication of the nutrient removal capability of the ATS with a particular screen, the screen types which produced the greatest mass of accumulated solids were compared for solids accumulation and solids nutrient (nitrogen and phosphorus) content. The screen type with the greatest solids accumulation and highest nitrogen and phosphorus content was used to cover one side of the divided floway so that the screen-covered and bare -liner sides could be compared. Following a month long study comparing the treatment and solids accumulation of the screened side and the liner side of the floway, the second side of the floway was covered with the screen.

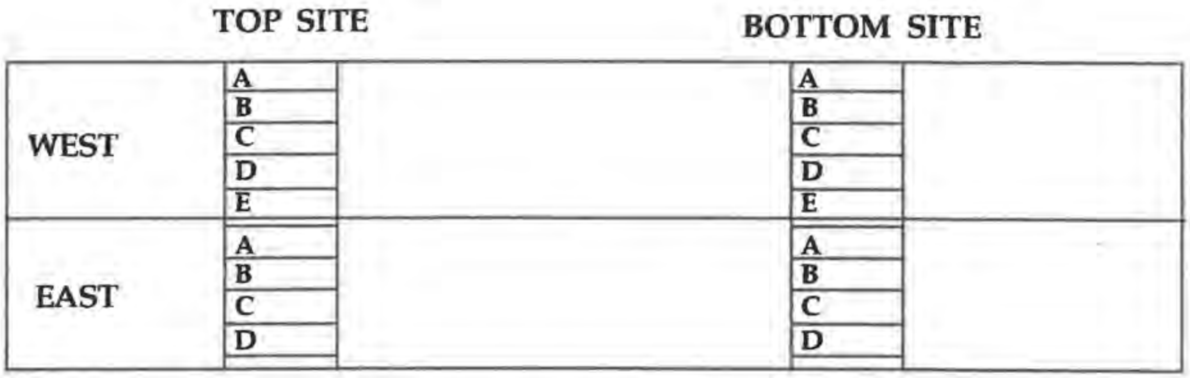

Figure 2.5 Position of the test sites for the screen experiments on the ATS split floway.

2) Hydraulic loading velocity

The influent was pumped using two 3-HP centrifugal pumps (Dayton Electric Mfg. Co., Illinois). To determine the effect of hydraulic loading on treatment performance and solids accumulation rate of the ATS, the influent hydraulic loading velocity of one or both sides of the split floway was varied from a maximum of 1.36 m d^{-1} during the summer to a minimum of 0.11 m d^{-1} during the winter. The flow rate was measured using a Doppler flow meter (Dynamic fluid systems, New York, model HFM-1).

3) Floway Length

Nutrient and physical parameters were measured at 100' intervals down each side of the split floway to establish a performance profile.

4) Overnight flow

The effect of zero night time discharge on nutrient removal (especially pH-influenced release of phosphorus) and physical parameters was evaluated. The hydraulic loading on one or both sides of the split floway was stopped overnight while diurnal measurements of water chemistry were taken. The overall treatment performance of overnight flow and zero discharge regimes were determined.

5) Harvest Interval

The influence of harvest interval and hence algal standing crop on treatment performance and solids accumulation was investigated. One side of the split floway with harvest intervals of up to one month was compared to the control side with a weekly harvest interval.

6) Higher BOD influent

To evaluate the ATS for treatment of a wastewater with higher nitrogen and BOD concentrations, the influent was taken from the evaporation/infiltration Pond 1 (Fig. 2.1) from October 1st 1995 to January 16th 1996. The pond intermittently received raw sewage and was used to dispose of the sludge from the oxidation ditch at the plant. Initially the west and east sides of the floway had hydraulic loading velocities (HLVs) of 0.22 m d^{-1} and 0.44 m d^{-1} respectively. On November 15th, following the harvest the HLV of the east side was reduced to 0.22 m d^{-1} and on December 13th the HLV of both sides was further reduced to 0.11 m d^{-1}.

7) Ammonia Dosing

From January 16th 1996 onwards the influent from Pond 3A was supplemented with additional ammonium in the form of ammonium sulphate (in concentrations ranging from 5 mg l^{-1} to 30 mg l^{-1} N) to investigate the capability of the ATS process to remove ammonium from wastewater.

3.0 Results

The water quality data comparing the treatment efficiency of the west and east sides of the split ATS floway collected during weekly testing and diurnal studies over the eleven months of the second Phase of evaluation are graphed in appendices 1 and 2. Many operational parameters were changed during the evaluation period to determine their effect on treatment performance. The point of division between each period of operation are shown on a transparent figure which can be placed over each of the figures. Although data collection was divided into separate periods during which a particular operational parameter was investigated the yearly mean ± s.d. values of all the parameters measured during the study provide a summary of the general treatment capability of the ATS system (Table 3.1). The large standard deviations of the yearly means were due to the wide variation of parameter levels in the influent and the operational changes (Table 3.1).

The general treatment capabilities of the ATS system were:

- Temperature, dissolved oxygen concentration (DO) and pH of the wastewater were all increased by the ATS system (Table 3.1).
- Alkalinity, conductivity and hardness of the wastewater were all reduced by the ATS system (Table 3.1).
- Concentrations of both ammonium and particulate organic nitrogen were reduced by the ATS system, while the concentration of nitrite/nitrate was increased (Table 3.1).
- Concentrations of all forms of phosphorus were reduced by the ATS system (Table 3.1).
- The ATS system was reduced turbidity and suspended solids and increased the UV % transmittance of the wastewater (Table 3.1).
- Although TDS concentrations were slightly increased by the ATS system (Table 3.1) the hardness was reduced and consequently the water was slightly softened.

These mean yearly treatment capabilities were very similar to those found during Phase 1 of the evaluation (Table 3.2; Appendices 3 & 4), although the influent and effluent concentrations of many of the parameters measured in Phase 2 were higher. The increase in the effluent nitrite/nitrate concentrations over the influent concentrations did not occur during Phase 1, but nitrite/nitrate was the main source of influent nitrogen in that study (Tables 3.1 & 3.2). Solids accumulation varied with seasonal changes in solar irradiance and temperature over the period of study (Fig. 3.1). The solids accumulation means for the west and east sides of the split floway were 17.72 ± 9.76 and 18.43 ± 11.06 g m^{-2} d^{-1} (dry wt) respectively which were considerably lower than that of floway in the initial evaluation (23.75 ± 16.39 g m^{-2} d^{-1} (dry wt)) (Fig. 3.2). The volatile solids content of the Phase 2 accumulated solids (49 %) was higher than that of Phase 1 (Tables 3.1 & 3.2). The N content of the solids was higher in Phase 2 than in the initial evaluation (Tables 3.1 & 3.2), whereas the P content was lower.

The results from the studies of each operational parameter are presented below:

3.1 Background Operation

Background operational data comparing the treatment efficiency of the west and east sides of the split ATS floway was collected over a six week period from June 7th to July 18th 1995. The hydraulic loading velocity of both the west and east sides of the floway was 1.36 m d^{-1}. Mean ± s.d. background daily and diurnal data for the west and east sides of the floway are shown in tables 3.3 and 3.4 respectively. The overall treatment by the west side was similar to that of the east. Treatment measured by water chemistry was slightly better for the west side than the east. Concentrations of all forms of nitrogen were reduced (Tables 3.3 & 3.4). The accumulated solids of the west were lower than the east and resulted in the lower nitrogen and phosphorus accumulation by the west (Table 3.3). The calculated nutrient accumulation was higher than the calculated nutrient removal on both sides (Table 3.3). Nutrient removal values for the diurnal study over the 26-27th June were similar on both sides, although N removal was higher than that calculated from the mean daily values and P removal was lower. The diurnal N and P removal was below the daily N and P accumulation values (Tables 3.3 & 3.4).

3.2 Floway Texture: Screening Experiments

The mean values for accumulated solids, volatile solids, nitrogen accumulation and phosphorus accumulation for each of the screens tested are shown in tables 3.5 to 3.8 respectively. The screens were ranked according to mean accumulated solids or nutrient removal. Solids accumulation and nutrient accumulation were higher for all the screen types than for the liner alone (Table 3.5 to 3.8). Screen rank was independent of floway test site, with similar solids and accumulation values found for the same screen placed at both the top and bottom test sites. The volatile content of the solids of each screen type was generally the same (40 to 50 %) and did not change the ranking order of the screens (Table 3.6). The nitrogen and phosphorus content of the accumulated solids varied little between the screens and did not alter the ranking order (Tables 3.7 & 3.8). White or natural colored screens had slightly higher accumulated solids than the black screens of the same mesh size (Table 3.5). The Conwed screen (XV1678), which has been used on previous ATS floways, and the larger mesh Conwed screen (XB1131) and Naltex screen (191-3317-1) with the same mesh size had the highest covering of filamentous algae. None of the screens tested were affected by Chironomids during the test period.

3.3 Floway Texture: Comparison of Screened and unscreened floways

Mean ± s.d. daily and diurnal data comparing the treatment provided by the screened west and unscreened east sides of the split ATS floway are shown in tables 3.9 and 3.10. Treatment by the ATS was only slightly improved by the addition of the screen. Organic nitrogen removal was improved by the screen addition, although the total N removal was lower than in the background study, while N removal by the unscreened floway remained the same (Tables 3.3 & 3.9). Daily and diurnal P removal was improved by the screen addition (Tables 3.9 & 3.10). Diurnal P removal was lower than that found for the background operation diurnal (Tables 3.4 & 3.10). Biomass accumulation on the screened floway was much lower than on the unscreened floway during this period of testing (Table 3.9).

3.4 Hydraulic loading velocity

Various hydraulic loading velocities were used throughout the eleven month study. During the study of background operation of the two sides of the split ATS floway both sides had a hydraulic loading velocity of 1.36 m d^{-1}. This loading velocity was considerably higher than the loadings used in Phase 1 of the evaluation when the highest loading was 1.21 m d^{-1} for the 1000 m^2 floway during the spring quarter of testing. Treatment by the ATS at this high loading velocity was found to be poor with little change between influent and effluent concentrations of both nitrogen and phosphorus (Tables 3.3 & 3.4).

The effects of three hydraulic loading velocities on treatment by the ATS system were measured between October 3rd and January 16th and are shown in tables 3.11 to 3.18. Table 3.14 best illustrates the results and shows that the lower hydraulic loading velocity (0.22 m d^{-1}) increased both the reduction of alkalinity, conductivity and hardness and the removal of all forms of phosphorus and organic nitrogen (Table 3.14). However, higher effluent nitrate concentrations were found at the lower hydraulic loading velocity (Table 3.14). Nitrogen and phosphorus removal and accumulation were both greater at the higher hydraulic loading velocity (0.44 m d^{-1}) (Table 3.14).

3.5 Floway Length: Profile studies

The results of a treatment profile down the length of the ATS split floway are shown in Figures 3.3 to 3.7. The change in many parameters (for example, DO, temperature and all forms of nitrogen) had a linear correlation with floway length (Figs. 3.3 & 3.6). There was and inverse relationship between ammonium removal and nitrate production down the length of the floways (Fig 3.6). Other parameters (particularly, pH, soluble reactive phosphorus, hardness and conductivity) all changed more rapidly at or after a length of 91.5 m (300 ft) (Figs. 3.3, 3.4 & 3.7). The relationship between solid removal and floway length was less apparent (Fig. 3.5).

3.6 Overnight Flow

Over the course of this second phase of evaluation of the ATS system three diurnal studies were conducted during which the flow to one or both sides of the split floway was stopped (Tables 3.13, 3.17 & 3.19; Appendix 2). In the first of these studies mean effluent concentrations of most parameters were lower for the floway without overnight flow (Table 3.13). Overnight release of high concentrations of nutrients and solids was observed on the west floway with overnight flow (Appendix 2). Mean weekly removal of both nitrogen and phosphorus was greater for the side with overnight flow. Mean 24 hour effluent nutrient concentrations in the second diurnal in which neither floway had overnight flow (Table 3.17) were lower than those from the previous diurnal when overnight flow was maintained (Table 3.16) despite similar influent concentrations. However, the lower volume of water treated on the side with no overnight flow resulted in lower weekly N and P removal. Mean phosphorus effluent concentrations were lower, while mean nitrogen effluent concentrations were higher for the floway without overnight flow during the third diurnal study (Table 3.19). As a result the weekly phosphorus removal was higher for the floway without overnight flow.

3.7 Harvest interval

The mean ± s.d. and % change of parameters measured over a one month period during which the west floway was not harvested and the east floway was harvested at weekly intervals are given in Tables 3.20 to 3.23. Both sides of the floway showed fairly similar treatment during week one when both had a 7-day harvest interval (Table 3.20). However, the reverse was true for nitrate effluent concentrations which increased over influent concentrations and resulted in higher N removal by the unharvested side. Accumulation of solids and N and P on the floways decreased with increasing harvest interval (Table 3.20 to 3.23). Organic nitrogen effluent concentrations were higher for the unharvested side of the floway than the side with a weekly harvest interval over the duration of the investigation. Removal of all forms of phosphorus was higher on the side with the weekly harvest interval.

3.8 Higher BOD influent

The total and soluble BOD concentrations of the influent and effluents of the split ATS floway for the test period using a high BOD influent are shown in Figures 3.8 and 3.9 respectively. The results show initial removal of both total and soluble BOD at 75 % by the west side and 50 % by the east side of the floway when their flows were 0.22 and 0.44 m d^{-1} respectively. Both influent BOD concentrations and removal declined throughout the length of the study, while effluent SBOD concentrations actually increased over influent levels from December 5th onwards. The west floway was not harvested for the period between November 22nd and December 13th, and although a two-week harvest interval did not decrease BOD removal, three-week and four-week harvest intervals had lower removal compared to the east floway which was harvested at weekly intervals. Total BOD removal was reduced overnight but much of the changes in effluent concentrations reflected those in the influent (Figures 3.10 & 3.11). Soluble BOD removal was variable over the diurnal study (Fig. 3.11).

3.9 Ammonium Dosing

The daily and diurnal mean ± s.d. values of the parameters measured during the period of ammonium dosing are shown in Tables 3.24 and 3.25 respectively. Ammonium removal by both floways was similar and can be correlated to production of nitrite/nitrate. This can most easily be seen during the January 29-30th diurnal (Table 3.25; Appendix 2). A comparison of ammonium influent and effluent concentrations (Fig. 3.12) showed that ammonium removal was independent of influent concentration, with a mean of approximately 50 %. Although release of ammonium occurred overnight in previous diurnal studies (Table 3.16) it was not observed during this study period (Table 3.25; Appendix 2). A comparison of ammonium removal to nitrate production calculated for the daily water chemistry values during the whole Phase 2 study showed that nitrate production increased linearly with ammonium removal (Fig. 3.13).

3.10 Turf species composition

Species composition of the algal turf was similar to that of Phase 1 (Table 3.26). The predominant algal species were cyanobacteria (*Oscillatoria* sp. and an unidentified fine filamentous sp.) and diatoms (*Navicula* sp., *Nitzschia* sp. and *Cyclotella* sp.). Two green filamentous species (*Ulothrix sp.* and *Stigeoclonium* sp.) which were prevalent on the floway during the summer months, died back during the winter. However they remained present under the screen provided the cyanobacteria/diatom mat was harvested regularly. Fewer filamentous species were present in Phase 2 than were established during Phase 1 when species such as *Cladophora* sp., *Spyrogyra* sp., *Tribonema* sp., and *Rhizoclonium* sp. were more prevalent.

Several invertebrate species were found on the floway. The most abundant were the amphipods and midge larvae or chironomids. The chironomids settled on the floway surface and dislodged the algal turf surrounding their cocoons. Although Chironomids caused a major reduction in the covering of algae on the floway during Phase 1, this did not occur during Phase 2.

4.0 Discussion

During this second phase of the evaluation of the Algal Turf Scrubber system various operational parameters were tested under ambient conditions over eleven months from May 3rd, 1995 to March 5th, 1996. Data collection was greatly facilitated by splitting the floway into two sides, enabling one side to be used either as an environmental control or as a duplicate of the experimental side. The background operation study at the beginning of Phase 2 showed that there was very little difference between the treatment capability of the two sides (Tables 3.3 & 3.4).

Four screen types were selected in the screen study, based on their ability to accumulate solids and the volatile, nitrogen and phosphorus content of the solids (Tables 3.5 to 3.8). These screens were the green Tenax screen, the white Naltex screen (191-3317), the black Conwed screen (XB1131) (which had a similar mesh size to the Naltex screen) and the large mesh black Conwed screen (XB2970). The white Naltex (191-3317-1) screen was selected over the other three. The green Tenax screen did not seem to be made of strong enough material to withstand repeated harvesting. The black Conwed screens were discarded since they had lower treatment than the white screens (Table 3.5). The lower solids accumulation of black screens was possibly due to their greater heat absorbance than white screens.

The addition of the screen white Naltex screen to the floway surface (Tables 3.9 & 3.10) improved the treatment performance over the unscreened side and was probably due to the increased surface area afforded by the screen and the maintenance of a larger standing crop of algae beneath the screen following harvest. The screened side of the floway had slightly higher nutrient removal than the unscreened side even though the screened side had been previously dried out to attach the screen to the floway liner (Tables 3.9 & 3.10). The lower accumulation of solids on the surface of the screened side of the floway was due to the re-establishment of the algal mat during the study period.

The ATS floway was shown to be effective at removing nitrogen and phosphorus from both Patterson secondary clarified effluent from Pond 3A and settled wastewater from Pond 1 (Table 3.1). All forms of nitrogen were removed by the ATS. At low nitrogen concentrations both ammonium and nitrite/nitrate were removed simultaneously (Table 3.3). The lack of a preference for ammonium or nitrite/nitrate was probably due to the mixed assemblage of algal species present on the floway, including cyanobacteria which generally prefer nitrate and filamentous green algae which prefer ammonium as a nitrogen source. At high influent ammonium concentrations, however, much of the ammonium was not removed but converted to nitrite/nitrate (Tables 3.18 & 3.24). The good correlation between nitrite/nitrate production and ammonium removal (shown for the whole Phase 2 study (Fig. 3.13) and in the profile study (Fig. 3.6)) indicated that nitrifying bacteria were present on the floway, and probably took advantage of the elevated daytime dissolved oxygen concentration. The influence of dissolved oxygen concentration on nitrification of ammonium to nitrite/nitrate, is supported by the diurnal studies performed during the periods of high influent ammonium concentration, when ammonium reduction and nitrite/nitrate production were lower at night (Appendix 2). Diurnal variation in pH seemed to have little influence on ammonium removal, indicating that only a small proportion of removal was by volatilization at high pH. The lower nitrogen removal by the harvested side of the floway than by the unharvested side during the harvest interval study, was due to higher nitrification of ammonium to nitrite/nitrate on the harvested side (Tables 3.11 to 3.23).

Particulate nitrogen removal was highest when filamentous species were present on the floway. The filamentous biomass acted as a biofilter, straining particles from the wastewater. The decline in particulate nitrogen removal in November and December (Tables 3.11 & 3.14) was probably caused by the die-off of filamentous species from the floway.

The ATS removed all forms of phosphorus. Particulate phosphorus removal showed a similar pattern to that of particulate nitrogen and was attributed to the presence of filamentous species on the floway. Much of the soluble reactive phosphorus (SRP) removal was dependent upon the pH of the ATS effluent. For example, mean diurnal SRP removal and pH were lower than daily mean removal and pH (Tables 3.4, 3.16 and 3.17) as SRP was released at night when the pH declined below 9.0 (Appendix 2). SRP removal correlated well with the increase in pH down the ATS floway during the profile study (Figs. 3.3 & 3.7). The profile study also showed that the relationship between pH and SRP removal was not linear, rather a threshold pH of approximately 9.0 was required before much SRP removal occurred (Fig. 3.7). This pH threshold of 9.0 was achieved after the water had passed over 91.5 m of the 162.5 m floway. The precipitation of phosphorus with cations (such as Ca^{2+}, Mg^{2+}, and Al^{3+}) is known to begin between pH 8.9 - 9.5, depending upon the buffering capacity of the water (Belsare & Belsare, 1987). The increase in the pH of the ATS effluent most likely resulted from carbon limitation of the algal turf, and the subsequent use of bicarbonate for photosynthesis (Richmond, 1983; Fabregas *et al.*, 1984; Soeder & Hegewald, 1988). Higher phosphorus removal at the lower hydraulic loading velocity (0.22 m d^{-1}) measured by both the daily removal and the biomass content (Table 3.14), was probably due to increased pH-induced precipitation. Further evidence for pH-induced precipitation of SRP was shown by similar relationships of alkalinity, hardness and conductivity removal to increased pH in the profile study (Figs. 3.3 & 3.4) and in the diurnal studies during the evaluation of the effect of different hydraulic loading velocities on treatment performance (Appendix 2). Stopping overnight flow was effective in maintaining a lower mean effluent SRP concentration (Table 3.13), especially when the flow was not restarted until the pH of the water pooled at the outflow of the floway was above pH 9.0. In the third altered flow diurnal, despite the flow being off for 14.5 hours overnight, the floway still had a higher mean phosphorus removal than the control side which had overnight flow and phosphorus release (Table 3.19; Appendix 2).

The mean nitrogen and phosphorus content of the accumulated solids of the west and east sides of the split ATS floway were 4.67 % and 4.55 % respectively for nitrogen and 1.55 % for phosphorus. The calculated nitrogen and phosphorus concentration of the volatile solids were 9.44 % and 9.25 % respectively for nitrogen and 3.15 % for phosphorus. The values for nitrogen are typical of algal biomass, however those for phosphorus are higher than the < 1 % normally associated with periphyton biomass (Swift, 1981; Auer & Canale, 1982; Kesler, 1983; Davis *et al.*, 1990; Adey *et al.* , 1993). Based on the percentages of N and P in the accumulated solids, the mean removal of nitrogen was 0.83 ± 0.46 g m^{-2} d^{-1} and 0.84 ± 0.50 g m^{-2} d^{-1} for the west and east floways respectively; mean removal of phosphorus was 0.27 ± 0.15 g m^{-2} d^{-1} and 0.29 ± 0.17 g m^{-2} d^{-1}. These values were less than during Phase 1 when nitrogen removal was 1.11 ± 0.48 g m^{-2} d^{-1} and phosphorus removal was 0.73 ± 0.28 g m^{-2} d^{-1}.

The nitrogen and phosphorus content of the algal biomass varied over the duration of the Phase 2 evaluation. The mean nitrogen content increased when influents with high nitrogen concentrations were used (Tables 3.11 onwards), while the phosphorus content declined, suggesting that the ATS biomass was nitrogen limited. During the hydraulic loading velocity study the nitrogen content of the biomass was reduced at the lower hydraulic loading (Table 3.14) further demonstrating the nitrogen limitation of the floway algae. The lower phosphorus content of the algal biomass in the present study compared to Phase 1 may have been due to precipitation of phosphate beneath the screen. An ATS system which is operated to optimize phosphorus removal by precipitation may be more efficient without a screen. The mass of nitrogen and phosphorus removed by the ATS based on both mean daily removal and mean 24 hour removal was either greater or less than the mass removed based on the nitrogen and phosphorus content of the accumulated solids. These discrepancies in mass balancing occurred for a variety of reasons. The lower nutrient accumulation than removal in the Pond 1 effluent background study (Table 3.11) was probably due to the large amounts of filamentous algae left beneath the screen after harvest which was not accounted for. In the ammonium dosing study, the lower accumulation was probably due to the large amount of biomass which was washed off the floways during heavy rain storms (Table 3.24). For the remainder of the study the higher accumulation of nutrients than removal could have been a result of fixation of nitrogen in anaerobic portions of the mat or precipitation of phosphorus under the liner which was not harvested from the floway but was sampled in the accumulated solids test.

Reducing the hydraulic loading velocity did increase the removal efficiency of the ATS system, producing an effluent with lower concentrations of nutrients, solids and BOD (Table 3.14). However if the ATS is to be operated to maximize nitrogen and phosphorus accumulation in the biomass (regardless of flow) and effluent quality is unimportant, then high flow rates should be used since the decrease in the mass of nitrogen and phosphorus removed by the ATS system at the lower hydraulic loading velocity was mainly due to the lower volume of water treated (Table 3.14). An example of this application would be the export of N and P from a eutrophic lake (lake restoration).

The mean accumulated solids observed in this study (17.72 g m^{-2} d^{-1} and 18.43 g m^{-2} d^{-1} for the west and east sides of the floway respectively were lower than that measured last year (23.84 g m^{-2} d^{-1}) but were still similar to the 22 g m^{-2} d^{-1} previously reported for periphyton water treatment systems (Davis *et al.*, 1990). The lower accumulated solids values in Phase 2 were probably a result of the many operational changes made during the period of peak productivity (June to August) (Tables 3.1 & 3.2; Figs. 3.1 & 3.2). Both floways were dried out to attach the screens to the liner, after which a new algal mat had to be established. Previous studies have found that floways reached full production after 6 to 12 weeks (Adey & Loveland, 1991), however despite the low productivity of the dried out floways in the present study, nutrient removal was better than that of the established floway (Table 3.9).

In the Phase 1 evaluation it was concluded that harvest interval should be varied with seasonal changes in solar irradiance and temperature to maintain sufficient biomass on the ATS floway. A harvest interval of less than one week was suggested when the highest productivity's were recorded during the summer, while intervals of up to a month were suggested for the winter when productivity was at its lowest. In contrast, the results of the Phase 2 harvest study which was performed during the winter, show that a weekly harvest interval consistently produced lower effluent concentrations of N and P and higher solids accumulation than a longer harvest interval, even though daily and diurnal pH and DO values were higher on the unharvested side (Tables 3.16 & 3.17 and 3.20 through 3.23). Other operational problems can be caused by not harvesting the floways. For example, during the December 11th to 12th, 1995 diurnal, which did not have overnight flow and the west floway had not been harvested for three weeks (Table 3.17), heavy rainfall detached and washed large amounts of algae off the floway. Algal sloughing occurred particularly just after the floway had been turned on again at 8:00 am and caused increased effluent concentrations of many parameters.

A high degree of BOD/TSS removal was achieved when filamentous species covered the ATS floway (Tables 3.14 through 3.21). Removal declined with a change from filamentous species to a cyanobacterial and diatomaceous mat (Tables 3.22 & 3.23; Figs. 3.8 & 3.9). The high organic loading of the influent may have contributed to this species shift since there was a visible increase in the bacterial content of the accumulated solids. A similar change occurred at the same time of year during Phase 1 and is probably also a result of the seasonal reduction in solar radiation and temperature. BOD removal can be attributed to both particulate filtration by filamentous algae and bacterial oxidation at the high dissolved oxygen concentrations on the floway since removal decreased overnight (Appendix 2).

A comparison of the data collected during Phase 2 of the ATS research project with the data collected during Phase 1 (October 1st, 1993 through November 30th, 1994) shows that both the yearly mean influent and effluent values were higher in Phase 2 (Tables 3.1 & 3.2). There were several differences in the Phase 2 study from the initial study which may account for the lower treatment by the floway. The climatic conditions, particularly ambient solar irradiance and temperature during the second phase were lower than in Phase 1 (Table 4.1). Pond 1 settled effluent was used as the influent during Phase 2 for three and a half months, while in Phase 1 only secondary clarified effluent was used directly or from Pond 3A. Far more operational changes (including addition of screens, alteration of flow rates and harvest regimes) were made during the second phase of evaluation. The population density and algal species diversity in the present study were similar to those previously described (Adey & Hackney, 1989; Adey & Loveland, 1991; Adey *et al.*, 1993) and to those found in Phase 1, when cyanobacteria and diatoms predominated during much of the year (Table 3.26). However, seeding the floway with collected or harvested algae did not establish the diversity of filamentous species present on the floway in Phase 1 (Table 3.26). Filamentous species were lost from the floway during Phase 1 but the screen and scraping harvest method probably enabled them to be maintained over the winter during the present study. The filamentous species were lost during Phase 1. The method of determining accumulated solids was changed from the wet vacuum used in Phase 1 to scraping the top of the screen with a plastic shovel. Both of these methods simulated the actual method of harvesting the floway at that time. Scraping the top surface of the screen left a standing crop of algae beneath the screen which was unaccounted for. Chironomid larvae had little effect on algal productivity during Phase 2 whereas in Phase 1 it was necessary to dry out the floway in the fall. Chironomid infestation, although a seasonal problem has been observed in most studies of periphyton growth (Lock *et al.*, 1984; Cook *et al.*, 1986; Davis *et al.*, 1990), and appears to be worse in the eastern states than in California.

Table 4.1 Comparison of ambient condition over the duration of Phase one and Phase two of the evaluation of the ATS floway.

Parameter		Phase one	Phase two
Light intensity (1000 lux)		78.27 ± 32.01	70.38 ± 35.39
Light irradiance (mol $m^{-2} d^{-1}$)		36.70 ± 7.25	31.84 ± 17.48
Temperature (°C)	Maximum	28.23 ± 8.21	25.57 ± 8.53
	Minimum	8.13 ± 5.21	9.42 ± 3.96

5.0 Conclusions

The results presented in this report further indicate the potential of the ATS system for the tertiary polishing of secondary treated wastewater. The ATS system has been shown to remove high concentrations of nitrogen and phosphorus. However, much of the removal of ammonium during this study was offset by the production of nitrite/nitrate through nitrification, nitrogen fixation may have also contributed to the nitrogen content of the accumulated solids. Phosphorus removal was probably due to a combination of biological uptake (including luxury uptake), particulate filtration and precipitation. Precipitation seemed to be the dominant process, with the removal of soluble reactive phosphorus correlating to the increased pH of the ATS effluent above a threshold pH of 9.0. Maintenance of the pH of the ATS system effluent above that at which precipitation occurs could provide a simple means of optimizing phosphorus removal by the ATS. The present study has shown that a particular pH may be achieved by controlling the length of time the wastewater is in contact with the algal turf, either by reducing the hydraulic loading velocity of the floway (Table 3.14), or passing the wastewater down a longer floway. (Fig. 3.3). Resolution of precipitated phosphorus at night was prevented by stopping overnight flow until the pH had reached 9.0 the following day (Table 3.19). Particulate nitrogen, phosphorus and BOD were all removed in high quantities when filamentous algal species were present on the floway. BOD removal was also associated with elevated dissolved oxygen concentrations in the ATS effluent. A short harvest interval enabled increased nutrient removal and solids accumulation, while also reducing sloughing of the algae during rainfall and the susceptibility of the ATS to invertebrate infestation. The addition of a screen to the floway surface enhanced floway performance.

These results indicate that ATS treatment systems may simply be controlled by alteration of operational parameter such as hydraulic loading, floway length and harvest period. From our existing knowledge of ATS systems, they appear to be most suited for application in nutrient polishing, lakes restoration and biomass production.

6.0 Further Research

To date ATS treatment systems have been tested under two modes of operation:

1) Low hydraulic loading velocity with reduced overnight flow for increased phosphorus removal by precipitation, as described in the present study.

2) High hydraulic loading velocity for nutrient assimilation by a filamentous algal flow, as demonstrated by previous studies (Adey & Loveland, 1991).

Two other floway configurations which would increase contact time should also be tested:

1) High hydraulic loading velocity over a long floway.

2) High hydraulic loading velocity with recirculation of part of the effluent.

Perhaps these configurations would enable both efficient nutrient removal and promote the growth of filamentous algae. Evaluation of both configurations could be done at Patterson by (1) recirculating the effluent of one side to the top of the other to double the length of the floway and (2) recirculating a portion of the effluent to the top to mix with the influent.

Many operational parameters were tested during the Phase 2 evaluation although for statistical verification of the results a more prolonged period of evaluation is required during which a single operational parameter is measured on replicate floways so that seasonal variations can be taken into account.

More long term studies need to be done with unchanged operational parameters to properly determine the mass balances of nitrogen and phosphorus removal and the mechanisms by which removal is taking place.

Studies using high BOD effluent need to be done to determine if high BOD loading has a lasting change on the species diversity of algal turf.

Further research into the treatment properties of particular algal species, and the ability to maintain the dominance of these species on a floway should also be performed.

Further research is required into liner texture to promote and maintain the species diversity of the algal turf.

More research needs to be done on the factors influencing Chironomid settlement and if there are any other means of control than drying out the floway.

Bioassays for the acute and chronic toxicity need to be done on the ATS effluent, although the effluent from the Patterson wastewater treatment facility has previously passed these tests at the dilution of the effluent with the river water. The elevated temperature and pH of the ATS effluent are unlikely to cause any problems to aquatic life once diluted, while the higher DO concentration and reduced nutrient concentrations of the ATS effluent should be beneficial to the receiving water.

The bacterial and viral content of the biomass should be determined to establish a safe handling practice, and the suitability for use as a fertilizer and feed amendment.

The ability of the ATS floway to remove heavy metals has yet to be determined. A preliminary study conducted by the City of Modesto, Industrial Pollution Department showed that the ATS can remove zinc, silver and arsenic, even from the low levels found in the Patterson treatment facility effluent (Craggs *et al.*, 1994). Analysis of the harvested solids shows that many metals are incorporated into the algal turf biomass. Laboratory experiments, have previously demonstrated the removal of heavy metals and organic compounds from industrial effluents (Adey *et al.*, 1994).

7.0 Algal Turf Scrubber Engineering and Cost Analysis

In the current studies the "Algal Turf Scrubber (ATS)" has been found to be capable of removing residuals of nitrogen and phosphorus without added chemicals and with a minimum of energy expenditure. Because of this capability the ATS may turn out to be a powerful tool for removing of trace amounts of phosphorus and ammonium and for nitrifying ammonium. The major applications of the ATS may then be remediation of eutrophic reservoirs and lakes, for polishing tertiary effluents, and for algal biomass production. Because the ATS is basically a reducing system and because most of the dissolved molecular oxygen produced during photosynthesis of the turf is released to the air, the ATS should not be expected to remove large amounts of Biochemical Oxygen Demand (BOD). However, due to its filtration action, the ATS is capable of removing significant amounts of suspended solids and the BOD associated with these suspended solids. In some of our experiments presenting the ATS with wastewater containing reduced compounds, i.e. BOD, caused bacterial slime formation that blocked out light and hence was inimical to the algal turf. There are, of course, many adequate systems for oxidizing BOD so there is little need to employ the ATS for such a purpose.

In the following engineering analysis we will first examine elementary cost constituents and their application to the ATS. We then will examine the application of the ATS in lake and reservoir remediation, in effluent polishing and in biomass production.

Cost

The basic parameters which influence the cost of processing wastewater in any system, including the ATS, are:

1. The cost of unit area, e. g. $\$ m^{-2}$; $\$ ft^{-2}$.
2. The hydraulic loading velocity (HLV), e.g. $m\ d^{-1}$; $ft\ d^{-1}$.
3. The change in concentration of an element or compound in the wastewater as a result of contact of the wastewater with the ATS surface, e.g. nitrogen or phosphate removal.
4. The cost of bringing wastewater to the system and removing treated water from the system.
5. The cost of removing biomass from the ATS surface (harvesting).

6. The net cost of processing and marketing the biomass.
7. General operations and maintenance.

The experiments conducted thus far are useful in proving the technical feasibility of the ATS system and in suggesting determinants for some of the important parameters that may influence improvements. Much more scientific work and practical experience is needed before one can reach definite conclusions regarding the economic feasibility of the ATS system. The following analysis which deals in some detail, with each item in the above list is intended to provide some guidelines and points of departure for future studies, possible improvements, and economical applications of the ATS.

Areal Cost

Basic parameters which influence the cost of unit area of ATS are the costs of the following items:

1. Land including road access, electrical power, potable water, communications, security, buffer zones, taxes and insurance.
2. Grading, sloping, smoothing, and compacting the earth surface beneath the ATSs liner.
3. Lateral guides and the impervious ATS liner including surface drainage, materials, placement, and anchorage. The useful life of the liner, i.e. the time from placement until replacement, will greatly effect costs.
4. Biomass retention screen including materials, placement, and fastening. Like the impervious liner, the useful life of the screens will greatly influence their cost.
5. Liquid application system, pumping, and distribution over the width of the ATS.
6. Harvester and harvest operations.
7. Effluent disinfection and final liquid disposal system.
8. Influent and effluent instrumentation, monitoring and reporting system.
9. Size of the system (economy of scale).
10. Biomass processing system.
11. Useful life of the whole system.

Land Costs

Factors influencing the cost of land are: cost of adjacent land, accessibility, slope, proximity to power and water, current use and projected future use, zoning regulations, and many other factors.

Site Preparation

Site preparation, grading and compaction are all closely related to the climate rainfall intensity duration frequency, previous use of the land, soil characteristics, drainage and slope of land, and many other factors.

Base Liner

The type of materials used for the liner may be portland cement concrete, asphaltic concrete, high density polyethylene, polyvinyl chloride or possibly sprayed on catayzed asphaltic or plastic surfaces. It is necessary to have raised sides on the floway to contain the water. In early studies these side units doubled as guide rails for the algal harvester. They are expensive but were valuable in maintaining line and grade for the base liner. One major problem with the base liner was its tendency to form ridges and creases during expansion and contraction with changing sunlight. These discontinuities prevented smooth sheet flow over the entire floway surface and interfered with uniform harvest as well as being unsightly. It is obvious that it would be costly to overcome these problems. A liner with minimal expansion and contraction should be examined in future studies (for example, XR5 geomembrane, Seaman Corporation, Wooster, Ohio).

Biomass Retention

The biomass retention screens are important to retain seed biomass after harvesting. It is important that this screen material be bonded to the base coat so that it does not detach from the base coat, float up, wrinkle or gather during harvest operations. Blue green algal (Cyanobacterial) growth was often found under these screens. Many of these genera are known to fix nitrogen. If N fixation occurs on the floways, it could benefit algal production but not nutrient removal. From a hydraulic standpoint the biomass retention screens greatly increase the relative roughness of the bed; consequently, they slow the flow velocity and increase flow depth, hydraulic residence time and time that the wastewater contacts the growing biomass. These screen effects should improve assimilation of nitrogen and both assimilation and/or precipitation of phosphorus.

Liquid Application

Various types of liquid application systems have been tried for pulsed application including low-head, high-volume, pulsed pumping and dump troughs. There is some question whether pulsed flow or continuous flow is best. Experiments should be done over a sufficient time to provide reliable comparisons of pulsed vs. continuous application in terms of biomass growth and nutrient removal.

Harvest

The original harvest system designed by Kyle Jenson was a tractor supported on guide rails and equipped with a revolving brush ahead of a powerful vacuum of the street cleaner type. This unit basically removed almost all of the periphyton biomass from the floway, and, as a result, it was necessary to reestablish the filamentous algae after each harvest. Harvesting experiments reported herein involved harvesting over the biomass retaining screens with a Draper type of harvester that scraped biomass off the screens and brought the mass to a hopper by means of porous conveyor belts. This harvester was not confined to rails but used broad low pressure tires to avoid creating ruts in the earth ATS sub base. Each type of harvester required an operator. Although it may be possible in the future to develop an automatic unit, it would likely be expensive and prone to breakdowns. For small ATS systems the manned harvester can be a very significant operational expense.

Disinfection

Because of the very short residence time on the flowway there should be only insignifica removal of Coliform bacteria. Coliform bacteria are well known reliable indicators of pollution and are expected to indicate the possible presence of disease causing organisms such as Typhoid and Cholera bacteria, parasite ova, viruses and prions. Modern disinfection regulations require a very low turbidity in effluents prior to disinfection. In the present work (Phase one) ATS turbidities were too high to meet requirements for effective disinfection and would have required screening and filtration to meet disinfection standards. Screening and filtration therefore should be included in any cost analysis. If effluents are to be disposed into subsurface wetlands, filtration and disinfection may not be required. Subsurface wetlands, however, cost on the order of $1.00 ft^{-2} and consequently may cost more than filtration and disinfection.

Instrumentation, Monitoring, Reporting

All permitted systems must provide the responsible regulating agency with periodic reports of influent and effluent BOD, suspended solids and MPN. Likely to be added in the near future are reporting requirements for nitrogen, phosphorus, heavy metals and VOCs. Heavy metals and VOCs were not included in the present study but should be studied to help complete the evaluation.

System Size

The economy of scale is primarily related to operations and maintenance since in small systems one operator may greatly influence cost but be barely noticeable in a cost analysis of very large systems. Many other items are affected by scale as well. For example, instrumentation and reporting are simple in small systems but become very complex and expensive in large systems. Influent waste distribution and effluent collection are another example of disproportionate expense in large systems.

Biomass Processing

Biomass, as it is removed from the surface of the floway, usually does not exceed 5% solids and may be less. To transport this material, which is highly putrescible it is necessary to remove most of the moisture. Air drying on sand beds, filter pressing and drum or spray drying are some options. Unless there is some high-value extractable material in the biomass, its value probably does not exceed that of fertilizer which may be only 20 cents per lb. To be marketed as a fertilizer the material should be pasteurized or heat pelletized which will add to the cost but is necessary for sanitation purposes.

Useful Life

Each component of the ATS system will have a different life span after which repair or replacement will be required. Usually mechanical devices have a five-year life. Plastic, if it is sufficiently thick to avoid tearing and abrasion, will last for about ten years. If UV disinfection of liquid effluents is practiced, the UV bulbs are likely to require replacement yearly and will require cleaning every week or two. Sun drying of algae requires frequent replacement of sand on drying beds, so their useful life is only a few years. In climates were ATS may be appropriate technology, average useful life of all components of well constructed systems will probably not exceed 10 years. Cheaply constructed systems will obviously have a shorter life and thus will cost more in the long run. In table 7.1 we have assumed a range of useful lives namely 5, 7.5, 10, and 12.5 years. When these values for useful life are combined with assumed unit area costs and an assumed annual percentage interest rate, we are able to estimate the annual cost of a unit area. Because of wide variations in the useful life of the various components we have assumed an average useful life of 7.5 years.

Table 7.1 Algal Turf Scrubber Cost* Estimate, 1996 (US\$ ft^{-2} y^{-1}).

Useful Life (y)	**First cost (US\$ ft^{-2})**				
	1	**2****	**3**	**4**	**5**
5.0	0.275	0.550	0.675	0.875	1.075
7.5	0.208	0.341	0.475	0.608	0.742
10.0	0.175	0.275	0.375	0.475	0.575
12.5	0.155	0.235	0.315	0.395	0.474

* Straight line amortization (including interest at 7.5 % annum^{-1}).

** This is the approximate cost of the 1000 m^2 (10, 500 ft^2) floway at Patterson, California.

N.B. These costs do not include wastewater application, harvest equipment and operations.

Areal Cost

Estimation of the likely cost of any of the above items is problematical and consequently for economic analysis we use a stochastic approach in which we assume various levels for the integrated cost of all of the above items (except item 7) in terms of 1996 U. S. Dollars per unit area. Based on the records made available, the cost of the floway used in these experiments was about \$2.00 (U.S. 1992) per sq ft. This estimate was for the floway construction and related apparatus including equipment for disinfection and harvesting. It did not include all of the other items listed above. When items such as biomass retention screens. land, water supply, power and communications hookup, monitoring equipment and algal processing units are included, costs in the range of \$3.00 to \$4.00 per sq ft appear reasonable. In table 7.1 we use a range of unit costs that is likely to cover most cases. It must be emphasized that these unit areal costs do not include the cost of operators, electrical power, instrumentation, or any contingencies such as insurance, taxes, or profit.

Hydraulic Loading Velocity (HLV)

When costs per unit area per year are combined with HLV one can calculate the cost for processing unit volumes of water. HLVs varying from 1.35 m d^{-1} to 0.11 m d^{-1} were applied in the current studies. For the 990 m^{-2} floway a HLV of 1.00 m d^{-1} results in the processing of about 990 cubic meters (261,360 gallons or 34,941 cu ft per day) over the floway. In our more detailed analysis we have assumed various loading rates within a reasonable range based on the experimental levels that provided removal data for the various water quality criteria. The largest HLV explored during the first year was slightly greater than 1.00 m d^{-1} and in the second year was 1.35 m d^{-1}. During the second year the lowest HLV explored was 0.11 m d^{-1}. Table 7.2 illustrates the flows associated with the 990 m^2 floway under the 4 flow regimes studied during Phase 2.

Table 7.2 The flows associated with the 990 m^2 floway under the 4 flow regimes studied during Phase 2.

	Daily flows for a 990 m^2 floway.	
HLV (m d^{-1})	Full Floway (m^3 d^{-1})	Half Floway (m^3 d^{-1})
1.35	1336.00	668.30
0.44	435.60	217.80
0.22	217.80	108.90
0.11	108.90	54.45

Changes In Nutrient Levels

Changes in nutrient levels are shown for each experimental set in tables 3.9 to 3.18. The greatest changes clearly occurred when input concentrations were highest and the least change generally occurred when input concentrations were lowest. To examine the relative costs for removal of Nitrogen and Phosphorus we select from table 7.1 a cost of \$3.00 ft^{-2} and a useful life of 7.5 years. This results in a floway cost of \$0.475 ft^{-2} y^{-1} or for the entire raceway \$5060.00 per year. We then determine the change in concentrations of N and P over a year and obtain those parts of the removal costs that are related to the capital investment and interest. These results are shown in table 7.3 for total Nitrogen and in table 7.4 for total Phosphorus. It is emphasized that these are not total costs since they do not include operations, maintenance and miscellaneous costs. Obviously different estimates would result from changing first cost, interest and useful life. We have chosen values that we believe are rational. As in all removal processes removal of the lowest concentrations is most difficult and costly.

Table 7.3 The removal costs for Nitrogen that are related to the capital investment and interest. (US\$ kg^{-1}, 1996)*.

Projected Costs	Phase 1	Phase 2	
		West	East
Maximum	-	67.88	44.04
Minimum	-	4.56	3.60
Median	-	7.75	10.93

* Based on \$4.75 ft^{-2} over a 7.5 year ammortization period excluding O & M.

Table 7.4 The removal costs for Phosphorus that are related to the capital investment and interest. (US\$ kg^{-1}, 1996)*.

Projected Costs	Phase 1	Phase 2	
		West	East
Maximum	-	185.84	261.53
Minimum	-	12.96	14.26
Median	-	32.06	34.00

* Based on \$4.75 ft^{-2} over a 7.5 year ammortization period excluding O & M.

Algal Removal and Marketing

Microalgal concentrations on the floway generally reach levels that are easily removed, and organic productivity on a yearly average is about 10 $g\ m^{-2}\ d^{-1}$. Algal production on the 990 m^2 floway is then about 10 $kg\ d^{-1}$ (22 $lbs\ d^{-1}$) dry weight. At a fertilizer price of about 20 cents per lb, this material is worth \$4.40 per day or about \$1600 per year. The material may be more valuable than we have indicated, but markets for waste grown algae remain to be developed and must compete with soy bean prices which linger around 10 cents per lb. In spite of its likely low value it is vital that the algae be removed from the floway regularly to maintain a steady growth pattern and, of coarse, to remove nutrients. Self shading is one of the major deterrents to high growth rates and high productivity and can only be mitigated by frequent harvest. It is possible that on well managed floways the value of the algae may offset a significant fraction of the cost of harvesting but this also remains to be demonstrated.

Operations And Maintenance

As noted previously the preliminary costs shown in tables 4.3 and 4.4 do not include operations and maintenance costs. The primary reason for this is that they will vary widely with scale. It would be misleading to add to the amortized cost of the unit at Patterson. The cost of an operator at say \$30,000 per year because that sum is far out of proportion to other costs of this research installation.

One of the major reasons for the ATS is to produce water sufficiently low in nutrients that it is acceptable to discharge to nutrient sensitive bodies of water or to reuse in nutrient sensitive watersheds. The ATS at Patterson has shown great promise but has not yet achieved the levels of nutrient removal that are theoretically possible in such a system. Improvements in floway design, particularly in length, slope, surface development and in methods of loading and harvesting are still needed to meet its future market. We have always recommended and continue to recommend well controlled sustained experiments in an academic setting that would permit the development of hydraulic and biochemical ATS models. These studies would point the way to more effective prototypes that can achieve high levels of nutrient removal more economically than any present system.

8.0 Acknowledgments

The authors are particularly grateful to Larry Samarripa, Song Ling Ng, Abra Bentley and Paul Suto for their help with experimental analysis and sampling. We would also like to thank Richard Schroeder at the Patterson wastewater treatment facility for their help during this evaluation. The assistance of Stan Duck and Cathy Robocker while operating the ATS was most appreciated. We thank Richard Purgason for his useful input during the whole of this study. Funding for this study was provided by Aquatic Bio Enhancement Systems Inc. Texas. The algal turf scrubber process is a patented environmental control system developed by W. Adey and held by the Smithsonian Institution. Aquatic Bio Enhancement Systems Inc. holds an exclusive license for the technology.

Disclaimer

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Tables

Table 2.1 Parameters tested, the frequency and method of testing[a].

Parameter	Frequency	Method
Climate		
Light	Days 1 & 7	Lux Meter (LX 101, Lutron) Photometer (LI - 190SA, Licor, Nebraska).
Temperature	Days 1 & 7	Max/Min thermometer
Physical Parameters		
Dissolved Oxygen (mg l^{-1})	Days 1 & 7	DO/Temperature Meter
Temperature (^{o}C)	Days 1 & 7	(Model 820, Orion Research Inc, Massachusettes)
pH	Days 1 & 7	pH Meter (Model 240, Corning Science products, NY)
Alkalinity (mg l^{-1} as $CaCO_3$)	Days 1 & 7	Acid titration
Hardness (mg l^{-1} as $CaCO_3$)	Days 1 & 7	Chelation titration
Conductivity (mS m^{-1})	Days 1 & 7	Conductivity probe (Lectro mho-meter (lab-line inst., inc. Illinois).
Nutrients		
Ammonium(mgl^{-1})	Days 1 & 7	Alkaline distillation followed by an acid titration.
Nitrate/Nitrite (mg l^{-1})	Days 1 & 7	Cadmium reduction
Total Organic Nitrogen (mg l^{-1})	Days 1 & 7	Kjeldahl (acid digestion followed by an alkaline distillation and acid titration).
Soluble Reactive Phosphorus (mg l^{-1})	Days 1 & 7	Ascorbic acid
Total Phosphorus (mg l^{-1})	Days 1 & 7	Persulphate digestion and ascorbic acid
Organic Matter		
BOD (mg l^{-1})	Days 1 & 7	5-day incubation at 20 ^{o}C
Solids		
UV transmittance (%)	Days 1 & 7	Spectrophotometer at 253.7 nm (Spectronic 21, Milton Roy Co. Buffalo, NY).
Turbidity (NTU)	Days 1 & 7	Nephelometer (Model DRT 100, HF Scientific inc. Bolton, Ontario, Canada). (0.02 NTU reference HF Scientific inc.)
Total Suspended solids (mg l^{-1})	Days 1 & 7	Filtration and oven drying at 103-105 ^{o}C
Accumulated solids		
Total solids (g m^{-2} d^{-1})	Day 7	Oven drying at 105 ^{o}C
Volatile solids (g m^{-2} d^{-1})	Day 7	Muffle furness ashing at 550 ^{o}C
Nutrient content (g kg^{-1})	Day 7	Nitric acid digestion, measured on ICP (Phosphorus) Kjeldahl digestion (Nitrogen)
Microscopic analysis	Day 7	Compound Microscope (Fisher Micromaster, model CK, w/Trinocular)

[a] All methods carried out according to Standard Methods for the Examination of Water and Wastewater, 19th ed., 1995, unless otherwise indicated.

Table 3.1 Phase two yearly mean ± s.d. (n = 72) values of all parameters measured in the influent and effluents of west and east sides of the split ATS floway.

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	18.18 ± 5.53	24.09 ± 7.39	23.90 ± 7.42
Dissolved Oxygen (mg l^{-1})	4.96 ± 2.86	22.65 ± 4.79	21.45 ± 4.42
pH	8.27 ± 0.64	9.65 ± 0.39	9.59 ± 0.42
Alkalinity (mg l^{-1} as $CaCO_3$)	277.09 ± 34.41	218.02 ± 34.28	218.32 ± 34.22
Hardness (mg l^{-1} as $CaCO_3$)	482.74 ± 27.53	453.15 ± 32.33	456.43 ± 35.15
Conductivity (mS m^{-1})	230.50 ± 9.83	218.80 ± 9.59	220.50 ± 9.03
Nutrients			
Ammonium (mg l^{-1})	8.32 ± 9.73	3.29 ± 4.87	2.87 ± 4.54
Nitrate/Nitrite (mg l^{-1})	0.85 ± 0.90	2.72 ± 2.96	3.27 ± 3.38
Particulate Nitrogen (mg l^{-1})	6.76 ± 4.82	5.18 ± 3.48	5.15 ± 3.23
Total Organic Nitrogen (mg l^{-1})	15.09 ± 10.47	8.47 ± 6.83	8.01 ± 6.10
Soluble Reactive Phosphorus (mg l^{-1})	1.65 ± 1.35	0.62 ± 0.59	0.61 ± 0.56
Particulate Phosphorus (mg l^{-1})	1.53 ± 1.29	1.01 ± 1.03	0.96 ± 0.88
Total Phosphorus (mg l^{-1})	3.08 ± 1.26	1.57 ± 0.99	1.52 ± 0.84
Solids			
UV transmittance (%)	47.75 ± 19.74	51.04 ± 15.59	51.68 ± 14.92
Turbidity (NTU)	40.39 ± 40.33	23.69 ± 27.58	20.97 ± 21.90
Total suspended solids (mg l^{-1})	55.19 ± 41.73	36.29 ± 29.57	35.40 ± 27.11
Total dissolved solids (mg l^{-1})	1106.66 ± 128.01	1108.79 ± 148.14	1123.88 ± 154.96
Biomass Solids (n = 38)			
Accumulated solids (g m^{-2} d^{-1})		17.72 ± 9.76	18.43 ± 11.06
% Volatile solids		49.46 ± 8.22	49.14 ± 11.06
% Nitrogen		4.67 ± 1.07	4.55 ± 1.35
% Phosphorus		1.55 ± 0.40	1.55 ± 0.40
Weekly Treatment			
N Removal (kg $week^{-1}$)		3.95 ± 2.48	4.10 ± 3.13
P Removal (kg $week^{-1}$)		1.61 ± 0.79	1.70 ± 0.86
N Accumulation (kg $week^{-1}$)		5.35 ± 2.46	5.99 ± 2.79
P Accumulation (kg $week^{-1}$)		1.79 ± 1.25	2.23 ± 1.70

Table 3.2 Phase one yearly mean ± s.d. values of all parameters measured in the influent and effluent of the ATS/UV system.

Parameter	**ATS/UV System Influent**	**ATS/UV System Effluent**
	Mean ± s.d.	**Mean ± s.d.**
Physical Parameters		
Temperature (°C)	18.86 ± 5.25	24.43 ± 6.94
Dissolved Oxygen (mg l^{-1})	4.79 ± 3.13	24.86 ± 4.94
pH	8.43	9.48
Alkalinity (mg l^{-1} as $CaCO_3$)	235.00 ± 34.35	210.39 ± 30.79
Hardness (mg l^{-1} as $CaCO_3$)	460.67 ± 26.99	434.98 ± 23.09
Conductivity (mS m^{-1})	215.31 ± 10.10	206.00 ± 9.13
Nutrients		
Ammonium (mg l^{-1})	3.25 ± 6.66	2.53 ± 5.61
Nitrate/Nitrite (mg l^{-1})	4.98 ± 7.45	3.79 ± 5.89
Total Organic Nitrogen (mg l^{-1})	4.95 ± 9.54	3.86 ± 6.02
Soluble Reactive Phosphorus (mg l^{-1})	2.69 ± 1.16	1.18 ± 0.98
Total Phosphorus (mg l^{-1})	3.14 ± 1.01	1.67 ± 0.91
Solids		
UV transmittance (%)	66.39 ± 12,86	66.18 ± 12.40
Turbidity (NTU)	7.88 ± 9.01	6.34 ± 7.62
Total Suspended solids (mg l^{-1})	15.08 ± 25.73	12.69 ± 18.86
Biomass Solids		
Accumulated solids (g m^{-2} d^{-1})		23.84 ± 16.55
% Volatile solids		43.50 ± 5.27
% Nitrogen		3.09 ± 0.30
% Phosphorus		2.07 ± 0.20
Weekly Treatment		
N removal (kg $week^{-1}$)		6.91 ± 13.27
P removal (kg $week^{-1}$)		4.41 ± 3.27
N accumulation (kg $week^{-1}$)		5.22 ± 3.62
P accumulation (kg $week^{-1}$)		3.50 ± 2.43

Table 3.3 Background operation (June 7th through July 18th) values of all parameters measured in the influent and effluents of west and east sides of the split ATS floway. Values are means ± s.d. (n = 13). The hydraulic loading velocity of both sides was 1.35 m d^{-1}.

Parameter	**Influent Mean ± s.d.**	**West Effluent Mean ± s.d.**	**East Effluent Mean ± s.d.**
Physical Parameters			
Temperature (°C)	23.50 ± 3.50	27.95 ± 4.74	27.82 ± 4.87
Dissolved Oxygen (mg l^{-1})	6.85 ± 4.36	18.04 ± 2.49	17.76 ± 2.57
pH	9.10 ± 0.29	9.51 ± 0.22	9.52 ± 0.22
Alkalinity (mg l^{-1} as $CaCO_3$)	230.17 ± 19.74	219.44 ± 17.88	217.12 ± 17.62
Hardness (mg l^{-1} as $CaCO_3$)	455.27 ± 20.27	445.88 ± 19.44	442.62 ± 20.10
Conductivity (mS m^{-1})	221.65 ± 7.06	218.62 ± 7.33	218.71 ± 7.91
Nutrients			
Ammonium (mg l^{-1})	0.56 ± 0.67	0.28 ± 0.44	0.29 ± 0.34
Nitrate/Nitrite (mg l^{-1})	0.79 ± 0.44	0.54 ± 0.39	0.52 ± 0.38
Particulate Nitrogen (mg l^{-1})	5.12 ± 2.43	5.10 ± 2.03	5.20 ± 1.89
Total Organic Nitrogen (mg l^{-1})	5.67 ± 2.58	5.38 ± 2.17	5.49 ± 2.03
Soluble Reactive Phosphorus (mg l^{-1})	0.94 ± 0.37	0.61 ± 0.27	0.60 ± 0.28
Particulate Phosphorus (mg l^{-1})	0.72 ± 0.30	0.71 ± 0.19	0.73 ± 0.24
Total Phosphorus (mg l^{-1})	1.66 ± 0.28	1.32 ± 0.24	1.32 ± 0.22
Solids			
UV transmittance (%)	52.72 ± 8.54	55.23 ± 7.20	55.43 ± 6.71
Turbidity (NTU)	17.68 ± 8.10	14.62 ± 7.35	14.91 ± 8.19
Total suspended solids (mg l^{-1})	41.88 ± 22.42	35.27 ± 18.51	38.58 ± 17.02
Total dissolved solids (mg l^{-1})	1124.31 ± 89.77	1127.30 ± 84.12	1186.75 ± 78.90
Biomass Solids (n = 10)			
Accumulated solids (g m^{-2} d^{-1})		17.99 ± 9.55	23.05 ± 12.2
% Volatile solids		40.00 ± 5.88	36.78 ± 7.37
% Nitrogen		3.49 ± 0.14	3.19 ± 0.29
% Phosphorus		2.19 ± 0.42	2.19 ± 0.46
Weekly Treatment			
N Removal (kg $week^{-1}$)		2.50 ± 1.60	1.77 ± 2.49
P Removal (kg $week^{-1}$)		1.70 ± 0.37	1.67 ± 0.47
N Accumulation (kg $week^{-1}$)		5.47 ± 2.49	6.57 ± 2.54
P Accumulation (kg $week^{-1}$)		3.65 ± 1.89	4.77 ± 2.28

Table 3.4 Background operation diurnal (June 26th through 27th) values of all parameters measured in the influent and effluents of west and east sides of the split ATS floway. Values are means ± s.d. ($n = 9$). The hydraulic loading rate of both floways was 1.35 m d^{-1} and was constant.

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	28.84 ± 1.78	28.99 ± 4.03	28.89 ± 4.01
Dissolved Oxygen (mg l^{-1})	7.50 ± 6.80	9.70 ± 6.90	9.90 ± 6.70
pH	9.11 ± 0.20	9.25 ± 0.24	9.27 ± 0.25
Alkalinity (mg l^{-1} as $CaCO_3$)	214.52 ± 7.22	211.88 ± 5.55	213.70 ± 8.29
Hardness (mg l^{-1} as $CaCO_3$)	430.71 ± 2.96	427.21 ± 7.30	437.57 ± 29.10
Conductivity (mS m^{-1})	210.29 ± 7.36	211.27 ± 8.17	214.02 ± 4.86
Nutrients			
Ammonium (mg l^{-1})	1.11 ± 0.60	0.60 ± 0.40	0.55 ± 0.25
Nitrate/Nitrite (mg l^{-1})	0.61 ± 0.22	0.42 ± 0.16	0.42 ± 0.16
Particulate Nitrogen (mg l^{-1})	4.74 ± 1.12	4.65 ± 0.90	4.72 ± 0.97
Total Organic Nitrogen (mg l^{-1})	5.85 ± 1.07	5.25 ± 0.88	5.27 ± 0.92
Soluble Reactive Phosphorus (mg l^{-1})	0.73 ± 0.15	0.62 ± 0.16	0.60 ± 0.18
Particulate Phosphorus (mg l^{-1})	0.73 ± 0.20	0.53 ± 0.15	0.56 ± 0.11
Total Phosphorus (mg l^{-1})	1.46 ± 0.26	1.15 ± 0.2	1.17 ± 0.2
Solids			
UV transmittance (%)	48.91 ± 5.22	53.24 ± 2.26	52.67 ± 2.48
Turbidity (NTU)	20.50 ± 4.08	12.57 ± 0.90	12.86 ± 1.98
Total suspended solids (mg l^{-1})	33.43 ± 14.88	22.57 ± 5.42	23.14 ± 8.41
Total dissolved solids (mg l^{-1})	1251.71 ± 225.25	1242.00 ± 218.75	1252.57 ± 166.52
Weekly Treatment			
N Removal (kg $week^{-1}$)		3.74	3.65
P Removal (kg $week^{-1}$)		1.47	1.41

Table 3.5 Comparison of accumulated solids removal by various test screens on the ATS split floway. Values are means ± s.d. (n = 6 weekly samples).

Screen Type	**Screen Position**	**Accumulated solids ($g\ m^{-2}\ d^{-1}$)**
Naltex (191-3317-1) white	TWB	57.41 ± 21.69
Tenax (green)	TWA	55.24 ± 17.71
Naltex (191-3317-1) white	BEE	51.58 ± 20.13
Conwed (XB1131) black	BWA	44.94 ± 12.82
Tenax (green)	BED	43.36 ± 14.71
Conwed (XB2970) black	BWB	42.35 ± 15.62
Conwed (XN2410) white	TED	42.23 ± 15.42
Tensar (LG400321) black	TWD	40.63 ± 14.44
Conwed (XN1678) white	BWD	39.20 ± 12.88
Conwed (XN1678) white	TEA	38.61 ± 17.63
Conwed (XB2970) black	TEB	38.48 ± 14.37
Conwed (XN2410) white	BEB	37.81 ± 8.82
Jason Mills (1999MF60NAT) PE	TWC	36.79 ± 11.79
Tenax (grid) white	TEE	35.89 ± 10.26
Conwed (XV1678) black	BWC	34.34 ± 16.50
Jason Mills (65MF50WAT) PE	BEA	21.82 ± 6.30
Liner	TEC	18.86 ± 5.91
Liner	BEC	15.46 ± 5.05

TE - Top East (A-E)
TW - Top West (A-D)
BE - Bot East (A-E)
BW - Bot West (A - D)

Table 3.6 Comparison of % volatile solids and accumulated volatile solids removal by various test screens on the ATS split floway. Values are means ± s.d. (n = 6 weekly samples).

Screen Type	Screen position	% Volatile solids	Accumulated volatile solids ($g\,m^{-2}\,d^{-1}$)
Tenax (green)	TWA	47.62 ± 4.99	26.30 ± 8.43
Naltex (191-3317-1) white	TWB	45.05 ± 1.83	25.86 ± 9.77
Naltex (191-3317-1) white	BEE	47.31 ± 2.16	24.40 ± 9.52
Tenax (green)	BED	49.79 ± 5.31	21.59 ± 7.32
Conwed (XB1131) black	BWA	46.33 ± 3.00	20.82 ± 5.94
Conwed (XB2970) black	BWB	47.37 ± 4.55	20.06 ± 7.40
Conwed (XN2410) white	TED	46.00 ± 2.09	19.43 ± 7.09
Tensar (LG400321) black	TWD	45.93 ± 1.85	18.66 ± 6.63
Conwed (XB2970) black	TEB	47.24 ± 3.85	18.18 ± 6.79
Conwed (XN1678) white	BWD	46.28 ± 1.42	18.14 ± 5.96
Conwed (XN1678) white	TEA	46.41 ± 2.20	17.92 ± 8.18
Conwed (XN2410) white	BEB	46.96 ± 3.21	17.76 ± 4.14
Jason Mills (1999MF60NAT) PE	TWC	45.83 ± 1.59	16.86 ± 5.40
Conwed (XV1678) black	BWC	45.81 ± 1.37	15.73 ± 7.56
Tenax (grid) white	TEE	42.94 ± 3.11	15.41 ± 4.41
Jason Mills (65MF50WAT) PE	BEA	49.15 ± 1.56	10.73 ± 3.10
Liner	TEC	40.47 ± 1.52	7.63 ± 2.39
Liner	BEC	48.12 ± 2.87	7.44 ± 2.43

TE - Top East (A-E)
TW - Top West (A-D)
BE - Bot East (A-E)
BW - Bot West (A - D)

Table 3.7 Comparison of nitrogen removal by various test screens on the ATS split floway. Values are means ± s.d. (n = 3 weekly samples).

Screen Type	Screen position	Nitrogen removal (g m^{-2} d^{-1})
Tenax (green)	TWA	3.11 ± 0.22
Naltex (191-3317-1) white	TWB	2.87 ± 0.27
Naltex (191-3317-1) white	BEE	2.59 ± 0.27
Tenax (green)	BED	2.58 ± 0.00
Conwed (XB2970) black	BWB	2.43 ± 0.00
Tensar (LG400321) black	TWD	2.33 ± 0.28
Conwed (XN2410) white	TED	2.32 ± 0.15
Conwed (XB1131) black	BWA	2.06 ± 0.08
Conwed (XN1678) white	BWD	2.04 ± 0.35
Conwed (XN1678) white	TEA	2.03 ± 0.19
Conwed (XN2410) white	BEB	1.94 ± 0.09
Conwed (XV1678) black	BWC	1.87 ± 0.27
Tenax (grid) white	TEE	1.61 ± 0.01
Conwed (XB2970) black	TEB	1.60 ± 0.00
Liner	BEC	0.75 ± 0.11
Liner	TEC	0.71 ± 0.16

TE - Top East (A-E)
TW - Top West (A-D)
BE - Bot East (A-E)
BW - Bot West (A - D)

Table 3.8 Comparison of phosphorus removal by various test screens on the ATS split floway. Values are means ± s.d. (n = 3 weekly samples).

Screen Type	Screen position	Phosphorus removal ($g\ m^{-2}\ d^{-1}$)
Conwed (XB2970) black	BWB	1.52 ± 0.00
Naltex (191-3317-1) white	TWB	1.25 ± 0.07
Naltex (191-3317-1) white	BEE	1.18 ± 0.21
Tenax (green)	TWA	1.02 ± 0.07
Conwed (XN2410) white	BEB	0.99 ± 0.06
Tenax (green)	BED	0.95 ± 0.00
Conwed (XN2410) white	TED	0.89 ± 0.14
Conwed (XN1678) white	BWD	0.88 ± 0.11
Conwed (XB1131) black	BWA	0.86 ± 0.09
Conwed (XB2970) black	TEB	0.81 ± 0.00
Tensar (LG400321) black	TWD	0.81 ± 0.05
Conwed (XN1678) white	TEA	0.79 ± 0.19
Conwed (XV1678) black	BWC	0.76 ± 0.03
Tenax (grid) white	TEE	0.58 ± 0.08
Liner	TEC	0.31 ± 0.08
Liner	BEC	0.28 ± 0.06

TE - Top East (A-E)
TW - Top West (A-D)
BE - Bot East (A-E)
BW - Bot West (A - D)

Table 3.7 Comparison of nitrogen removal by various test screens on the ATS split floway. Values are means ± s.d. (n = 3 weekly samples).

Screen Type	Screen position	Nitrogen removal (g m^{-2} d^{-1})
Tenax (green)	TWA	3.11 ± 0.22
Naltex (191-3317-1) white	TWB	2.87 ± 0.27
Naltex (191-3317-1) white	BEE	2.59 ± 0.27
Tenax (green)	BED	2.58 ± 0.00
Conwed (XB2970) black	BWB	2.43 ± 0.00
Tensar (LG400321) black	TWD	2.33 ± 0.28
Conwed (XN2410) white	TED	2.32 ± 0.15
Conwed (XB1131) black	BWA	2.06 ± 0.08
Conwed (XN1678) white	BWD	2.04 ± 0.35
Conwed (XN1678) white	TEA	2.03 ± 0.19
Conwed (XN2410) white	BEB	1.94 ± 0.09
Conwed (XV1678) black	BWC	1.87 ± 0.27
Tenax (grid) white	TEE	1.61 ± 0.01
Conwed (XB2970) black	TEB	1.60 ± 0.00
Liner	BEC	0.75 ± 0.11
Liner	TEC	0.71 ± 0.16

TE - Top East (A-E)
TW - Top West (A-D)
BE - Bot East (A-E)
BW - Bot West (A - D)

Table 3.8 Comparison of phosphorus removal by various test screens on the ATS split floway. Values are means ± s.d. (n = 3 weekly samples).

Screen Type	Screen position	Phosphorus removal ($g\ m^{-2}\ d^{-1}$)
Conwed (XB2970) black	BWB	1.52 ± 0.00
Naltex (191-3317-1) white	TWB	1.25 ± 0.07
Naltex (191-3317-1) white	BEE	1.18 ± 0.21
Tenax (green)	TWA	1.02 ± 0.07
Conwed (XN2410) white	BEB	0.99 ± 0.06
Tenax (green)	BED	0.95 ± 0.00
Conwed (XN2410) white	TED	0.89 ± 0.14
Conwed (XN1678) white	BWD	0.88 ± 0.11
Conwed (XB1131) black	BWA	0.86 ± 0.09
Conwed (XB2970) black	TEB	0.81 ± 0.00
Tensar (LG400321) black	TWD	0.81 ± 0.05
Conwed (XN1678) white	TEA	0.79 ± 0.19
Conwed (XV1678) black	BWC	0.76 ± 0.03
Tenax (grid) white	TEE	0.58 ± 0.08
Liner	TEC	0.31 ± 0.08
Liner	BEC	0.28 ± 0.06

TE - Top East (A-E)
TW - Top West (A-D)
BE - Bot East (A-E)
BW - Bot West (A - D)

Table 3.9 Comparison of treatment (July 18th through August 22nd) by the screened west and unscreened east sides of the split ATS floway. Values are means ± s.d. (n = 9). The hydraulic loading rate on both sides was 0.44 m d^{-1}.

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	26.40 ± 2.01	34.81 ± 2.50	34.81 ± 2.38
Dissolved Oxygen (mg l^{-1})	6.01 ± 1.02	22.97 ± 4.67	21.79 ± 2.45
pH	9.07 ± 0.20	10.17 ± 0.14	10.01 ± 0.16
Alkalinity (mg l^{-1} as $CaCO_3$)	261.47 ± 14.88	200.82 ± 24.51	207.53 ± 17.87
Hardness (mg l^{-1} as $CaCO_3$)	492.50 ± 18.43	431.06 ± 22.13	443.33 ± 19.08
Conductivity (mS m^{-1})	229.76 ± 4.97	223.77 ± 6.49	225.49 ± 6.39
Nutrients			
Ammonium (mg l^{-1})	0.05 ± 0.00	0.05 ± 0.00	0.06 ± 0.01
Nitrate/Nitrite (mg l^{-1})	1.03 ± 1.34	0.37 ± 0.66	0.39 ± 0.81
Particulate Nitrogen (mg l^{-1})	2.47 ± 0.90	1.96 ± 0.67	2.09 ± 0.71
Total Organic Nitrogen (mg l^{-1})	2.52 ± 0.90	2.01 ± 0.67	2.15 ± 0.71
Soluble Reactive Phosphorus (mg l^{-1})	114.00 ± 0.34	0.15 ± 0.07	0.24 ± 0.08
Particulate Phosphorus (mg l^{-1})	0.38 ± 0.23	0.17 ± 0.09	0.25 ± 0.12
Total Phosphorus (mg l^{-1})	1.52 ± 0.16	0.32 ± 0.09	0.49 ± 0.10
Solids			
UV transmittance (%)	63.35 ± 4.53	62.44 ± 3.25	61.29 ± 3.75
Turbidity (NTU)	8.33 ± 4.48	3.09 ± 1.36	4.39 ± 1.98
Total suspended solids (mg l^{-1})	23.39 ± 8.51	9.78 ± 3.99	14.22 ± 5.39
Total dissolved solids (mg l^{-1})	1032.33 ± 85.31	1008.11 ± 101.64	1051.83 ± 97.53
Biomass Solids (n = 5)			
Accumulated solids (g m^{-2} d^{-1})		21.57 ± 7.86	35.62 ± 4.45
% Volatile solids		50.26 ± 2.54	40.62 ± 2.92
% Nitrogen		3.54 ± 0.50	2.92 ± 0.21
% Phosphorus		1.38 ± 0.11	1.27 ± 0.05
Weekly Treatment			
N Removal (kg $week^{-1}$)		2.12 ± 0.63	1.79 ± 0.60
P Removal (kg $week^{-1}$)		1.75 ± 0.18	1.50 ± 0.16
N Accumulation (kg $week^{-1}$)		5.14 ± 2.19	6.53 ± 2.27
P Accumulation (kg $week^{-1}$)		2.99 ± 1.61	4.03 ± 1.77

Table 3.10 Comparison of diurnal (August 7th through 8th) treatment of the screened west and unscreened east sides of the split ATS floway. Values are means ± s.d. (n = 7). The hydraulic loading rate of both sides was 0.44 m d^{-1} and the flow was constant.

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	25.94 ± 2.92	25.00 ± 6.50	24.29 ± 6.40
Dissolved Oxygen (mg l^{-1})	5.90 ± 2.00	14.90 ± 9.90	14.00 ± 8.50
pH	8.91 ± 0.18	9.49 ± 9.90	14.00 ± 8.50
Alkalinity (mg l^{-1} as $CaCO_3$)	267.79 ± 6.03	258.14 ± 30.81	260.98 ± 31.64
Hardness (mg l^{-1} as $CaCO_3$)	505.79 ± 5.18	486.79 ± 52.69	495.86 ± 38.58
Conductivity (mS m^{-1})	230 ± 3.20	227.95 ± 6.79	230.48 ± 5.03
Nutrients			
Ammonium (mg l^{-1})	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00
Nitrate/Nitrite (mg l^{-1})	1.85 ± 0.68	1.04 ± 0.62	0.79 ± 0.44
Particulate Nitrogen (mg l^{-1})	1.49 ± 0.24	1.24 ± 0.27	1.33 ± 0.26
Total Organic Nitrogen (mg l^{-1})	1.54 ± 0.24	1.29 ± 0.27	1.38 ± 0.26
Soluble Reactive Phosphorus (mg l^{-1})	1.43 ± 0.15	0.96 ± 0.70	0.96 ± 0.63
Particulate Phosphorus (mg l^{-1})	0.18 ± 0.04	0.11 ± 0.03	0.12 ± 0.02
Total Phosphorus (mg l^{-1})	1.61 ± 0.13	1.07 ± 0.72	1.09 ± 0.62
Solids			
UV transmittance (%)	66.24 ± 0.67	65.79 ± 1.19	65.26 ± 1.13
Turbidity (NTU)	4.69 ± 0.32	2.01 ± 0.51	2.46 ± 0.54
Total suspended solids (mg l^{-1})	24.29 ± 5.28	16.57 ± 5.42	18.00 ± 5.95
Total dissolved solids (mg l^{-1})	1283.29 ± 218.32	1288.14 ± 226.51	1301.57 ± 214.39
Weekly Treatment			
N Removal (kg $week^{-1}$)		1.64	1.87
P Removal (kg $week^{-1}$)		0.82	0.79

Table 3.11 Background operation using high BOD effluent (October 3rd through 24th). Values are means ± s.d. (n = 8). The hydraulic loading rate was 0.43 m d^{-1}.

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	18.45 ± 1.62	26.50 ± 2.79	26.36 ± 2.84
Dissolved Oxygen (mg l^{-1})	2.78 ± 1.99	19.14 ± 3.38	18.24 ± 3.32
pH	7.84 ± 0.21	9.50 ± 0.26	9.53 ± 0.23
Alkalinity (mg l^{-1} as $CaCO_3$)	276.52 ± 5.69	239.57 ± 13.25	238.10 ± 16.00
Hardness (mg l^{-1} as $CaCO_3$)	508.56 ± 40.32	489.63 ± 44.16	481.56 ± 47.90
Conductivity (mS m^{-1})	234.43 ± 2.80	224.12 ± 5.10	225.86 ± 7.04
Nutrients			
Ammonium (mg l^{-1})	0.86 ± 0.72	0.08 ± 0.07	0.07 ± 0.05
Nitrate/Nitrite (mg l^{-1})	0.83 ± 0.69	1.25 ± 0.33	1.24 ± 0.45
Particulate Nitrogen (mg l^{-1})	12.47 ± 1.70	5.46 ± 1.50	5.26 ± 1.58
Total Organic Nitrogen (mg l^{-1})	13.34 ± 1.41	5.54 ± 1.50	5.33 ± 1.60
Soluble Reactive Phosphorus (mg l^{-1})	1.53 ± 0.23	0.53 ± 0.19	0.46 ± 0.06
Particulate Phosphorus (mg l^{-1})	1.96 ± 0.29	0.85 ± 0.44	0.70 ± 0.32
Total Phosphorus (mg l^{-1})	3.40 ± 0.16	1.32 ± 0.46	1.16 ± 0.37
Solids			
UV transmittance (%)	28.26 ± 1.95	43.64 ± 6.21	44.74 ± 5.94
Turbidity (NTU)	69.88 ± 9.16	28.68 ± 16.39	19.61 ± 10.41
Total suspended solids (mg l^{-1})	113.24 ± 14.68	52.29 ± 26.28	48.10 ± 29.39
Total dissolved solids (mg l^{-1})	1263.87 ± 123.07	1248.83 ± 120.40	1266.21 ± 159.61
Biomass Solids (n = 4)			
Accumulated solids (g m^{-2} d^{-1})		20.06 ± 4.95	16.51 ± 3.15
% Volatile solids		52.85 ± 6.01	52.43 ± 8.24
% Nitrogen		4.36 ± 0.59	4.47 ± 0.64
% Phosphorus		1.42 ± 0.10	1.36 ± 0.07
Weekly Treatment			
N Removal (kg $week^{-1}$)		9.74 ± 0.47	10.04 ± 0.46
P Removal (kg $week^{-1}$)		2.85 ± 0.37	3.08 ± 0.29
N Accumulation (kg $week^{-1}$)		6.94 ± 1.82	6.12 ± 0.92
P Accumulation (kg $week^{-1}$)		2.11 ± 0.56	1.68 ± 0.23

Table 3.12 Background operation of high BOD influent diurnal (October 16th through 17th) values of all parameters measured in the influent and effluents of west and east sides of the split ATS floway. Values are means ± s.d. (n = 7). The hydraulic loading rate of both floways was 0.44 m d^{-1} and overnight flow was constant.

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (^oC)	18.79 ± 0.51	19.77 ± 6.23	19.80 ± 6.37
Dissolved Oxygen (mg l^{-1})	2.10 ± 2.60	6.60 ± 5.80	6.60 ± 5.50
pH	7.97 ± 0.16	8.58 ± 0.89	8.66 ± 0.85
Alkalinity (mg l^{-1} as $CaCO_3$)	272.59 ± 8.5	260.11 ± 25.11	257.42 ± 30.18
Hardness (mg l^{-1} as $CaCO_3$)	524.43 ± 25.86	518.43 ± 41.64	525.50 ± 46.42
Conductivity (mS m^{-1})	224.18 ± 4.64	221.95 ± 6.47	222.60 ± 8.29
Nutrients			
Ammonium (mg l^{-1})	1.38 ± 0.32	0.80 ± 0.69	0.97 ± 0.74
Nitrate/Nitrite (mg l^{-1})	0.16 ± 0.13	0.41 ± 0.41	0.37 ± 0.36
Particulate Nitrogen (mg l^{-1})	11.12 ± 2.44	7.08 ± 3.79	5.81 ± 1.97
Total Organic Nitrogen (mg l^{-1})	12.50 ± 2.37	7.88 ± 4.21	6.78 ± 2.55
Soluble Reactive Phosphorus (mg l^{-1})	1.65 ± 0.08	1.62 ± 0.96	1.63 ± 1.01
Particulate Phosphorus (mg l^{-1})	1.82 ± 0.13	0.86 ± 0.44	0.77 ± 0.44
Total Phosphorus (mg l^{-1})	3.48 ± 0.12	2.48 ± 1.34	2.46 ± 1.35
Solids			
UV transmittance (%)	28.89 ± 0.61	44.25 ± 8.75	45.60 ± 8.03
Turbidity (NTU)	75.43 ± 10.97	31.73 ± 20.97	30.21 ± 20.31
Total suspended solids (mg l^{-1})	168.57 ± 40.35	107.62 ± 55.40	100.95 ± 59.43
Total dissolved solids (mg l^{-1})	1397.41 ± 135.52	1371.90 ± 146.06	1480.48 ± 187.03
Weekly Treatment			
N Removal (kg $week^{-1}$)		6.68	8.42
P Removal (kg $week^{-1}$)		1.52	1.64

Table 3.13 Background operation of high BOD influent diurnal (October 23rd through 24th) values of all parameters measured in the influent and effluents of west and east sides of the split ATS floway. Values are means ± s.d. (n = 7). The hydraulic loading rate of both floways was 0.44 m d^{-1} and there was no overnight flow on the east side between 1800 and 0800.

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	16.14 ± 0.91	16.15 ± 5.33	22.16 ± 2.40
Dissolved Oxygen (mg l^{-1})	5.4 ± 5.3	9.8 ± 8.6	16.50 ± 4.60
pH	7.82 ± 0.47	8.37 ± 0.73	9.26 ± 0.25
Alkalinity (mg l^{-1} as $CaCO_3$)	277.87 ± 3.90	277.17 ± 17.10	267.35 ± 19.83
Hardness (mg l^{-1} as $CaCO_3$)	528.93 ± 7.19	524.79 ± 12.59	515.50 ± 5.76
Conductivity (mS m^{-1})	223.08 ± 5.63	223.96 ± 6.39	228.84 ± 2.15
Nutrients			
Ammonium (mg l^{-1})	0.18 ± 0.16	0.12 ± 0.18	0.11 ± 0.08
Nitrate/Nitrite (mg l^{-1})	1.63 ± 0.13	1.37 ± 0.74	1.79 ± 0.13
Particulate Nitrogen (mg l^{-1})	13.25 ± 1.24	6.71 ± 1.98	3.89 ± 0.20
Total Organic Nitrogen (mg l^{-1})	13.45 ± 1.16	6.84 ± 2.03	4.00 ± 0.18
Soluble Reactive Phosphorus (mg l^{-1})	1.13 ± 0.12	1.23 ± 0.58	0.90 ± 0.65
Particulate Phosphorus (mg l^{-1})	2.32 ± 0.37	1.11 ± 0.43	0.60 ± 0.25
Total Phosphorus (mg l^{-1})	3.45 ± 0.26	2.35 ± 0.96	1.50 ± 0.89
Solids			
UV transmittance (%)	23.79 ± 1.58	39.53 ± 6.51	48.32 ± 2.83
Turbidity (NTU)	69.07 ± 4.66	33.17 ± 14.97	14.98 ± 5.89
Total suspended solids (mg l^{-1})	120.48 ± 22.21	44.76 ± 18.59	24.17 ± 16.26
Total dissolved solids (mg l^{-1})	1298.10 ± 222.07	1295.36 ± 91.85	1425.00 ± 85.97
Weekly Treatment			
N Removal (kg $week^{-1}$)		7.56	5.85
P Removal (kg $week^{-1}$)		1.68	1.13

Table 3.14 Comparison of treatment (October 25th through November 14th) by west and east sides of the split ATS floway at two hydraulic loading velocities (0.22 and 0.43 m d^{-1} respectively). Values are means ± s.d. (n = 6).

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	17.22 ± 0.61	26.35 ± 1.48	25.07 ± 1.12
Dissolved Oxygen (mg l^{-1})	1.92 ± 1.16	20.23 ± 2.29	19.57 ± 3.52
pH	7.60 ± 0.10	9.71 ± 0.09	9.18 ± 0.10
Alkalinity (mg l^{-1} as $CaCO_3$)	288.91 ± 13.99	207.16 ± 8.44	251.11 ± 9.44
Hardness (mg l^{-1} as $CaCO_3$)	513.25 ± 5.12	465.58 ± 19.08	501.08 ± 7.36
Conductivity (mS m^{-1})	229.78 ± 1.55	216.96 ± 5.74	223.10 ± 2.89
Nutrients			
Ammonium (mg l^{-1})	2.47 ± 2.06	0.46 ± 0.60	0.77 ± 1.23
Nitrate/Nitrite (mg l^{-1})	0.64 ± 0.89	1.75 ± 1.09	1.09 ± 0.83
Particulate Nitrogen (mg l^{-1})	11.63 ± 1.14	5.34 ± 1.08	7.39 ± 1.38
Total Organic Nitrogen (mg l^{-1})	14.10 ± 1.42	5.65 ± 1.26	7.53 ± 2.52
Soluble Reactive Phosphorus (mg l^{-1})	1.69 ± 0.39	0.26 ± 0.05	0.69 ± 0.23
Particulate Phosphorus (mg l^{-1})	1.81 ± 0.18	0.66 ± 0.13	1.00 ± 0.17
Total Phosphorus (mg l^{-1})	3.50 ± 0.23	0.92 ± 0.17	1.69 ± 0.32
Solids			
UV transmittance (%)	26.62 ± 1.66	43.98 ± 4.78	39.42 ± 5.34
Turbidity (NTU)	84.08 ± 27.61	15.52 ± 6.67	30.42 ± 14.86
Total suspended solids (mg l^{-1})	101.11 ± 12.79	28.06 ± 13.82	46.11 ± 18.50
Total dissolved solids (mg l^{-1})	1204.72 ± 102.01	1271.94 ± 110.86	1327.78 ± 108.96
Organic Matter			
SBOD	24.29 ± 0.00	5.80 ± 0.00	11.67 ± 0.00
TBOD	106.20 ± 5.37	18.37 ± 7.38	41.38 ± 5.78
Biomass Solids (n = 3)			
Accumulated solids (g m^{-2} d^{-1})		21.04 ± 4.82	22.68 ± 8.80
% Volatile solids		62.28 ± 1.12	65.43 ± 1.91
% Nitrogen		6.01 ± 0.18	6.30 ± 0.06
% Phosphorus		1.36 ± 0.04	1.52 ± 0.09
Weekly Treatment			
N Removal (kg week^{-1})		5.75 ± 0.62	8.53 ± 1.60
P Removal (kg week^{-1})		2.06 ± 0.14	2.81 ± 0.16
N Accumulation (kg week^{-1})		8.90 ± 1.78	10.12 ± 3.89
P Accumulation (kg week^{-1})		2.04 ± 0.53	2.42 ± 0.86

Table 3.15 Treatment (November 14th through December 12th) by west and east sides of the split ATS floway at a hydraulic loading velocity of 0.22 m d^{-1}. Values are means ± s.d. (n = 10).

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	15.20 ± 1.23	20.57 ± 3.75	20.27 ± 3.64
Dissolved Oxygen (mg l^{-1})	3.04 ± 1.80	22.75 ± 2.97	20.58 ± 3.50
pH	7.89 ± 0.11	9.58 ± 0.24	9.32 ± 0.18
Alkalinity (mg l^{-1} as $CaCO_3$)	327.54 ± 4.93	267.07 ± 25.63	257.33 ± 22.55
Hardness (mg l^{-1} as $CaCO_3$)	495.40 ± 9.20	478.9 ± 12.76	483.65 ± 7.38
Conductivity (mS m^{-1})	239.22 ± 7.05	221.73 ± 8.24	225.21 ± 4.55
Nutrients			
Ammonium (mg l^{-1})	13.27 ± 2.64	6.50 ± 3.49	5.98 ± 2.94
Nitrate/Nitrite (mg l^{-1})	0.37 ± 0.37	1.40 ± 0.69	3.59 ± 1.85
Particulate Nitrogen (mg l^{-1})	12.41 ± 1.68	10.96 ± 2.35	10.01 ± 1.93
Total Organic Nitrogen (mg l^{-1})	25.67 ± 3.47	17.45 ± 4.98	16.00 ± 4.06
Soluble Reactive Phosphorus (mg l^{-1})	0.74 ± 0.80	0.31 ± 0.15	0.28 ± 0.21
Particulate Phosphorus (mg l^{-1})	3.55 ± 0.91	2.71 ± 0.95	2.38 ± 0.78
Total Phosphorus (mg l^{-1})	4.29 ± 0.28	3.02 ± 0.86	2.66 ± 0.70
Organic Matter			
SBOD	12.46 ± 7.85	9.41 ± 3.12	8.52 ± 4.47
TBOD	64.87 ± 22.20	46.29 ± 11.31	45.07 ± 13.14
Solids			
UV transmittance (%)	24.34 ± 1.58	28.10 ± 5.06	31.95 ± 4.38
Turbidity (NTU)	100.40 ± 29.02	72.65 ± 29.00	58.15 ± 22.39
Total suspended solids (mg l^{-1})	97.33 ± 16.40	78.17 ± 21.43	65.00 ± 21.19
Total dissolved solids (mg l^{-1})	1083.83 ± 75.83	1164.47 ± 69.81	1104.83 ± 108.14
Biomass Solids (n = 3)			
Accumulated solids (g m^{-2} d^{-1})		12.31 ± 4.31	13.23 ± 1.85
% Volatile solids		59.78 ± 2.29	60.75 ± 4.29
% Nitrogen		6.16 ± 0.17	6.27 ± 0.15
% Phosphorus		1.29 ± 0.19	1.34 ± 0.14
Weekly Treatment			
N Removal (kg $week^{-1}$)		5.34 ± 0.92	4.97 ± 0.90
P Removal (kg $week^{-1}$)		1.03 ± 0.48	1.25 ± 0.34
N Accumulation (kg $week^{-1}$)		5.41 ± 2.04	5.88 ± 0.88
P Accumulation (kg $week^{-1}$)		1.18 ± 0.59	1.27 ± 0.32

Table 3.16 Diurnal (December 4th through 5th) values of all parameters measured in the influent and effluents of west and east sides of the split ATS floway. Values are means ± s.d. (n = 7). The hydraulic loading rate of both floways was 0.22 $m\ d^{-1}$ and overnight flow was constant.

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (^oC)	14.91 ± 0.33	15.57 ± 4.13	15.63 ± 3.69
Dissolved Oxygen ($mg\ l^{-1}$)	2.20 ± 1.10	11.10 ± 10.00	10.60 ± 9.80
pH	7.68 ± 0.20	8.60 ± 0.85	8.49 ± 0.75
Alkalinity ($mg\ l^{-1}$ as $CaCO_3$)	327.01 ± 2.93	317.89 ± 33.10	304.94 ± 0.75
Hardness ($mg\ l^{-1}$ as $CaCO_3$)	497.14 ± 2.96	501.21 ± 8.81	502.29 ± 10.43
Conductivity ($mS\ m^{-1}$)	229.37 ± 4.30	225.73 ± 7.42	225.89 ± 5.65
Nutrients			
Ammonium ($mg\ l^{-1}$)	13.73 ± 0.86	12.08 ± 4.59	11.62 ± 3.85
Nitrate/Nitrite ($mg\ l^{-1}$)	1.51 ± 1.27	1.96 ± 0.91	2.54 ± 1.24
Particulate Nitrogen ($mg\ l^{-1}$)	13.88 ± 1.58	11.03 ± 1.60	11.06 ± 1.14
Total Organic Nitrogen ($mg\ l^{-1}$)	27.61 ± 1.04	23.11 ± 4.32	22.01 ± 2.83
Soluble Reactive Phosphorus ($mg\ l^{-1}$)	0.45 ± 0.48	1.31 ± 1.09	1.12 ± 0.91
Particulate Phosphorus ($mg\ l^{-1}$)	4.04 ± 0.48	2.82 ± 0.38	2.67 ± 0.37
Total Phosphorus ($mg\ l^{-1}$)	4.49 ± 0.16	4.13 ± 0.85	3.79 ± 0.77
Organic Matter			
SBOD	69.81 ± 7.03	48.13 ± 9.63	50.27 ± 8.70
TBOD	11.28 ± 2.12	12.93 ± 1.27	11.38 ± 4.27
Solids			
UV transmittance (%)	23.79 ± 1.52	33.59 ± 6.30	34.19 ± 4.51
Turbidity (NTU)	84.29 ± 12.79	57.86 ± 11.00	51.71 ± 7.74
Total suspended solids ($mg\ l^{-1}$)	100.95 ± 15.50	56.19 ± 29.03	63.81 ± 22.00
Total dissolved solids ($mg\ l^{-1}$)	1174.81 ± 117.78	1208.81 ± 52.34	1203.86 ± 126.37
Weekly Treatment			
N Removal ($kg\ week^{-1}$)		3.09	3.06
P Removal ($kg\ week^{-1}$)		0.27	0.53

Table 3.17 Diurnal (December 11th through 12th) values of all parameters measured in the influent and effluents of west and east sides of the split ATS floway. Values are means ± s.d. (n = 4). The hydraulic loading rate of both floways was 0.22 $m\ d^{-1}$ and there was no overnight flow between 1630 and 0730.

Parameter	**Influent** **Mean ± s.d.**	**West Effluent** **Mean ± s.d.**	**East Effluent** **Mean ± s.d.**
Physical Parameters			
Temperature (^oC)	13.78 ± 0.19	13.21 ± 0.68	13.19 ± 0.66
Dissolved Oxygen (mg l^{-1})	2.10 ± 0.10	11.40 ± 4.90	11.10 ± 5.10
pH	7.89 ± 0.06	8.66 ± 0.35	8.58 ± 0.35
Alkalinity (mg l^{-1} as $CaCO_3$)	336.67 ± 4.47	292.06 ± 23.16	284.92 ± 26.57
Hardness (mg l^{-1} as $CaCO_3$)	490.00 ± 7.08	465.38 ± 18.88	467.38 ± 21.74
Conductivity (mS m^{-1})	231.01 ± 3.25	217.90 ± 18.02	220.54 ± 16.52
Nutrients			
Ammonium (mg l^{-1})	17.54 ± 0.79	13.44 ± 2.19	12.37 ± 2.15
Nitrate/Nitrite (mg l^{-1})	0.26 ± 0.16	0.64 ± 0.30	1.30 ± 0.76
Particulate Nitrogen (mg l^{-1})	10.97 ± 0.58	12.04 ± 2.71	11.07 ± 3.19
Total Organic Nitrogen (mg l^{-1})	28.51 ± 0.59	25.48 ± 2.71	23.44 ± 4.03
Soluble Reactive Phosphorus (mg l^{-1})	0.73 ± 0.21	0.92 ± 1.16	0.95 ± 1.13
Particulate Phosphorus (mg l^{-1})	3.98 ± 0.17	4.85 ± 2.37	3.07 ± 0.81
Total Phosphorus (mg l^{-1})	4.70 ± 0.16	5.77 ± 3.48	4.02 ± 1.93
Solids			
UV transmittance (%)	24.69 ± 0.43	29.63 ± 2.03	35.03 ± 1.93
Turbidity (NTU)	157.03 ± 8.74	146.38 ± 41.92	94.63 ± 18.16
Total suspended solids (mg l^{-1})	94.58 ± 14.01	139.79 ± 77.51	87.92 ± 42.19
Total dissolved solids (mg l^{-1})	1155.62 ± 75.25	1249.58 ± 219.01	1202.71 ± 113.40
Weekly Treatment			
N Removal (kg $week^{-1}$)		1.15	1.76
P Removal (kg $week^{-1}$)		-0.46	0.30

Table 3.18 Comparison of treatment (December 13th through January 15th) by west and east sides of the split ATS floway. The hydraulic loading velocity of both floways was 0.11 m d^{-1}. Values are means ± s.d. (n = 6).

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	12.13 ± 1.19	14.30 ± 3.30	14.10 ± 3.20
Dissolved Oxygen (mg l^{-1})	5.12 ± 1.87	26.15 ± 5.22	24.17 ± 4.04
pH	7.98 ± 0.11	9.66 ± 0.30	9.82 ± 0.45
Alkalinity (mg l^{-1} as $CaCO_3$)	323.34 ± 10.34	229.84 ± 32.82	212.20 ± 39.80
Hardness (mg l^{-1} as $CaCO_3$)	485.42 ± 7.59	458.92 ± 19.61	45458 ± 34.96
Conductivity (mS m^{-1})	239.43 ± 3.13	222.46 ± 5.57	221.18 ± 4.33
Nutrients			
Ammonium (mg l^{-1})	19.28 ± 2.55	8.02 ± 3.33	6.33 ± 4.32
Nitrate/Nitrite (mg l^{-1})	0.36 ± 0.14	5.62 ± 3.55	7.41 ± 4.06
Particulate Nitrogen (mg l^{-1})	11.04 ± 1.55	9.26 ± 1.10	8.77 ± 1.33
Total Organic Nitrogen (mg l^{-1})	30.32 ± 1.32	17.27 ± 2.54	15.10 ± 3.61
Soluble Reactive Phosphorus (mg l^{-1})	0.31 ± 0.28	0.21 ± 0.11	0.22 ± 0.10
Particulate Phosphorus (mg l^{-1})	3.35 ± 0.60	2.58 ± 0.50	2.35 ± 0.40
Total Phosphorus (mg l^{-1})	3.72 ± 0.37	2.79 ± 0.40	2.57 ± 0.33
Organic Matter			
SBOD	6.59 ± 3.71	8.35 ± 2.86	8.86 ± 3.38
TBOD	22.33 ± 11.73	19.58 ± 5.50	21.11 ± 5.88
Solids			
UV transmittance (%)	26.71 ± 2.76	29.03 ± 2.86	30.54 ± 3.42
Turbidity (NTU)	68.54 ± 24.34	52.25 ± 19.78	43.17 ± 10.46
Total suspended solids (mg l^{-1})	83.43 ± 27.79	69.67 ± 23.48	66.61 ± 19.63
Total dissolved solids (mg l^{-1})	971.55 ± 112.46	1086.82 ± 138.84	1071.02 ± 121.32
Biomass Solids (n = 5)			
Accumulated solids (g m^{-2} d^{-1})		7.78 ± 3.33	8.09 ± 2.89
% Volatile solids		55.94 ± 1.45	59.23 ± 3.21
% Nitrogen		5.72 ± 0.12	6.05 ± 0.26
% Phosphorus		1.38 ± 0.03	1.44 ± 0.14
Weekly Treatment			
N Removal (kg $week^{-1}$)		2.99 ± 0.25	3.06 ± 0.14
P Removal (kg $week^{-1}$)		0.33 ± 0.07	0.41 ± 0.07
N Accumulation (kg $week^{-1}$)		4.00 ± 1.03	4.30 ± 1.03
P Accumulation (kg $week^{-1}$)		0.97 ± 0.26	1.01 ± 0.23

Table 3.19 Diurnal (February 12th through 13th) values of all parameters measured in the influent and effluents of west and east sides of the split ATS floway. Values are means ± s.d. (west n = 4; east n =7). The hydraulic loading rate of both floways was 0.22 m d^{-1} and there was no overnight flow on the west side between 2030 and 1100.

Parameter	**Influent** **Mean ± s.d.**	**West Effluent** **Mean ± s.d.**	**East Effluent** **Mean ± s.d.**
Physical Parameters			
Temperature (°C)	15.97 ± 1.46	21.28 ± 5.30	17.50 ± 5.88
Dissolved Oxygen (mg l^{-1})	3.70 ± 1.40	15.70 ± 7.90	11.80 ± 7.90
pH	7.81 ± 0.19	8.99 ± 0.63	8.69 ± 0.78
Alkalinity (mg l^{-1} as $CaCO_3$)	279.98 ± 4.68	204.92 ± 61.99	231.13 ± 58.30
Hardness (mg l^{-1} as $CaCO_3$)	473.79 ± 1.96	458.25 ± 24.64	468.57 ± 23.97
Conductivity (mS m^{-1})	225.41 ± 13.65	212.62 ± 7.25	213.39 ± 5.95
Nutrients			
Ammonium (mg l^{-1})	20.67 ± 14.92	11.56 ± 6.58	6.66 ± 3.96
Nitrate/Nitrite (mg l^{-1})	0.63 ± 0.20	5.79 ± 3.11	3.91 ± 3.89
Particulate Nitrogen (mg l^{-1})	1.61 ± 0.77	1.85 ± 0.66	1.72 ± 0.35
Total Organic Nitrogen (mg l^{-1})	22.28 ± 14.45	8.60 ± 4.69	5.35 ± 3.65
Soluble Reactive Phosphorus (mg l^{-1})	3.89 ± 0.19	2.61 ± 2.07	3.13 ± 1.89
Particulate Phosphorus (mg l^{-1})	0.92 ± 0.16	0.30 ± 0.10	0.65 ± 0.65
Total Phosphorus (mg l^{-1})	4.31 ± 1.32	3.20 ± 2.59	4.13 ± 2.72
Solids			
UV transmittance (%)	74.85 ± 0.32	69.80 ± 3.91	73.18 ± 2.84
Turbidity (NTU)	2.56 ± 0.29	3.20 ± 1.22	2.08 ± 0.64
Total suspended solids (mg l^{-1})	9.50 ± 3.37	12.25 ± 3.72	7.36 ± 1.73
Total dissolved solids (mg l^{-1})	1172.50 ± 81.44	1122.25 ± 57.32	1160.50 ± 65.53
Weekly Treatment			
N Removal (kg week^{-1})		4.31	10.42
P Removal (kg week^{-1})		0.35	0.13

Table 3.20 Influent and effluent concentrations of the ATS floway operated with a weekly harvest regime.

	21-Nov		
	Mean ± s.d. (% Removal)		
Parameter	**Influent**	**West Effluent**	**East Effluent**
Physical Parameters			
Temperature (^{o}C)	17.15 ± 0.25	22.60 ± 4.80 (-31.78)	22.40 ± 4.70 (-30.61)
Dissolved Oxygen (mg l^{-1})	0.50 ± 0.40	22.65 ± 2.65 (-4430.00)	18.75 ± 4.55 (-3650.00)
pH	7.78 ± 0.02	9.62 ± 0.16 (-23.73)	9.41 ± 0.16 (-20.96)
Alkalinity (mg l^{-1} as $CaCO_3$)	325.86 ± 3.36	233.48 ± 25.20 (28.35)	236.84 ± 26.88 (27.32)
Hardness (mg l^{-1} as $CaCO_3$)	497.00 ± 17.00	474.75 ± 1.75 (4.48)	489.50 ± 4.50 (1.51)
Conductivity (mS m^{-1})	232.37 ± 0.48	218.56 ± 0.29 (5.94)	222.34 ± 1.08 (4.32)
Nutrients			
Ammonium (mg l^{-1})	9.37 ± 1.62	2.29 ± 1.37 (75.53)	2.43 ± 1.44 (74.07)
Nitrate/Nitrite (mg l^{-1})	0.48 ± 0.25	2.23 ± 1.13 (-366.49)	2.21 ± 1.00 (-362.30)
Particulate Nitrogen (mg l^{-1})	11.12 ± 1.29	7.56 ± 1.70 (32.05)	7.80 ± 2.19 (29.87)
Total Organic Nitrogen (mg l^{-1})	20.49 ± 2.91	9.85 ± 3.07 (51.93)	10.23 ± 3.63 (50.08)
Soluble Reactive Phosphorus (mg l^{-1})	1.99 ± 0.31	0.46 ± 0.15 (76.95)	0.57 ± 0.29 (71.28)
Particulate Phosphorus (mg l^{-1})	2.11 ± 0.55	1.20 ± 0.44 (43.13)	1.15 ± 0.51 (45.50)
Total Phosphorus (mg l^{-1})	4.10 ± 0.24	1.66 ± 0.59 (59.52)	1.72 ± 0.80 (58.00)
Organic Matter			
SBOD (mg l^{-1})	29.90 ± 0.00	9.90 ± 0.00 (66.89)	8.41 ± 0.00 (71.87)
TBOD (mg l^{-1})	87.79 ± 2.39	41.23 ± 10.01 (53.03)	45.29 ± 4.32 (48.41)
Solids			
UV transmittance (%)	25.65 ± 0.45	36.33 ± 3.83 (-41.62)	37.62 ± 4.42 (-46.65)
Turbidity (NTU)	116.00 ± 16.50	49.50 ± 14.00 (57.33)	43.00 ± 19.50 (62.93)
Total suspended solids (mg l^{-1})	75.00 ± 13.33	41.67 ± 13.33 (44.44)	40.83 ± 15.83 (45.56)
Total dissolved solids (mg l^{-1})	1015.00 ± 11.67	1163.33 ± 55.00 (-14.61)	1078.33 ± 105.00 (-6.24)
Biomass Solids			
Accumulated solids (g m^{-2} d^{-1})		18.33	15.85
% Volatile solids		62.23	66.83
% Nitrogen		6.38	6.34
% Phosphorus		1.55	1.53
Weekly Treatment			
N Removal (kg $week^{-1}$)		6.65 ± 0.91	6.38 ± 0.38
P Removal (kg $week^{-1}$)		1.82 ± 0.26	1.78 ± 0.42
NAccumulation (kg $week^{-1}$)		8.28	7.12
P Accumulation (kg $week^{-1}$)		2.01	1.72

Table 3.21 Influent and effluent concentrations of the ATS floway operated with harvest intervals of two weeks on the west and one week on the east.

		28-Nov	
		Mean ± s.d. (% Removal)	
Parameter	**Influent**	**West Effluent**	**East Effluent**
Physical Parameters			
Temperature (^{o}C)	15.10 ± 1.20	22.00 ± 0.10 (-45.70)	21.55 ± 0.35 (-42.72)
Dissolved Oxygen (mg l^{-1})	4.45 ± 0.25	23.05 ± 1.05 (-417.98)	20.05 ± 1.65 (-350.56)
pH	7.84 ± 0.16	9.74 ± 0.03 (-24.31)	9.35 ± 0.10 (-19.27)
Alkalinity (mg l^{-1} as $CaCO_3$)	325.02 ± 0.84	252.79 ± 5.88 (22.22)	252.79 ± 7.56 (22.22)
Hardness (mg l^{-1} as $CaCO_3$)	495.75 ± 1.75	480.50 ± 4.00 (3.08)	479.75 ± 6.75 (3.23)
Conductivity (mS m^{-1})	232.18 ± 1.31	218.59 ± 0.33 (5.85)	223.93 ± 0.12 (3.55)
Nutrients			
Ammonium (mg l^{-1})	12.11 ± 1.00	4.67 ± 1.47 (61.45)	5.06 ± 1.31 (58.21)
Nitrate/Nitrite (mg l^{-1})	0.25 ± 0.22	1.24 ± 0.13 (-395.00)	3.42 ± 0.97 (-1268.00)
Particulate Nitrogen (mg l^{-1})	11.66 ± 0.40	10.62 ± 0.27 (8.90)	9.75 ± 1.54 (16.41)
Total Organic Nitrogen (mg l^{-1})	23.77 ± 0.59	15.29 ± 1.74 (35.67)	14.81 ± 2.85 (37.70)
Soluble Reactive Phosphorus (mg l^{-1})	0.94 ± 0.81	0.42 ± 0.12 (55.20)	0.34 ± 0.06 (63.47)
Particulate Phosphorus (mg l^{-1})	3.17 ± 0.64	2.30 ± 0.67 (27.25)	2.20 ± 0.67 (30.57)
Total Phosphorus (mg l^{-1})	4.10 ± 0.16	2.72 ± 0.56 (33.64)	2.54 ± 0.62 (38.09)
Organic Matter			
SBOD (mg l^{-1})	13.24 ± 0.00	13.07 ± 0.00 (1.28)	11.22 ± 0.00 (15.29)
TBOD (mg l^{-1})	81.11 ± 9.95	48.96 ± 8.30 (39.64)	55.79 ± 6.02 (31.22)
Solids			
UV transmittance (%)	25.25 ± 0.45	27.43 ± 3.28 (-8.61)	31.48 ± 3.88 (-24.65)
Turbidity (NTU)	75.25 ± 15.75	55.00 ± 4.50 (26.91)	46.25 ± 1.75 (38.54)
Total suspended solids (mg l^{-1})	90.83 ± 7.50	80.83 ± 14.17 (11.01)	63.33 ± 18.33 (30.28)
Total dissolved solids (mg l^{-1})	1016.67 ± 90.00	1120.83 ± 45.83 (-10.25)	1113.33 ± 40.00 (-9.51)
Biomass Solids			
Accumulated solids (g m^{-2} d^{-1})		10.10	11.99
% Volatile solids		60.37	57.88
% Nitrogen		5.97	6.06
% Phosphorus		1.20	1.27
Weekly Treatment			
N Removal (kg $week^{-1}$)		5.60 ± 0.92	4.33 ± 1.13
P Removal (kg $week^{-1}$)		1.03 ± 0.54	1.17 ± 0.58
NAccumulation (kg $week^{-1}$)		4.27	5.15
P Accumulation (kg $week^{-1}$)		0.86	1.08

Table 3.22 Influent and effluent concentrations of the ATS floway operated with harvest intervals of three weeks on the west and one week on the east.

	5-Dec Mean ± s.d. (% Removal)		
Parameter	**Influent**	**West Effluent**	**East Effluent**
Physical Parameters			
Temperature (^{o}C)	14.80 ± 0.60	21.55 ± 0.75 (-45.61)	21.05 ± 0.75 (-42.23)
Dissolved Oxygen (mg l^{-1})	5.50 ± 0.60	25.05 ± 2.05 (-355.45)	22.45 ± 3.75 (-308.18)
pH	8.01 ± 0.07	9.68 ± 0.13 (-20.79)	9.42 ± 0.09 (-17.60)
Alkalinity (mg l^{-1} as $CaCO_3$)	325.02 ± 0.84	272.11 ± 3.36 (16.28)	253.63 ± 15.12 (21.96)
Hardness (mg l^{-1} as $CaCO_3$)	498.50 ± 1.00	488.75 ± 2.75 (1.96)	488.25 ± 1.75 (2.06)
Conductivity (mS m^{-1})	242.79 ± 4.12	218.19 ± 12.37 (10.13)	225.74 ± 3.90 (7.02)
Nutrients			
Ammonium (mg l^{-1})	13.57 ± 0.49	6.35 ± 1.36 (53.20)	5.53 ± 1.20 (59.22)
Nitrate/Nitrite (mg l^{-1})	0.68 ± 0.61	1.50 ± 0.05 (-119.78)	4.70 ± 1.89 (-589.01)
Particulate Nitrogen (mg l^{-1})	13.19 ± 0.97	12.92 ± 0.96 (1.99)	11.48 ± 0.81 (12.97)
Total Organic Nitrogen (mg l^{-1})	26.75 ± 0.48	19.27 ± 0.40 (27.96)	17.01 ± 2.02 (36.43)
Soluble Reactive Phosphorus (mg l^{-1})	0.11 ± 0.08	0.21 ± 0.05 (-100.00)	0.13 ± 0.03 (-26.19)
Particulate Phosphorus (mg l^{-1})	4.08 ± 0.22	3.11 ± 0.11 (23.84)	2.87 ± 0.31 (29.78)
Total Phosphorus (mg l^{-1})	4.19 ± 0.15	3.32 ± 0.16 (20.73)	3.00 ± 0.34 (28.38)
Organic Matter			
SBOD (mg l^{-1})	4.41 ± 0.00	9.62 ± 0.00 (-118.46)	9.08 ± 0.00 (-106.15)
TBOD (mg l^{-1})	58.46 ± 16.78	55.71 ± 0.00 (4.70)	52.87 ± 4.88 (9.57)
Solids			
UV transmittance (%)	23.05 ± 2.10	24.10 ± 1.85 (-4.56)	27.60 ± 0.75 (-19.74)
Turbidity (NTU)	74.25 ± 7.25	59.00 ± 8.00 (20.54)	48.50 ± 11.50 (34.68)
Total suspended solids (mg l^{-1})	114.17 ± 0.83	92.50 ± 7.50 (18.98)	83.33 ± 18.33 (27.01)
Total dissolved solids (mg l^{-1})	1133.33 ± 26.67	1165.00 ± 106.67 (-2.79)	1072.50 ± 94.17 (5.37)
Biomass Solids			
Accumulated solids (g m^{-2} d^{-1})		8.48	11.85
% Volatile solids		56.72	57.54
% Nitrogen		6.13	6.40
% Phosphorus		1.12	1.21
Weekly Treatment			
N Removal (kg $week^{-1}$)		4.98 ± 1.08	4.07 ± 0.68
P Removal (kg $week^{-1}$)		0.65 ± 0.01	0.84 ± 0.13
NAccumulation (kg $week^{-1}$)		3.68	5.37
P Accumulation (kg $week^{-1}$)		0.67	1.02

Table 3.23 Influent and effluent concentrations of the ATS floway operated with harvest intervals of four weeks on the west and one week on the east.

	12-Dec		
	Mean ± s.d. (% Removal)		
Parameter	**Influent**	**West Effluent**	**East Effluent**
Physical Parameters			
Temperature (^{o}C)	14.50 ± 0.60	19.10 ± 3.30 (-31.72)	19.00 ± 3.30 (-31.03)
Dissolved Oxygen (mg l^{-1})	2.45 ± 0.35	21.30 ± 1.70 (-769.39)	20.50 ± 0.80 (-736.73)
pH	7.88 ± 0.01	9.41 ± 0.24 (-19.35)	9.15 ± 0.09 (-16.05)
Alkalinity (mg l^{-1} as $CaCO_3$)	330.90 ± 0.00	287.23 ± 8.40 (13.20)	263.71 ± 15.12 (20.30)
Hardness (mg l^{-1} as $CaCO_3$)	489.75 ± 9.25	468.50 ± 21.50 (4.34)	477.50 ± 8.50 (2.50)
Conductivity (mS m^{-1})	249.17 ± 2.46	230.15 ± 3.01 (7.63)	228.56 ± 1.59 (8.27)
Nutrients			
Ammonium (mg l^{-1})	15.50 ± 0.86	9.22 ± 0.93 (40.56)	8.17 ± 1.40 (47.28)
Nitrate/Nitrite (mg l^{-1})	0.17 ± 0.01	1.11 ± 0.16 (-551.47)	4.51 ± 2.13 (-2550.00)
Particulate Nitrogen (mg l^{-1})	13.74 ± 1.82	13.56 ± 0.70 (1.35)	10.23 ± 0.98 (25.55)
Total Organic Nitrogen (mg l^{-1})	29.24 ± 0.95	22.77 ± 0.23 (22.13)	18.40 ± 0.42 (37.07)
Soluble Reactive Phosphorus (mg l^{-1})	0.33 ± 0.29	0.21 ± 0.13 (37.12)	0.12 ± 0.04 (62.88)
Particulate Phosphorus (mg l^{-1})	4.24 ± 0.07	3.53 ± 0.05 (16.76)	2.92 ± 0.06 (31.15)
Total Phosphorus (mg l^{-1})	4.57 ± 0.22	3.74 ± 0.07 (18.23)	3.04 ± 0.10 (33.44)
Organic Matter			
SBOD (mg l^{-1})	8.56 ± 2.29	5.53 ± 0.15 (35.42)	5.30 ± 3.33 (38.07)
TBOD (mg l^{-1})	32.84 ± 6.10	31.95 ± 2.90 (2.69)	24.94 ± 1.06 (24.04)
Solids			
UV transmittance (%)	23.28 ± 1.38	25.60 ± 2.50 (-9.99)	32.43 ± 1.78 (-39.31)
Turbidity (NTU)	113.75 ± 3.75	98.25 ± 16.75 (13.63)	70.25 ± 5.75 (38.24)
Total suspended solids (mg l^{-1})	105.83 ± 0.83	90.00 ± 0.00 (14.96)	68.33 ± 1.67 (35.43)
Total dissolved solids (mg l^{-1})	1084.17 ± 7.50	1170.00 ± 53.33 (-7.92)	1053.33 ± 145.00 (2.84)
Biomass Solids			
Accumulated solids (g m^{-2} d^{-1})			
% Volatile solids			
% Nitrogen			
% Phosphorus			
Weekly Treatment			
N Removal (kg $week^{-1}$)		4.14 ± 0.76	5.08 ± 0.60
P Removal (kg $week^{-1}$)		0.62 ± 0.11	1.19 ± 0.09
NAccumulation (kg $week^{-1}$)			
PAccumulation (kg $week^{-1}$)			

Table 3.24 Comparison of treatment of ammonia dosed influent (January 16th through March 5th) by west and east sides of the split ATS floway. Both sides had a hydraulic loading velocity of 0.22 m d^{-1}. Values are means ± s.d. (n = 17).

Parameter	**Influent** **Mean ± s.d.**	**West Effluent** **Mean ± s.d.**	**East Effluent** **Mean ± s.d.**
Physical Parameters			
Temperature (°C)	12.98 ± 2.76	17.62 ± 5.16	17.55 ± 5.14
Dissolved Oxygen (mg l^{-1})	6.29 ± 2.08	25.74 ± 4.67	25.34 ± 3.83
pH	7.83 ± 0.21	9.46 ± 0.47	9.57 ± 0.50
Alkalinity (mg l^{-1} as $CaCO_3$)	257.47 ± 15.49	189.80 ± 27.91	185.75 ± 29.82
Hardness (mg l^{-1} as $CaCO_3$)	465.29 ± 13.14	440.85 ± 21.07	438.44 ± 25.41
Conductivity (mS m^{-1})	227.87 ± 13.13	210.20 ± 11.36	211.55 ± 9.87
Nutrients			
Ammonium (mg l^{-1})	18.91 ± 9.52	6.83 ± 6.38	5.82 ± 6.35
Nitrate/Nitrite (mg l^{-1})	1.43 ± 1.01	6.74 ± 1.43	7.17 ± 1.64
Particulate Nitrogen (mg l^{-1})	1.74 ± 0.73	2.58 ± 1.59	2.36 ± 1.12
Total Organic Nitrogen (mg l^{-1})	20.65 ± 9.55	9.41 ± 7.42	8.18 ± 6.93
Soluble Reactive Phosphorus (mg l^{-1})	3.68 ± 1.08	1.45 ± 0.61	1.26 ± 0.75
Particulate Phosphorus (mg l^{-1})	0.56 ± 0.36	0.35 ± 0.24	0.33 ± 0.20
Total Phosphorus (mg l^{-1})	4.05 ± 1.06	1.71 ± 0.62	1.50 ± 0.69
Solids			
UV transmittance (%)	71.52 ± 5.05	66.90 ± 7.53	68.29 ± 6.01
Turbidity (NTU)	5.27 ± 3.91	6.71 ± 5.06	5.06 ± 4.04
Total suspended solids (mg l^{-1})	10.26 ± 7.44	14.01 ± 7.14	10.04 ± 4.54
Total dissolved solids (mg l^{-1})	1106.40 ± 75.86	1059.06 ± 106.77	1062.07 ± 117.22
Biomass Solids (n = 6)			
Accumulated solids (g m^{-2} d^{-1})		10.65 ± 3.41	10.35 ± 3.52
% Volatile solids		46.80 ± 1.40	47.77 ± 1.56
% Nitrogen		4.89 ± 0.32	4.91 ± 0.45
% Phosphorus		1.41 ± 0.14	1.41 ± 0.16
Weekly Treatment			
N Removal (kg $week^{-1}$)		3.85 ± 2.06	4.37 ± 2.49
P Removal (kg $week^{-1}$)		1.74 ± 0.94	1.87 ± 0.95
N Accumulation (kg $week^{-1}$)		3.70 ± 1.21	3.64 ± 1.36
P Accumulation (kg $week^{-1}$)		1.06 ± 0.34	1.03 ± 0.35

Table 3.25 Diurnal (January 29th through 30th) values of all parameters measured in the influent and effluents of west and east sides of the split ATS floway. Values are means ± s.d. (n = 7). The hydraulic loading rate of both floways was 0.22 m d^{-1} and overnight flow was constant.

Parameter	Influent Mean ± s.d.	West Effluent Mean ± s.d.	East Effluent Mean ± s.d.
Physical Parameters			
Temperature (°C)	11.91 ± 0.43	10.77 ± 2.54	10.69 ± 2.63
Dissolved Oxygen (mg l^{-1})	5.20 ± 0.50	16.60 ± 11.40	16.20 ± 10.60
pH	7.99 ± 0.02	8.92 ± 0.83	8.98 ± 0.90
Alkalinity (mg l^{-1} as $CaCO_3$)	258.00 ± 7.96	235.35 ± 38.19	233.43 ± 40.60
Hardness (mg l^{-1} as $CaCO_3$)	461.43 ± 3.62	460.14 ± 17.34	460.79 ± 15.00
Conductivity (mS m^{-1})	213.23 ± 3.85	207.27 ± 7.40	208.63 ± 4.85
Nutrients			
Ammonium (mg l^{-1})	10.91 ± 0.57	6.59 ± 3.38	6.06 ± 3.79
Nitrate/Nitrite (mg l^{-1})	2.52 ± 0.47	4.01 ± 2.32	4.28 ± 2.66
Particulate Nitrogen (mg l^{-1})	1.50 ± 0.23	1.42 ± 0.67	1.84 ± 0.44
Total Organic Nitrogen (mg l^{-1})	12.41 ± 0.67	8.01 ± 3.63	7.90 ± 3.95
Soluble Reactive Phosphorus (mg l^{-1})	3.54 ± 0.42	2.40 ± 1.32	2.84 ± 1.40
Particulate Phosphorus (mg l^{-1})	0.20 ± 0.07	0.20 ± 0.14	0.25 ± 0.15
Total Phosphorus (mg l^{-1})	3.62 ± 0.29	2.99 ± 1.44	2.91 ± 1.61
Solids			
UV transmittance (%)	76.49 ± 1.89	75.55 ± 1.73	75.66 ± 1.56
Turbidity (NTU)	1.80 ± 0.14	1.66 ± 0.45	1.71 ± 0.36
Total suspended solids (mg l^{-1})	6.43 ± 3.77	5.86 ± 2.57	6.57 ± 2.60
Total dissolved solids (mg l^{-1})	1306.36 ± 91.63	1246.71 ± 107.73	1281.14 ± 89.66
Weekly Treatment			
N Removal (kg $week^{-1}$)		2.22	2.09
P Removal (kg $week^{-1}$)		0.48	0.55

Table 3.26 Dominant algal species of the ATS floway during phase one and phase two of the evaluation.

Algal Species	**Phase one**	**Phase two**
Cyanobacteria		
Anabena sp.	1	1
Fine filamentous sp.	3	4
Fine filamentous spot	-	3
Oscillatoria sp.	4	4
Spirulina sp.	2	2
Bacillariophyceae		
Cyclotella sp.	3	4
Fragillaria sp.	1	1
Melosira sp.	1	3
Navicula sp.	4	3
Nitzschia sp.	3	4
Stauroneis sp.	2	1
Surirella sp.	1	1
Small Oval D	-	3
Chlorophyceae		
Phytoplankton		
Chlamydomonas sp.	-	2
Chlorella sp.	1	4
Chroococcus sp.	1	1
Closterium sp.	1	3
Pediastrum sp.	-	4
Scenedesmus sp.	1	4
Selenastrum sp.	1	1
Micrasterias sp.	-	2
Phacus sp.	-	2
Ankismodesmus sp.	-	1
Periphyton		
Cladophora sp.	2	1
Hydradyction sp.	1	1
Microspora sp.	1	1
Rhizoclonium sp.	1	1
Spyrogyra sp.	1	1
Stigeoclonium sp.	1	3
Tribonema sp.	1	2
Ulothrix sp.	3	4
Small filamentous	-	2

(1 Present, 2 Few, 3 Many, 4 Major)

Figures

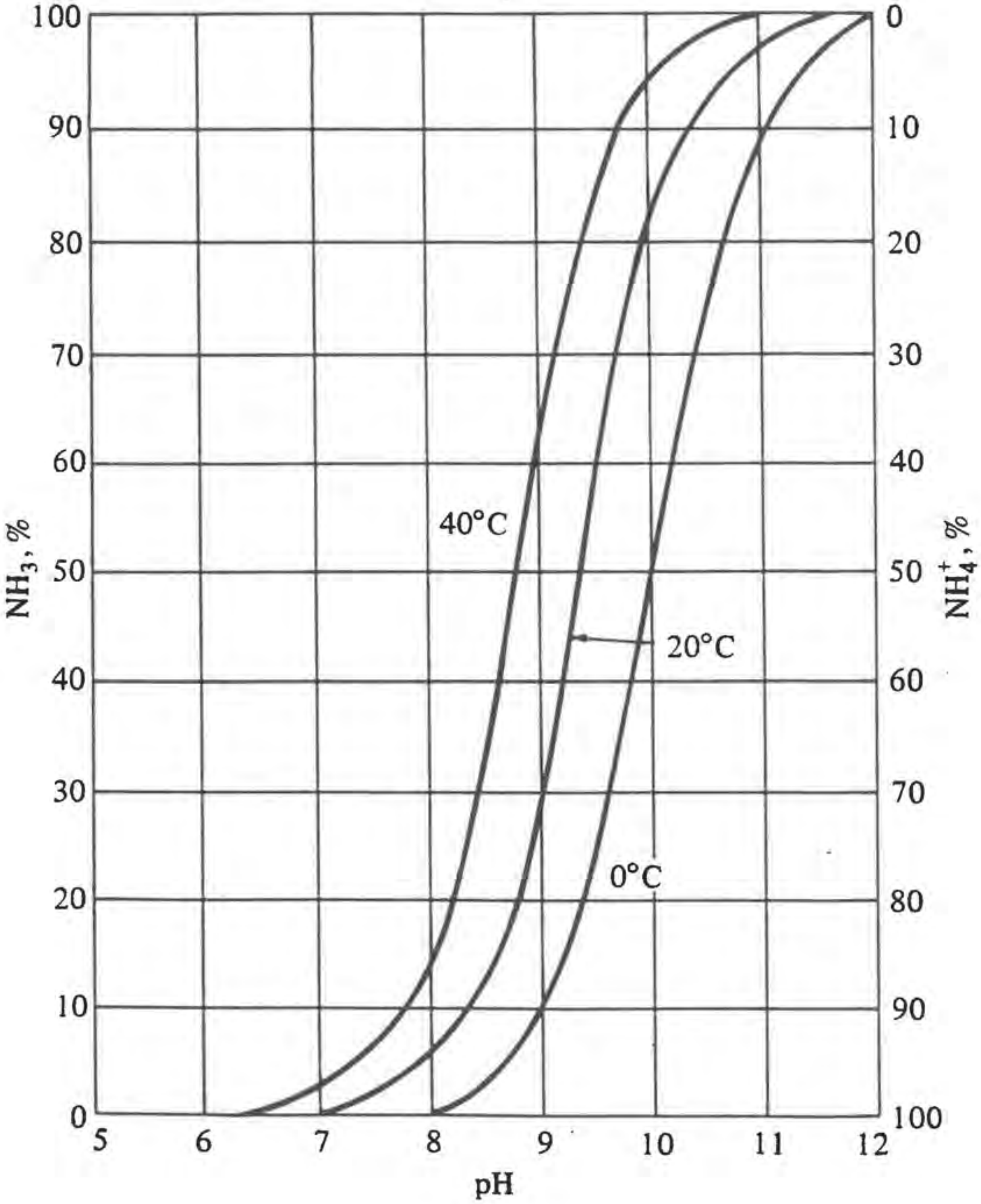


Figure 1.1 Effects of pH and temperature on distribution of ammonia and ammonium ions in water (from USEPA, 1977).

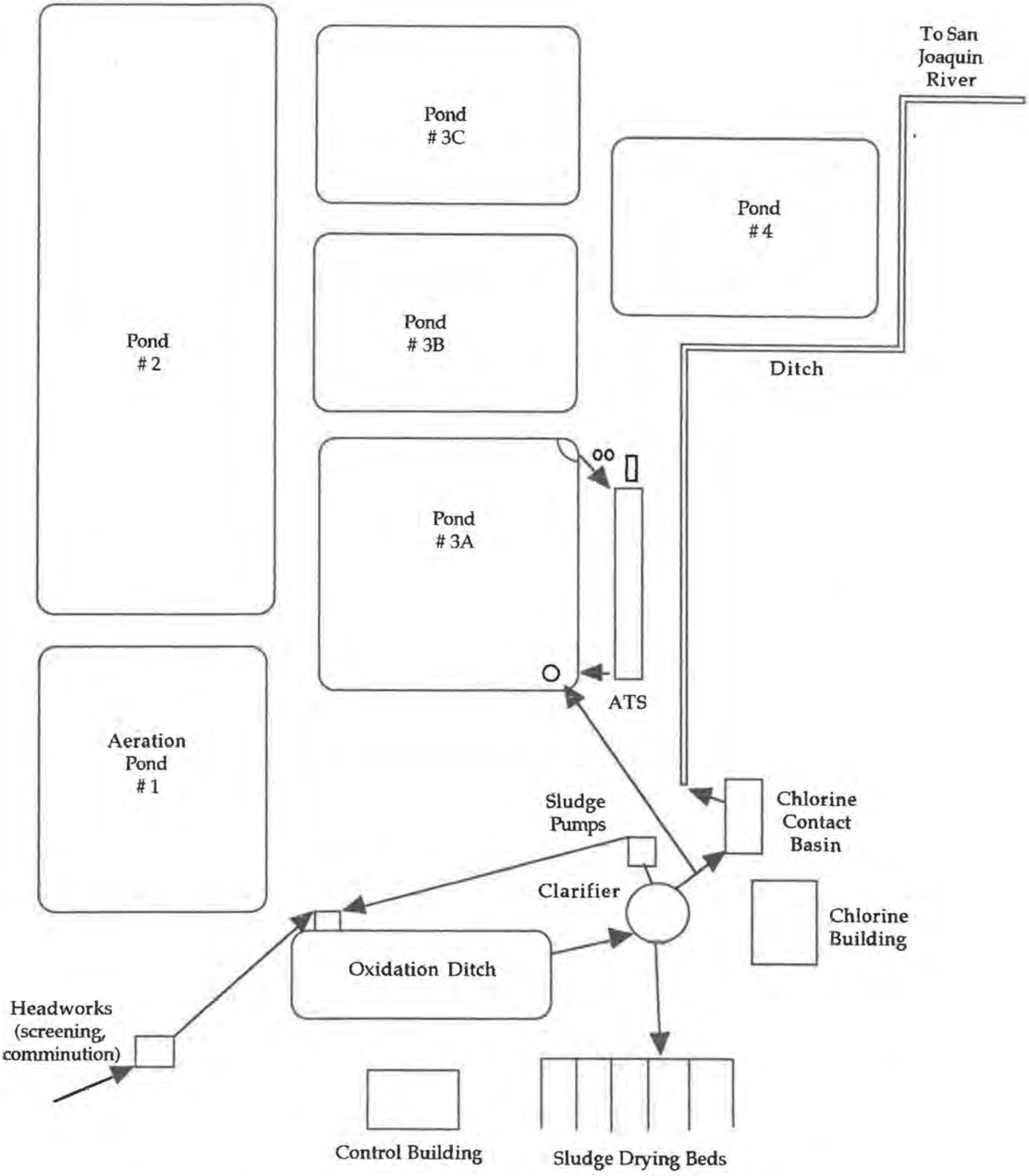


Figure 2.1 Schematic diagram of City of Patterson wastewater treatment facility, showing the location of the ATS/UV system.

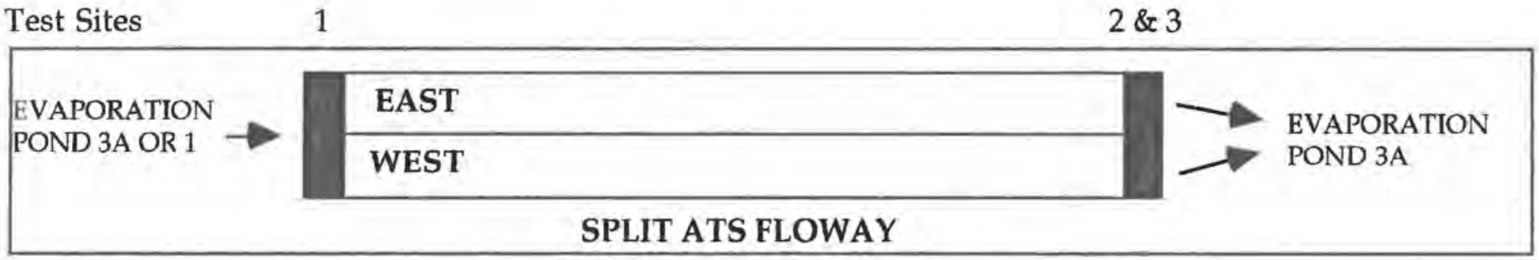
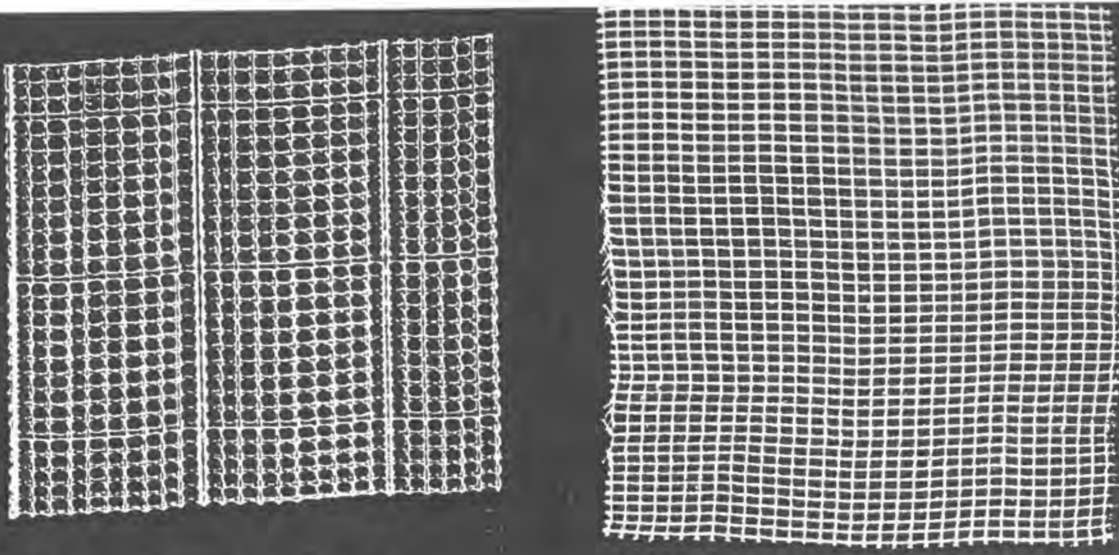
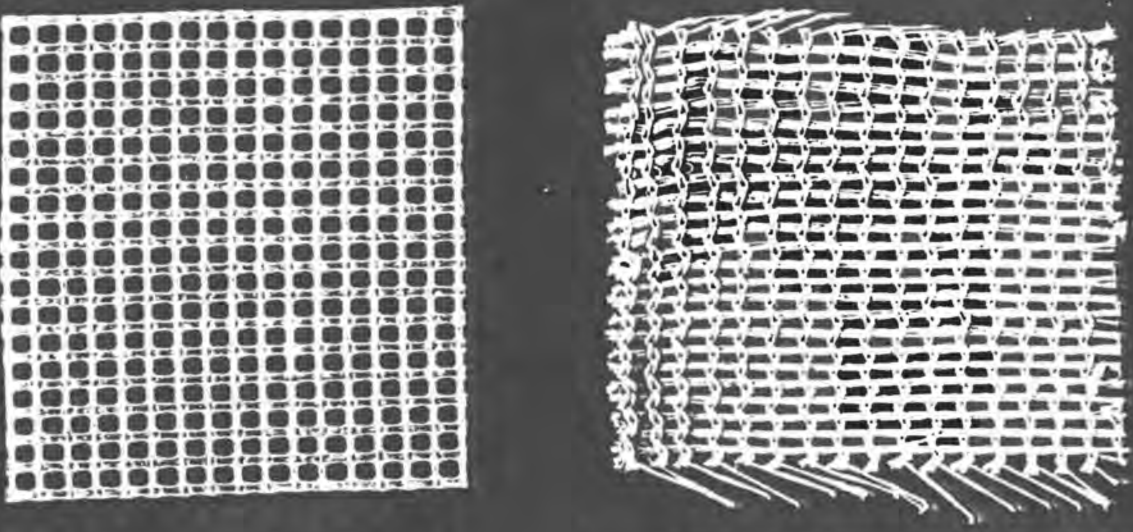


Figure 2.2 Configuration of the Patterson Algal Turf Scrubber wastewater treatment system during phase 2 of testing.



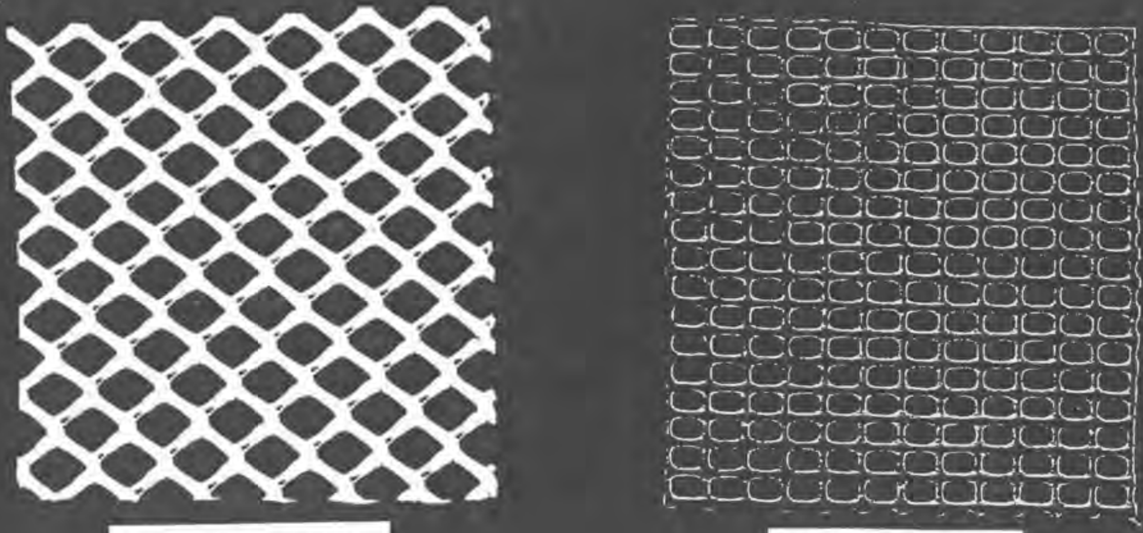
Tenax (grid)

Jason Mills (65MF50WAT) (Polyethylene)



Conwed (XN2410)

Jason Mills (1999MF60NAT) (Polyethylene)



Naltex (191-3317-1)

Conwed (XN1678)

Figure 2.3 Photocopied sections of the white screens used in the screen comparison experiment.

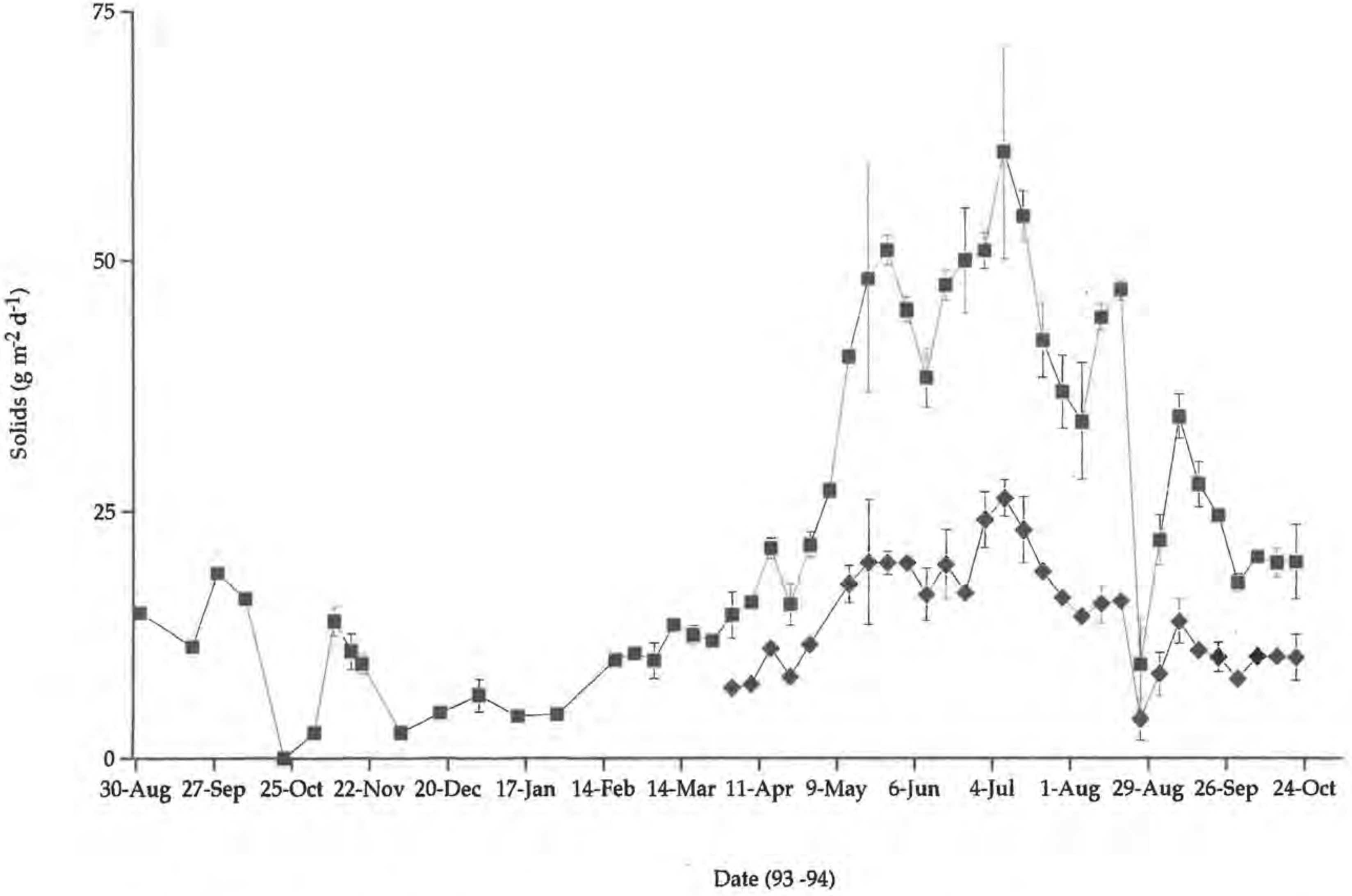


Figure 3.2 Total (■) and volatile (◆) accumulated solids from the ATS. Values are means ± s.d. of two composite samples, each from five sites.

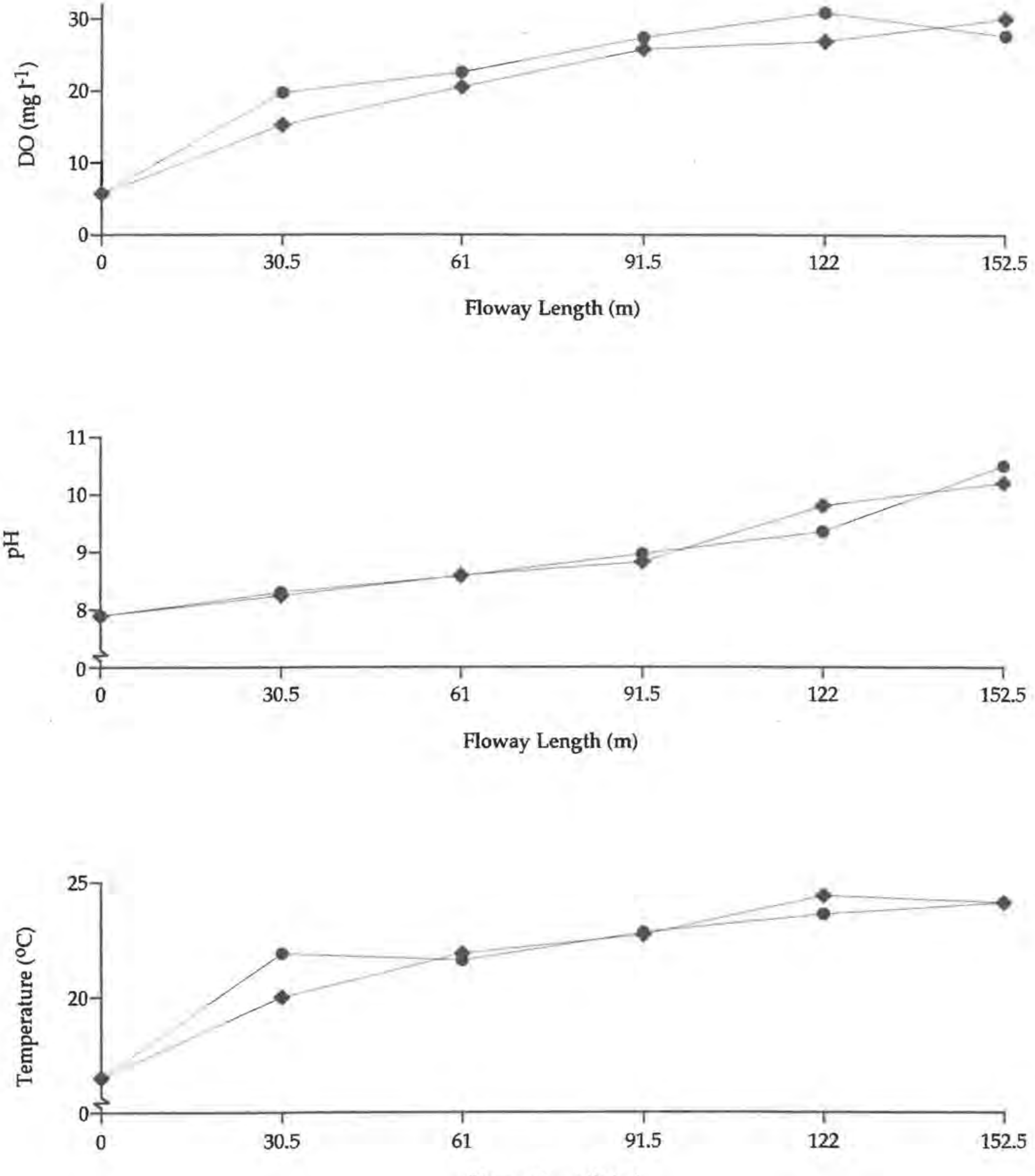


Figure 3.3 Profile of the change in dissolved oxygen, pH and temperature along the west (◆) and east (●) sides of the split ATS floway.

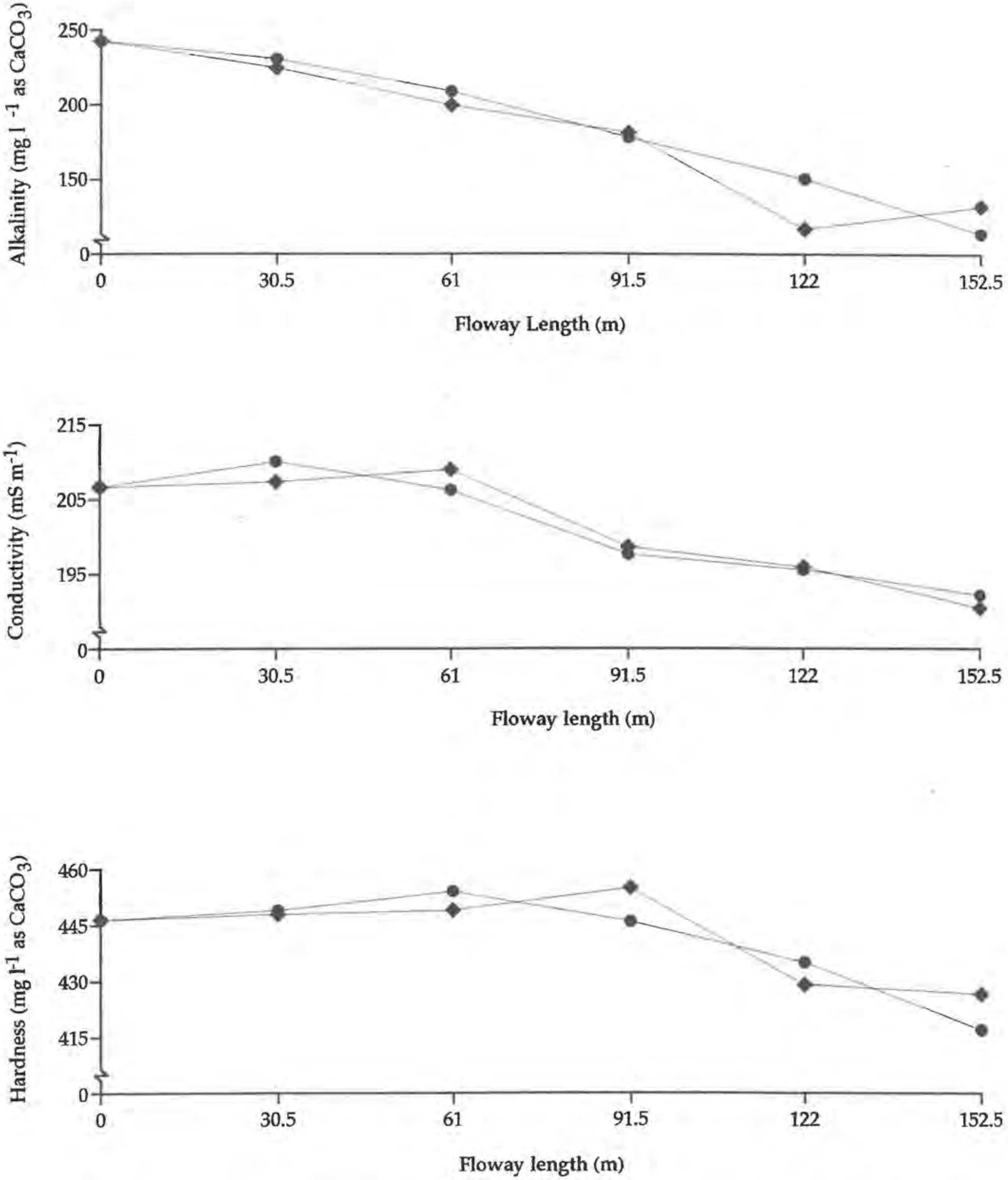


Figure 3.4 Profile of the change in alkalinity, conductivity and hardness along the west (◆) and east (●) sides of the split ATS floway.

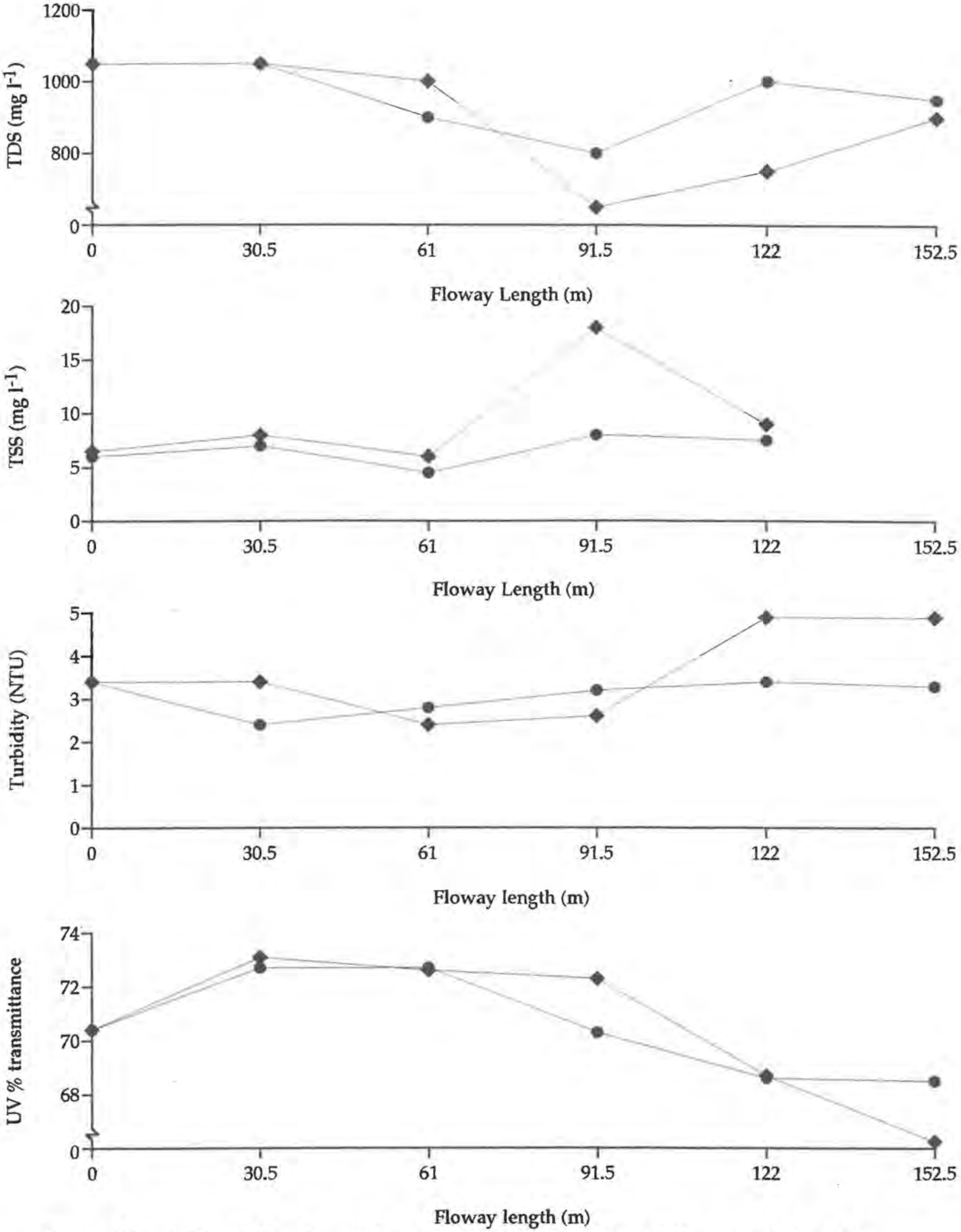


Figure 3.5 Profile of the change in total dissolved solids, total suspended solids, turbidity and UV % transmittance along the west (◆) and east (●) sides of the split ATS floway.

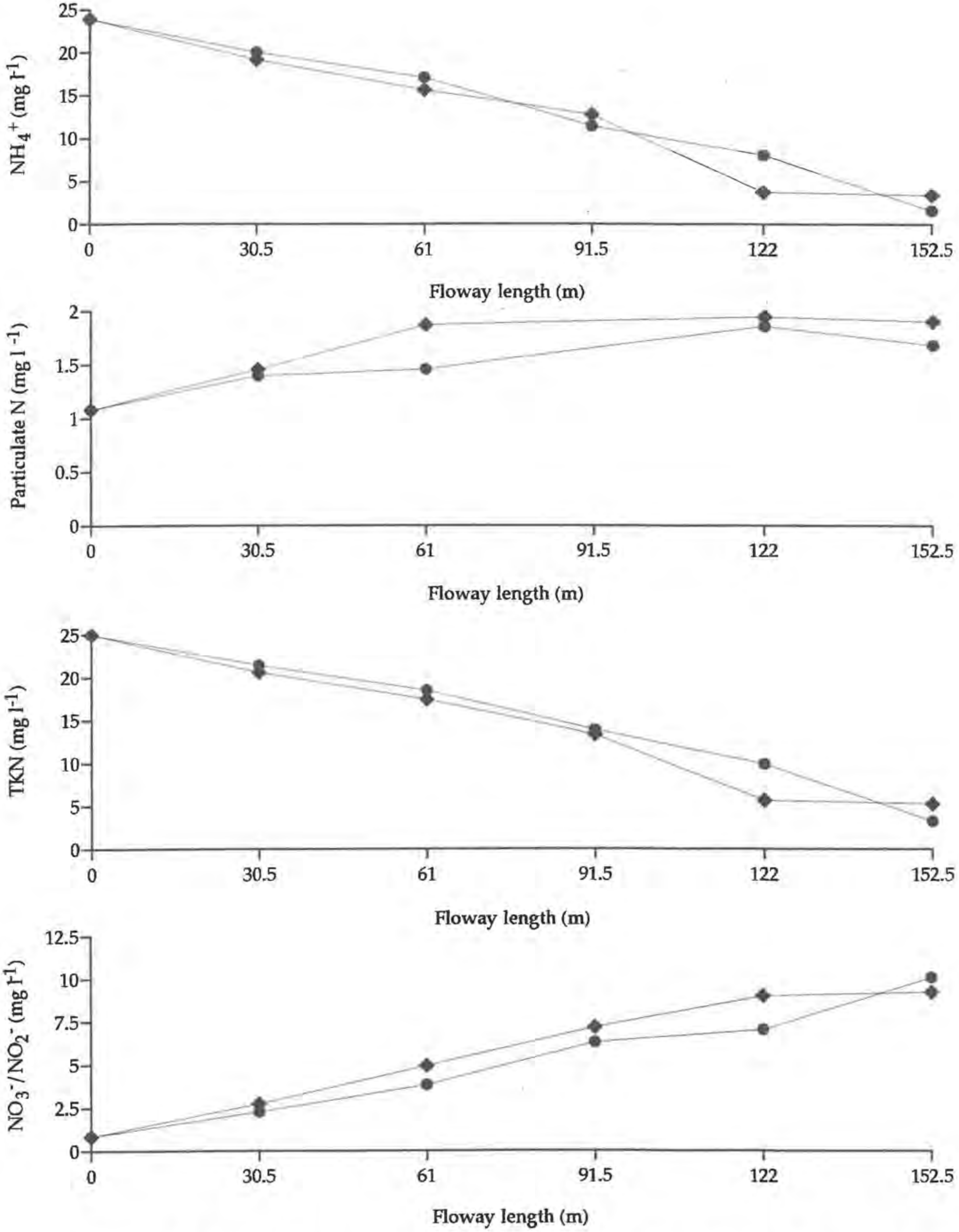


Figure 3.6 Profile of the change in ammonium, particulate nitrogen, total kjeldahl nitrogen and nitrate/nitrite concentrations along the west (◆) and east (●) sides of the split ATS floway.

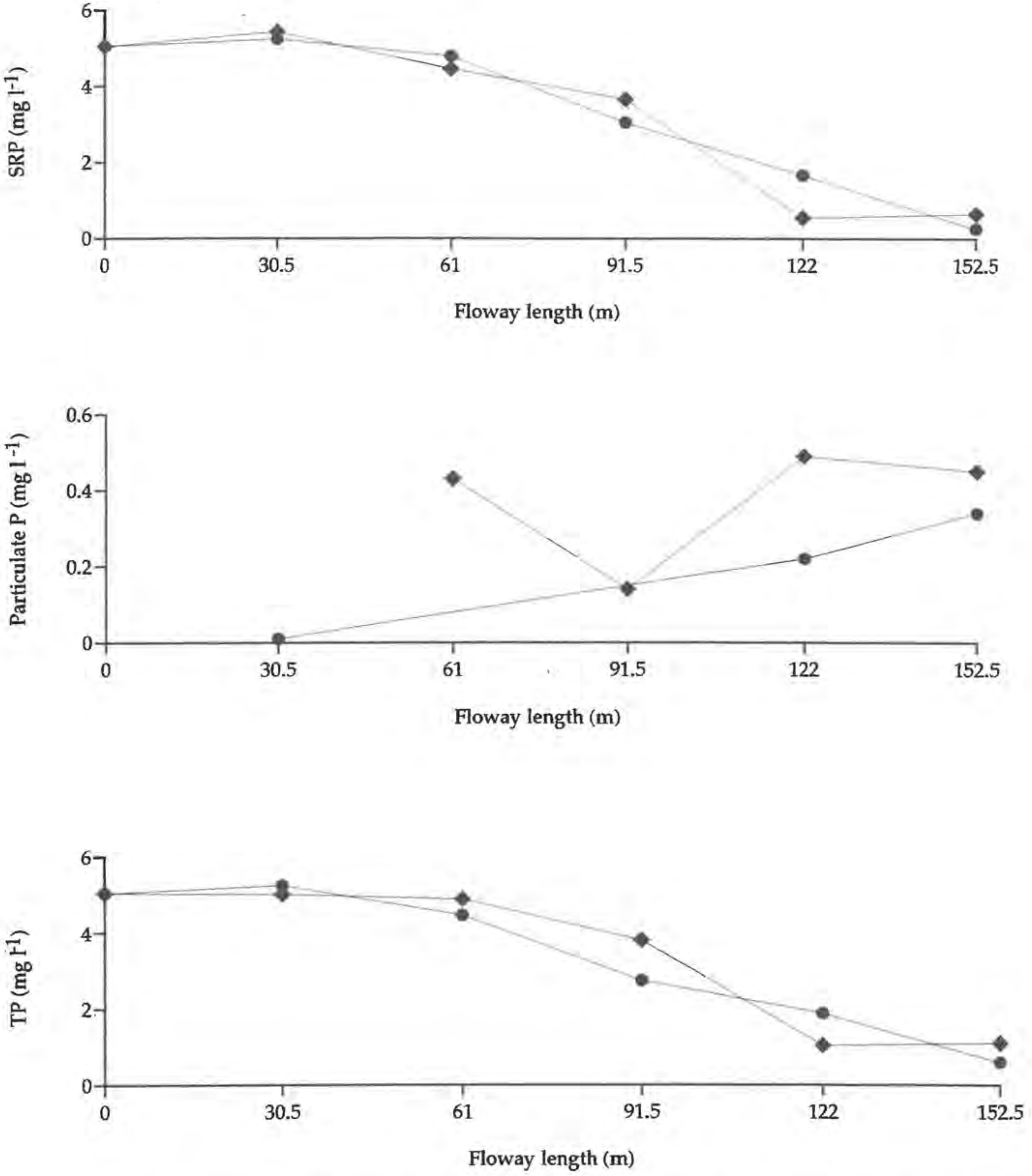


Figure 3.7 Profile of the change in soluble reactive phosphorus, particulate phosphorus and total phosphorus concentrations along the west (◆) and east (●) sides of the split ATS floway.

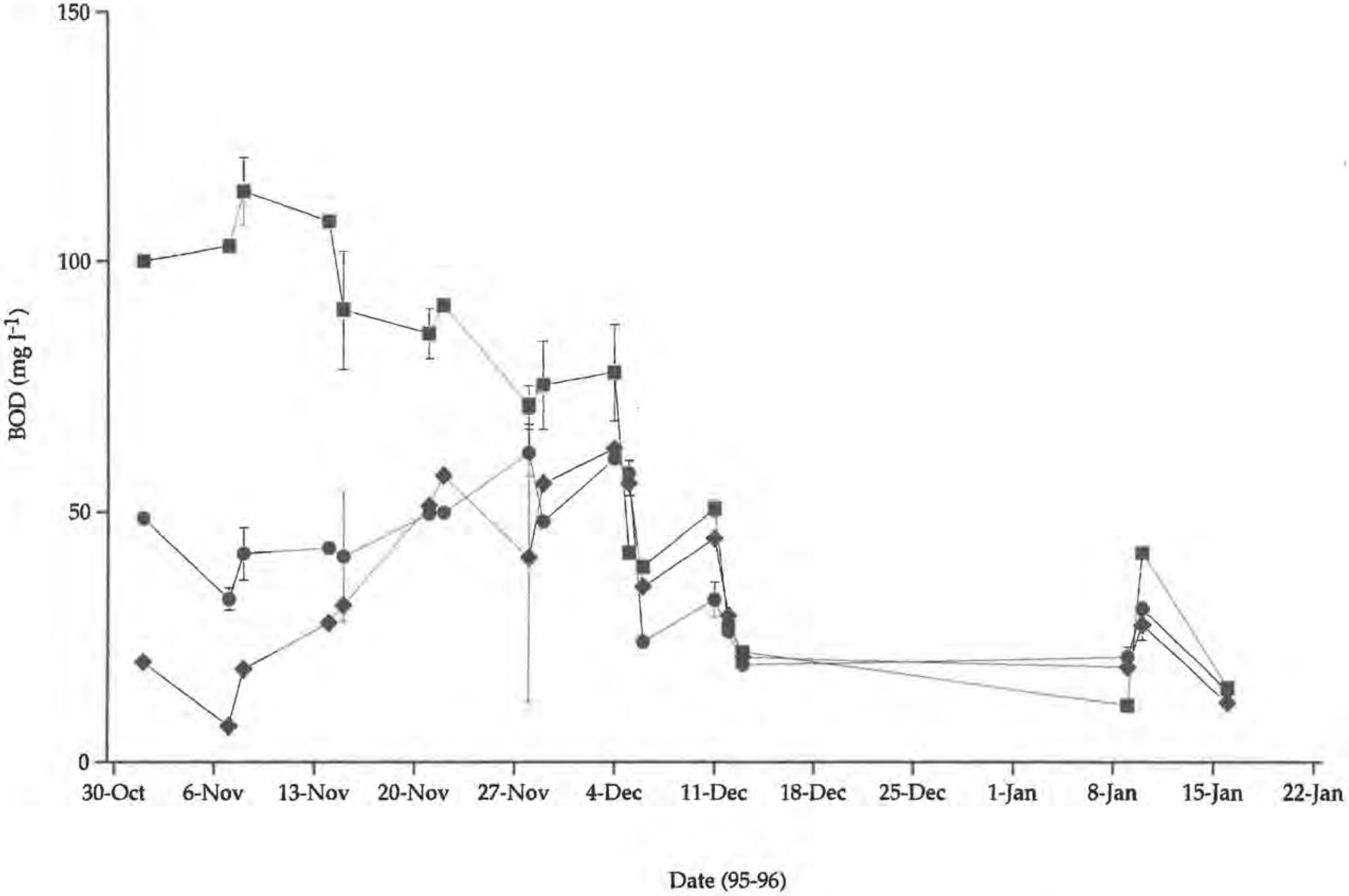


Figure 3.8 Total biochemical oxygen demand of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.

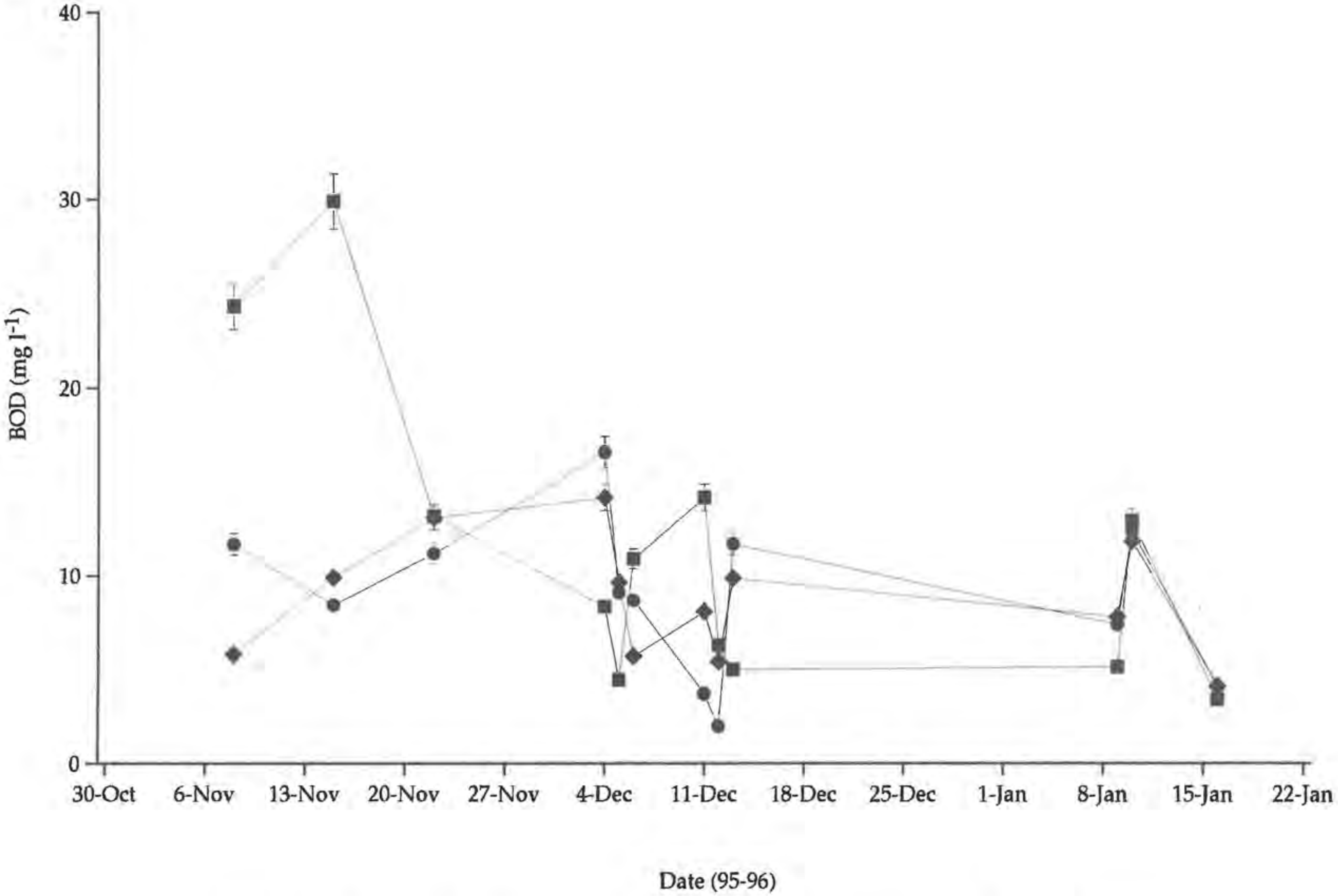


Figure 3.9 Soluble biochemical oxygen demand of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.

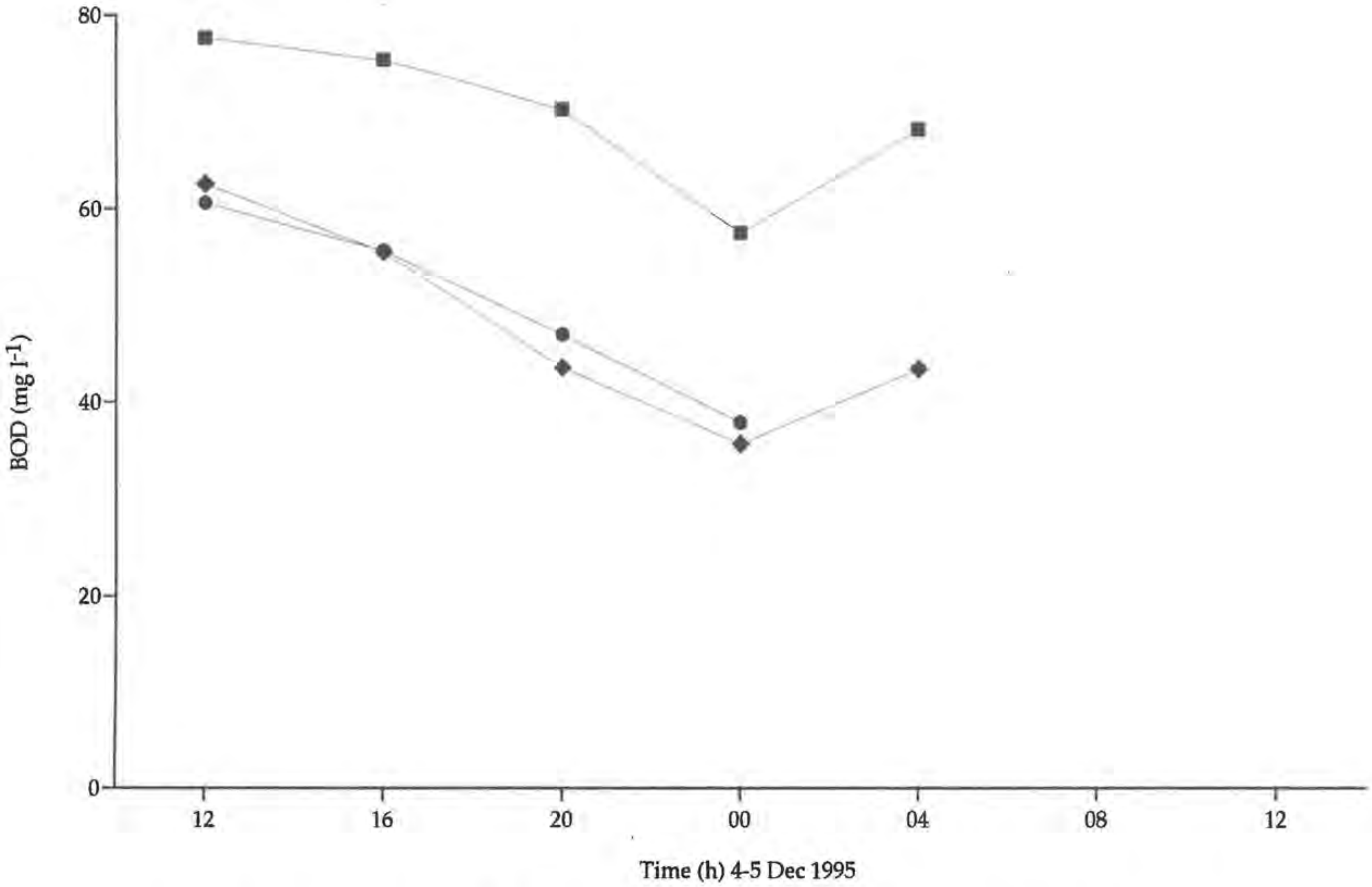


Figure 3.10 24 hour variation of total biochemical oxygen demand of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.

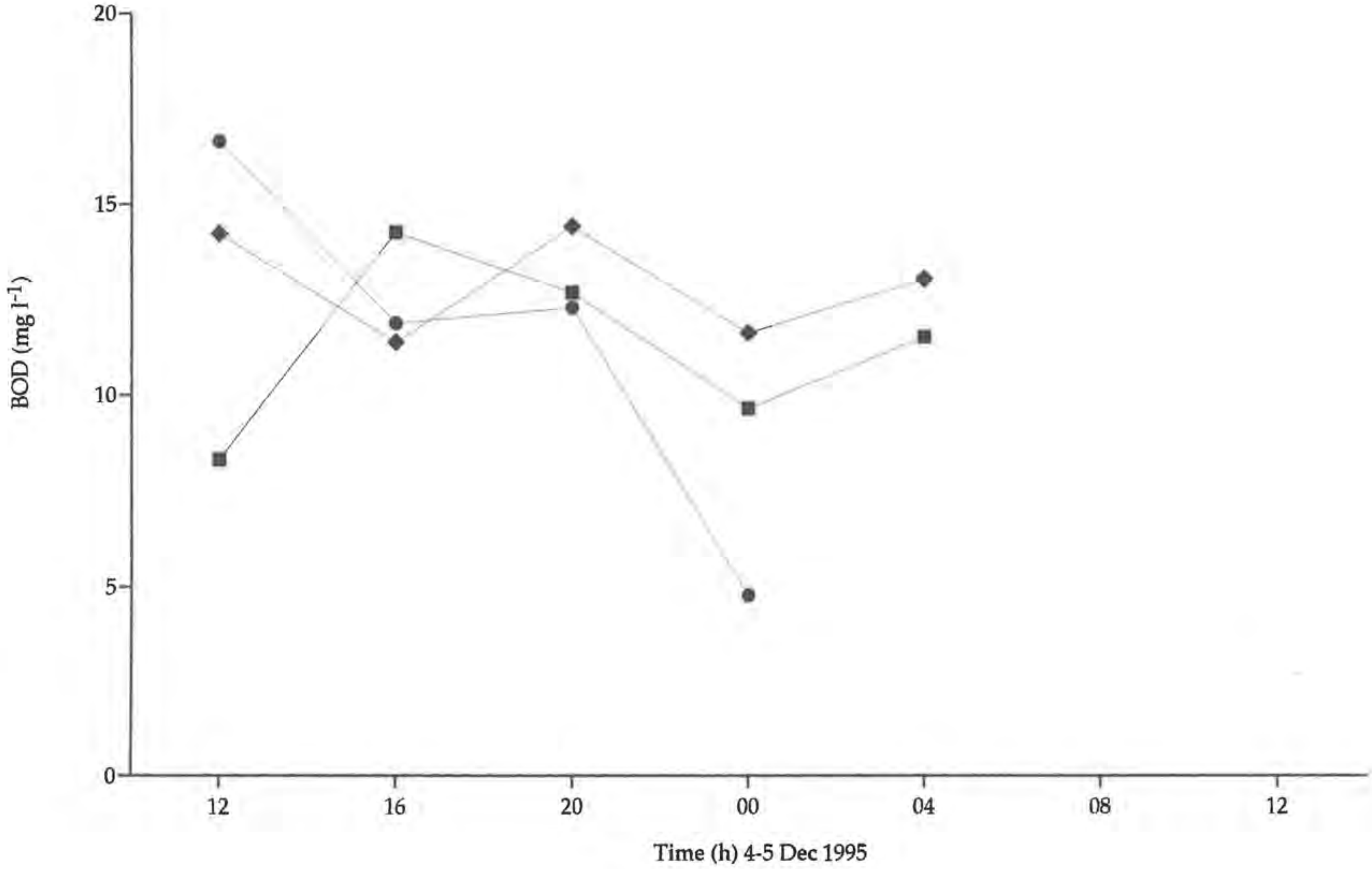


Figure 3.11 24 hour variation of soluble biochemical oxygen demand of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.

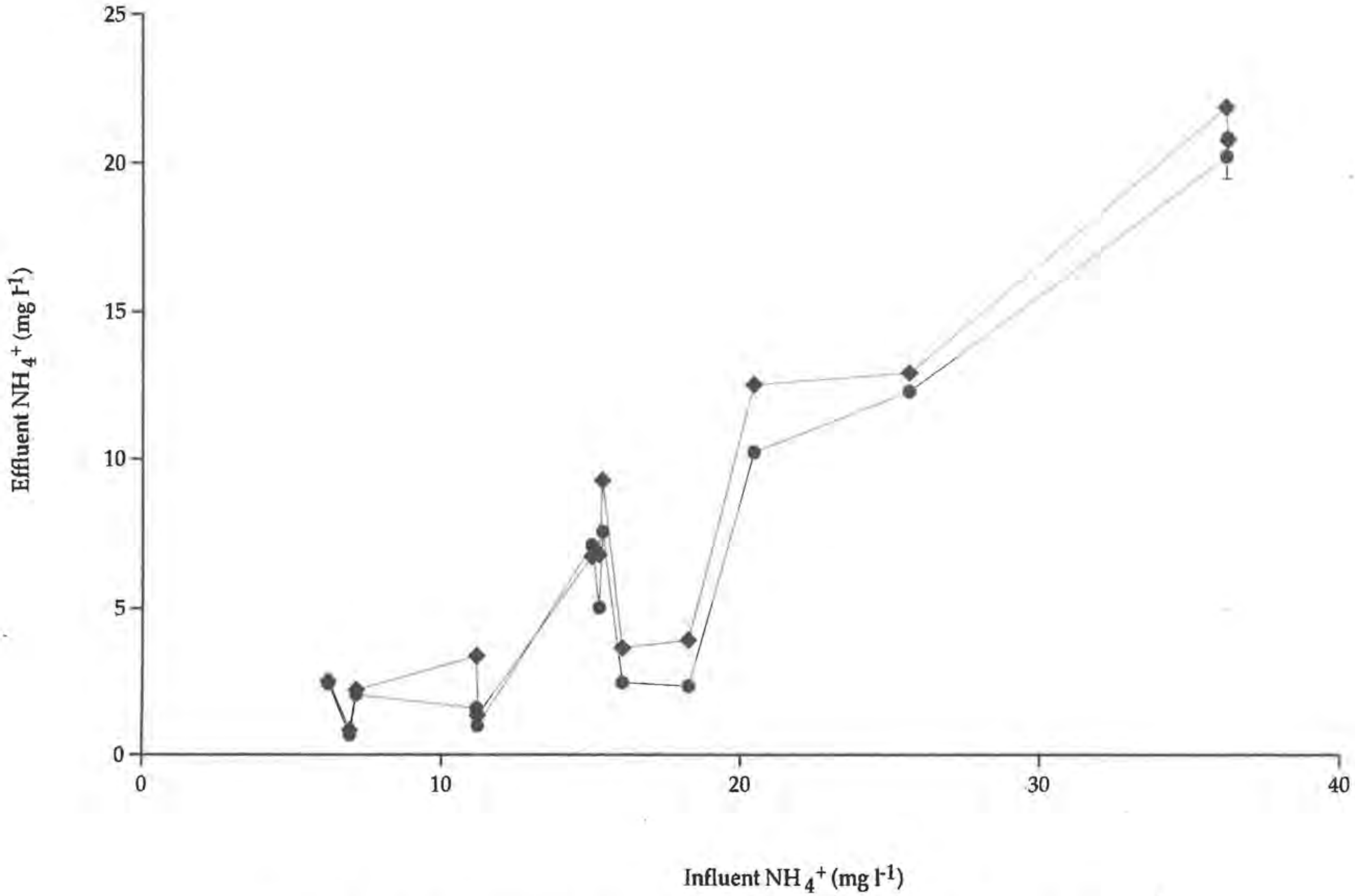


Figure 3.12 Relationship between ammonium concentrations in the influent, west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.

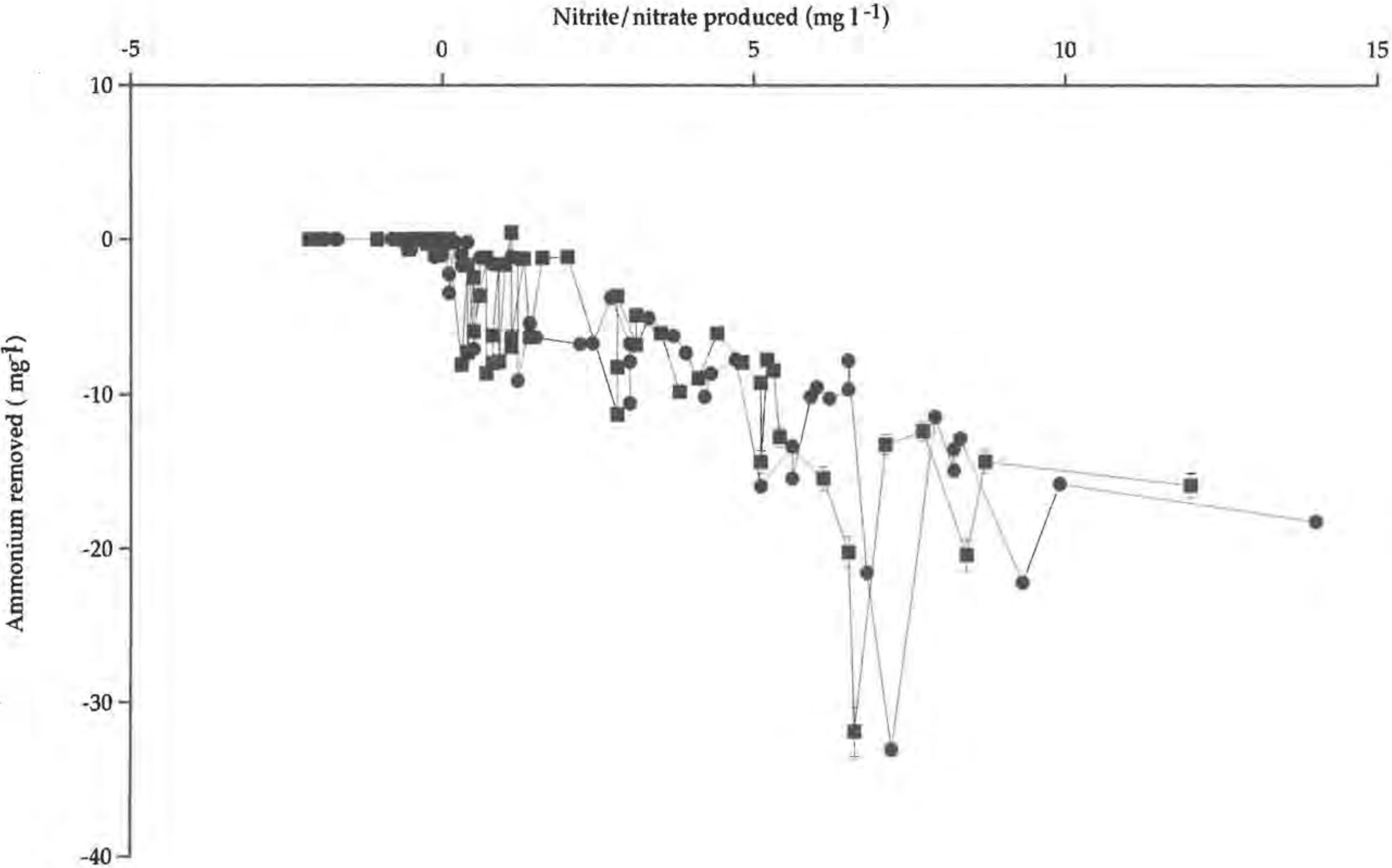
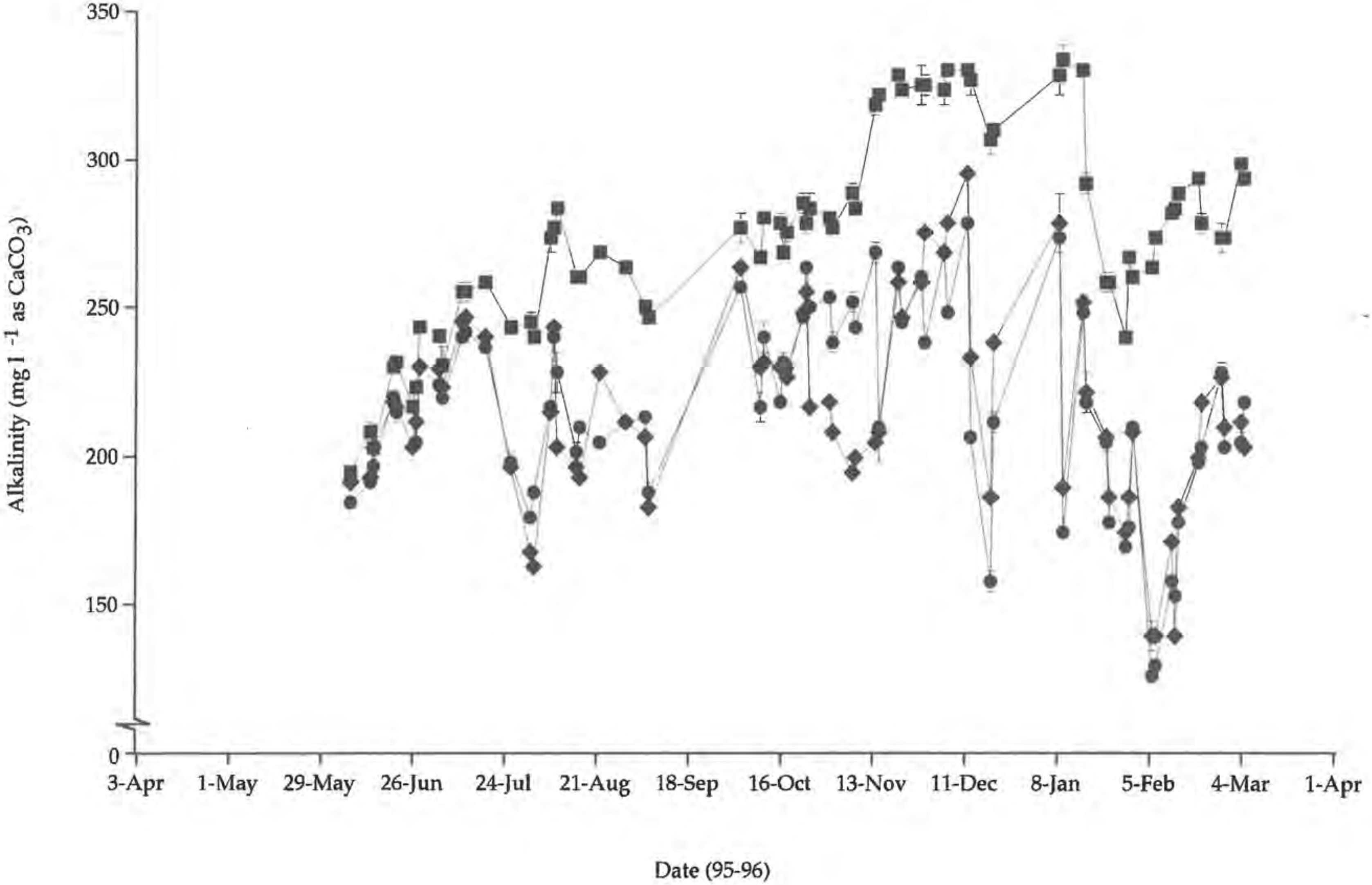
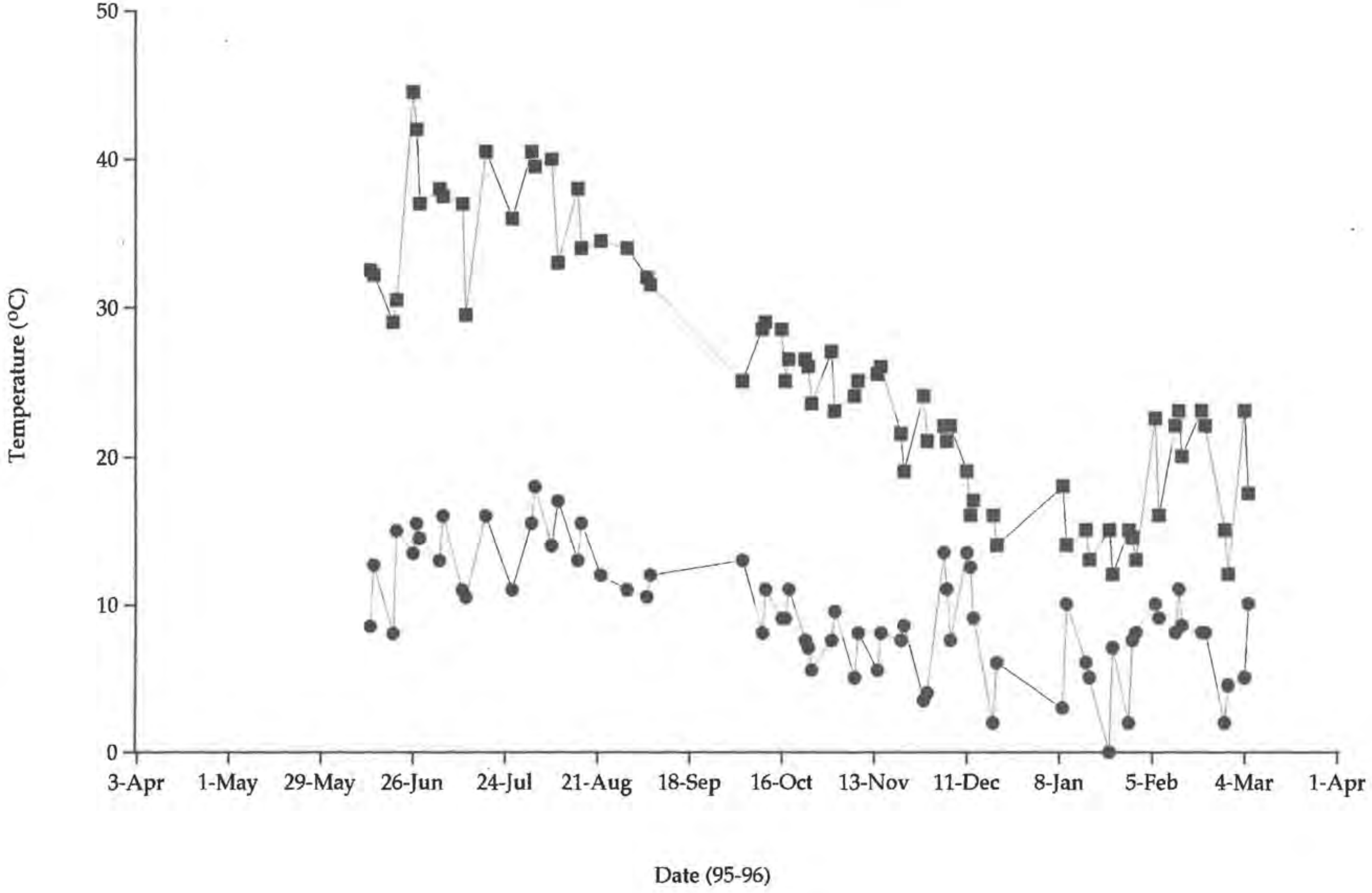


Figure 3.13 Relationship between ammonium removal and nitrite/nitrate production on the west (◆) and east (●) sides of the split ATS floway. Values are means of two replicate samples.

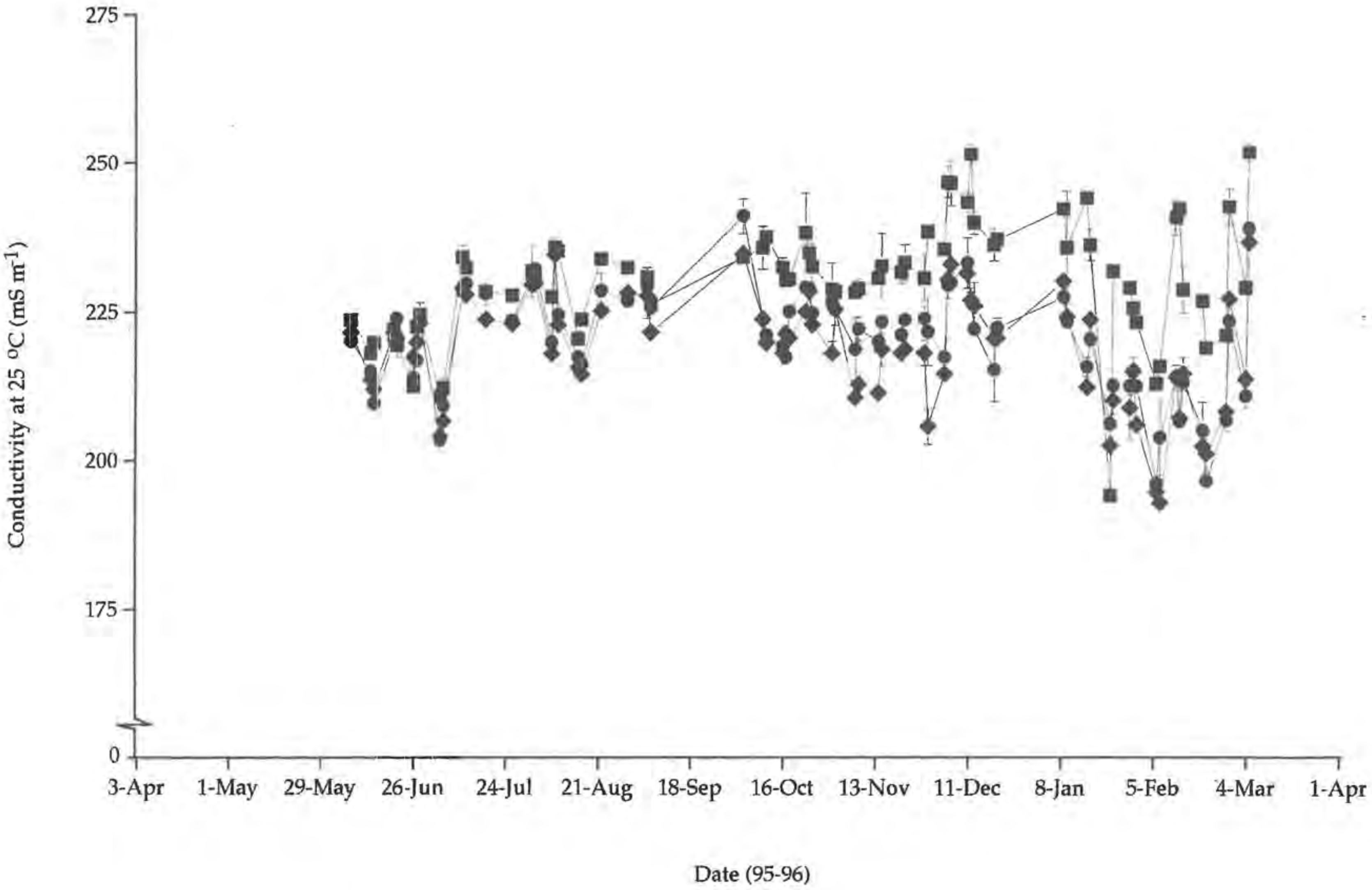
Appendix 1



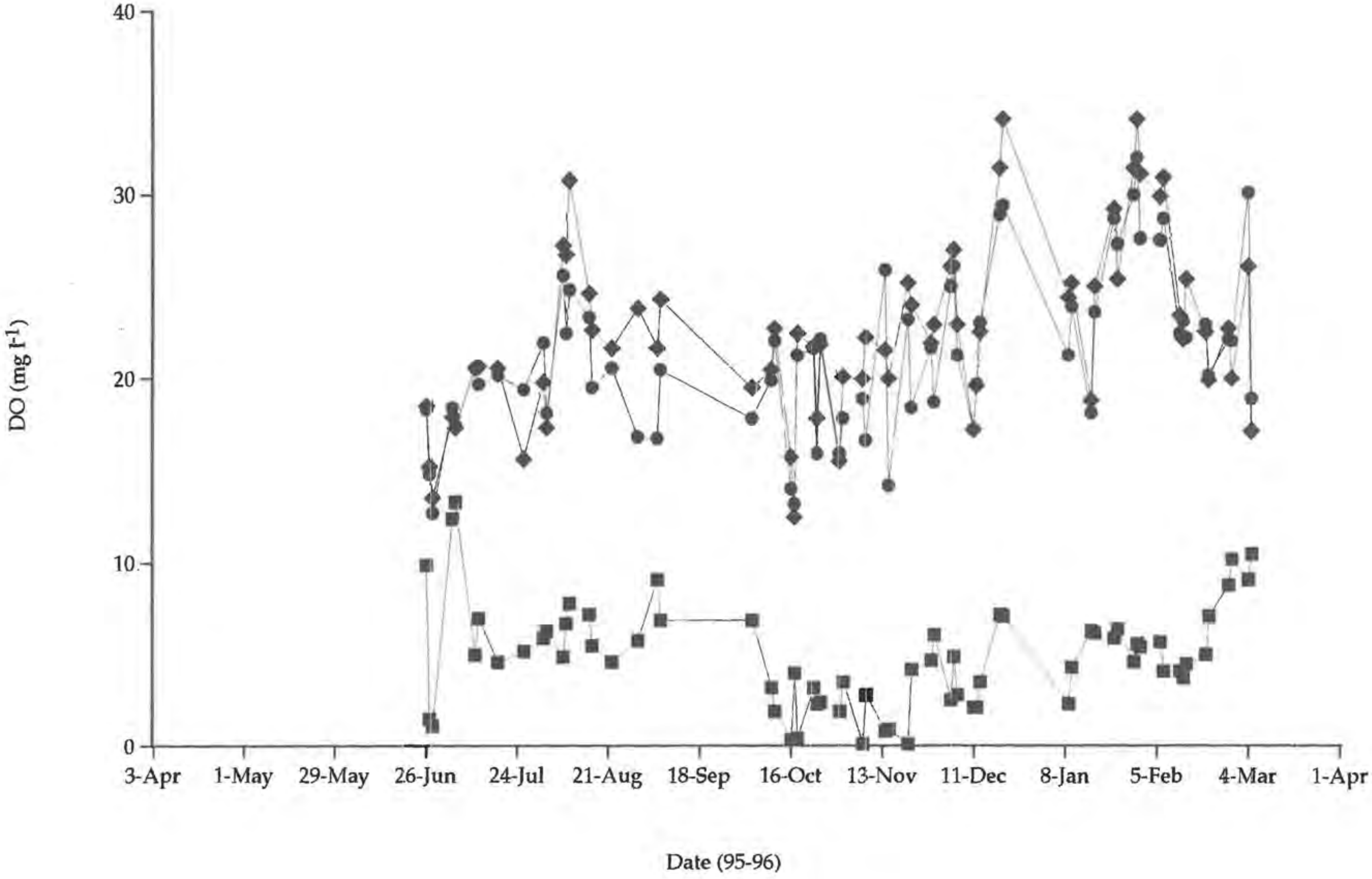
Alkalinity of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



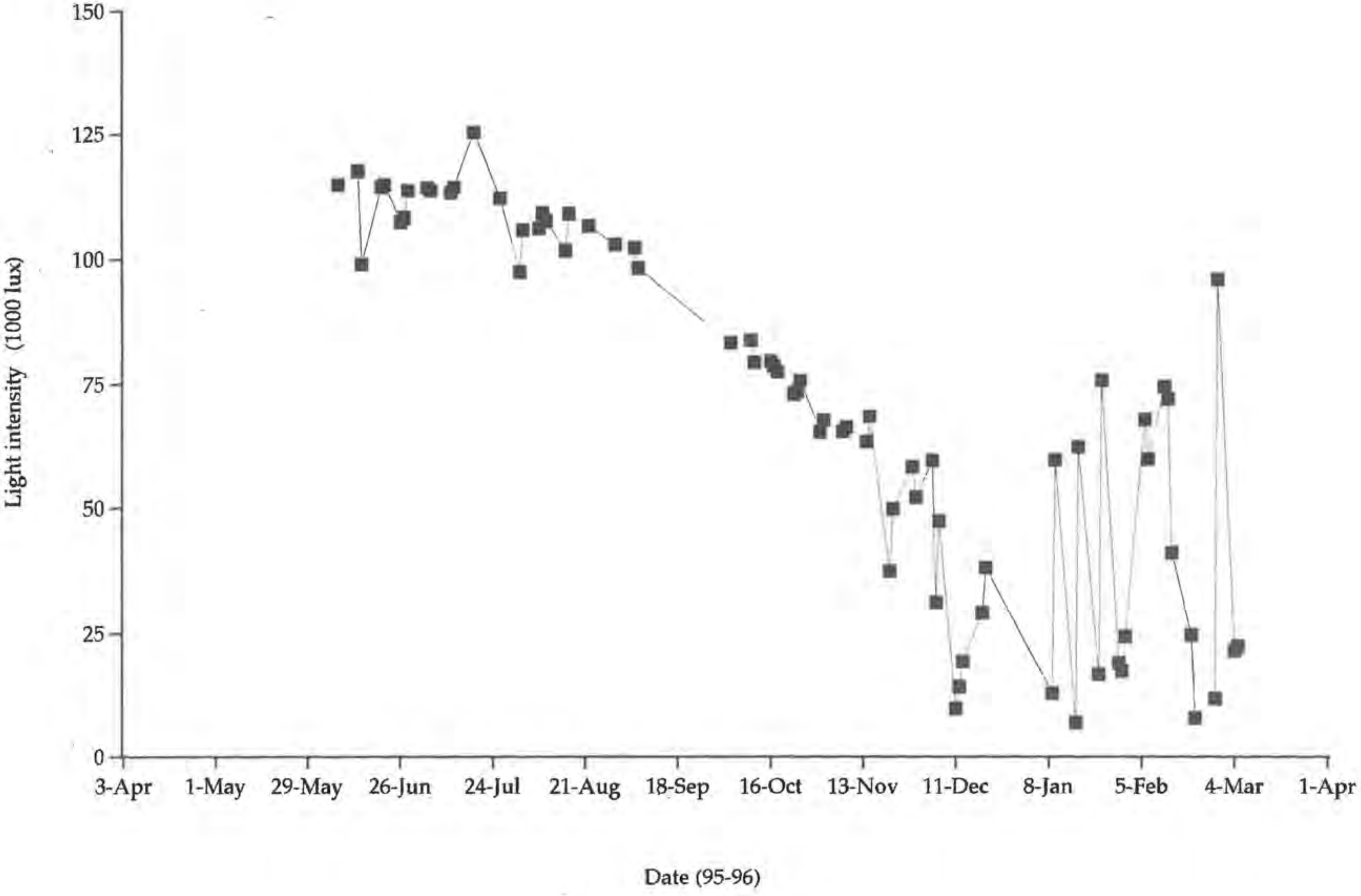
Minimum (■) and maximum (●) ambient temperature .



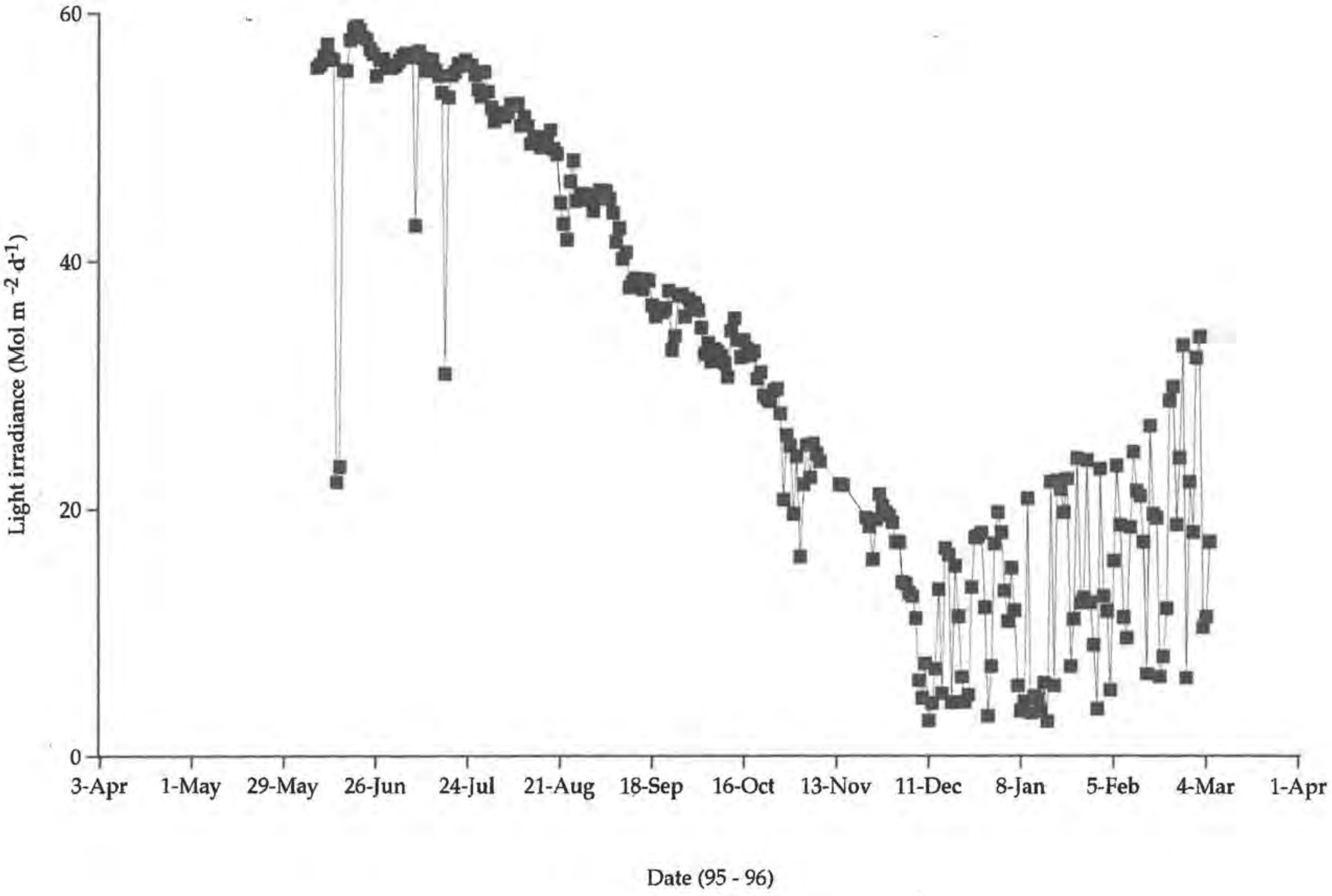
Conductivity of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



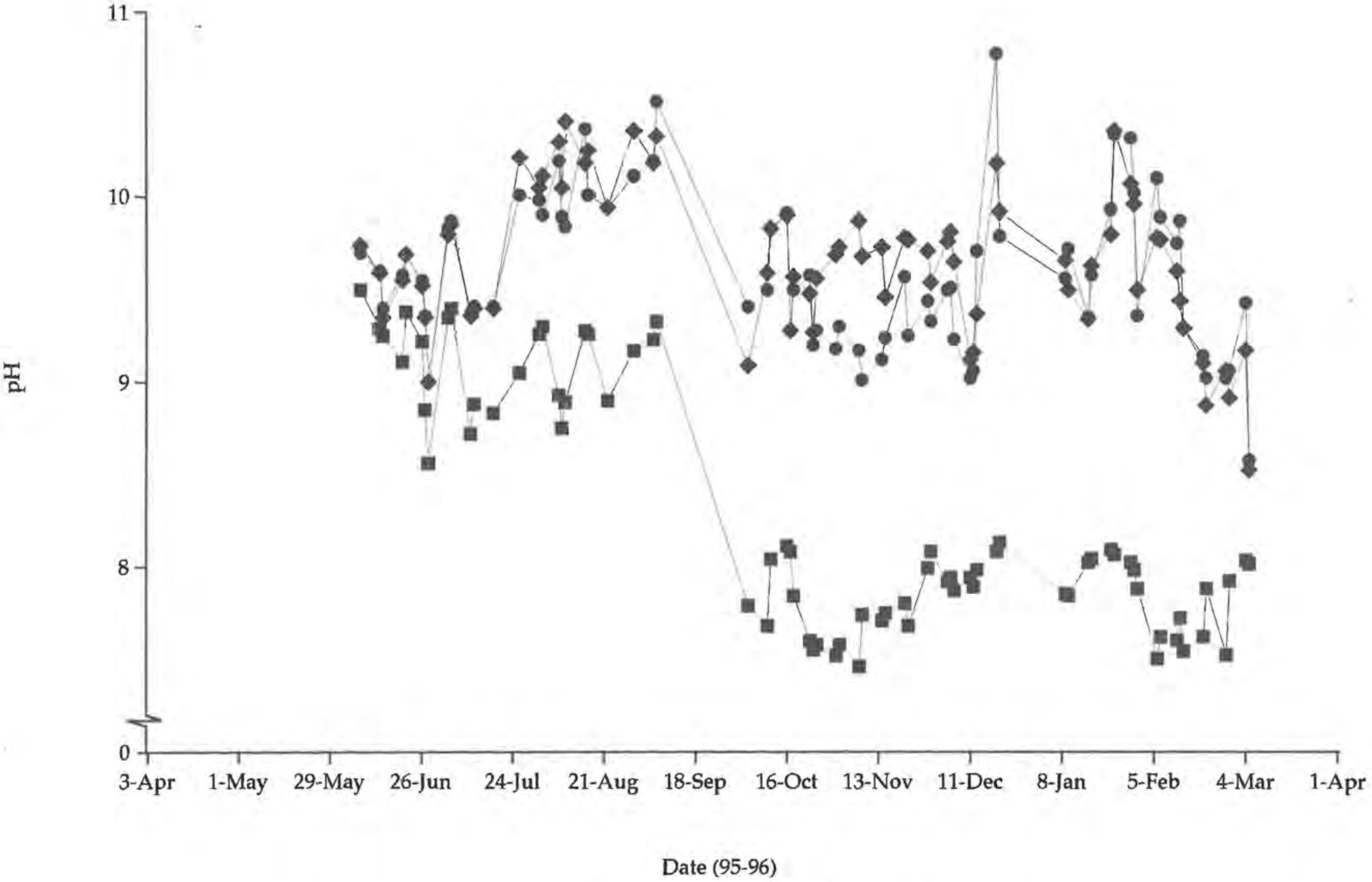
Dissolved oxygen concentration of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



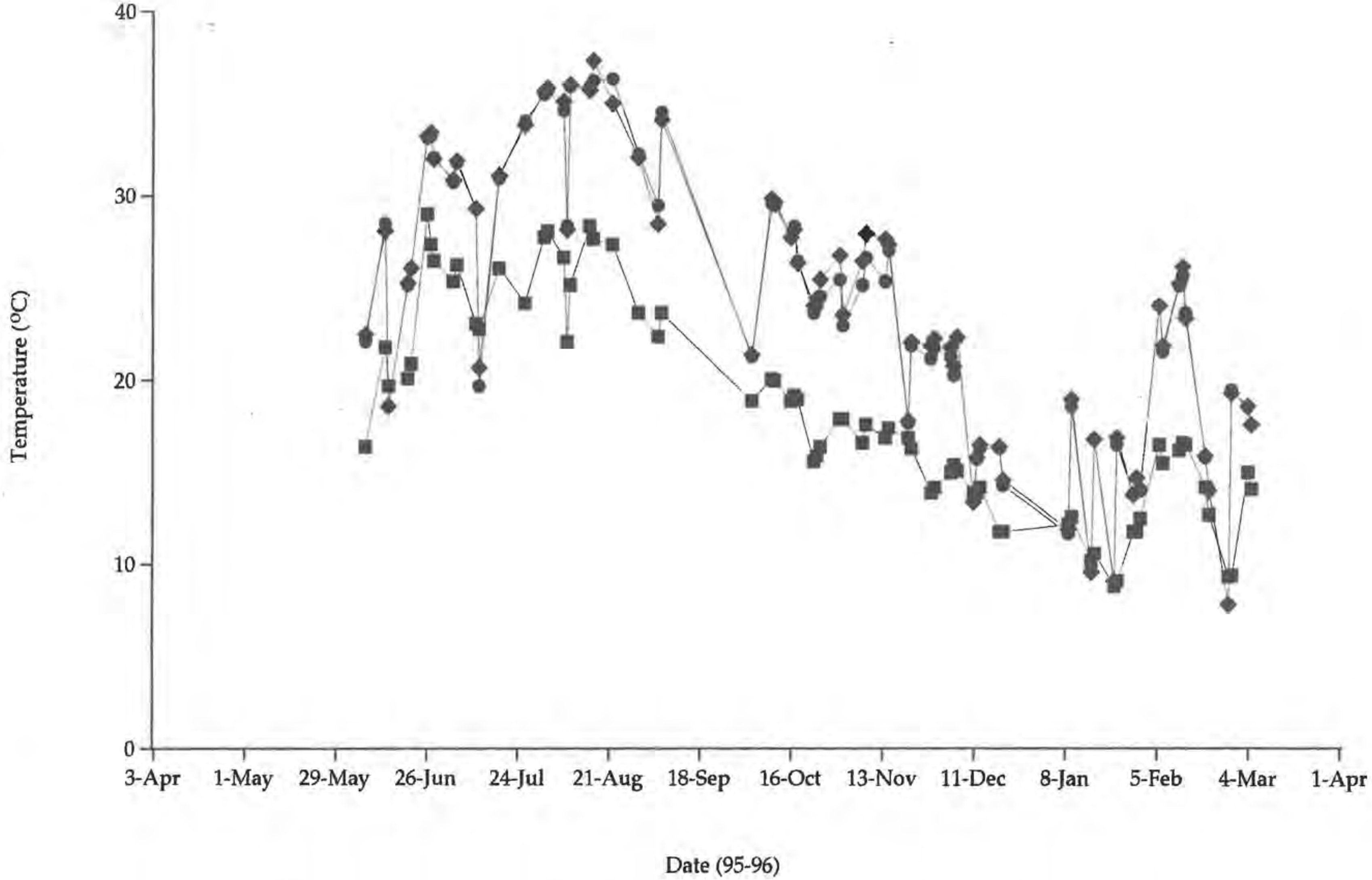
Light intensity measured at time of sampling (12.00 pm) .



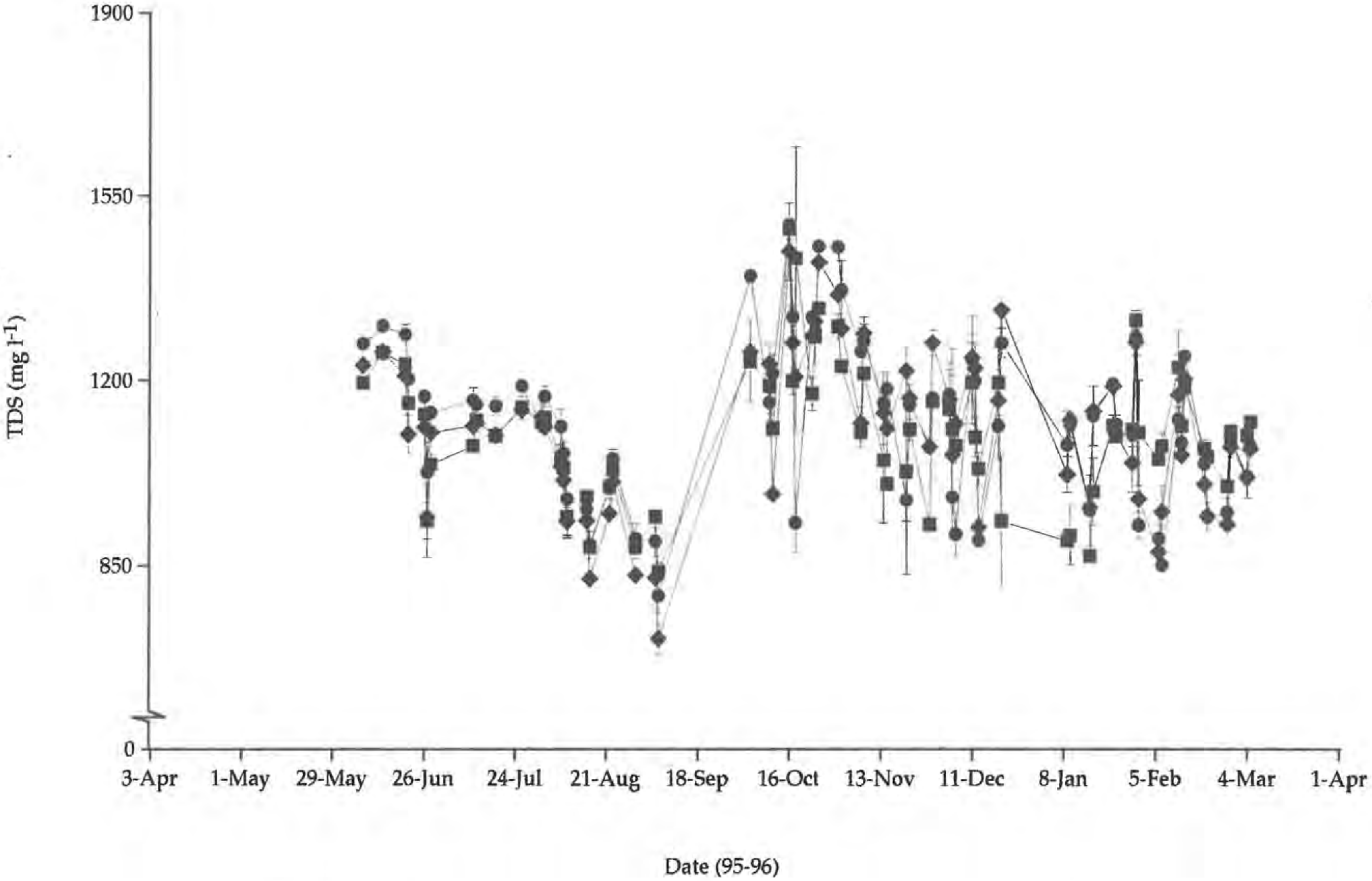
Total daily light irradiance.



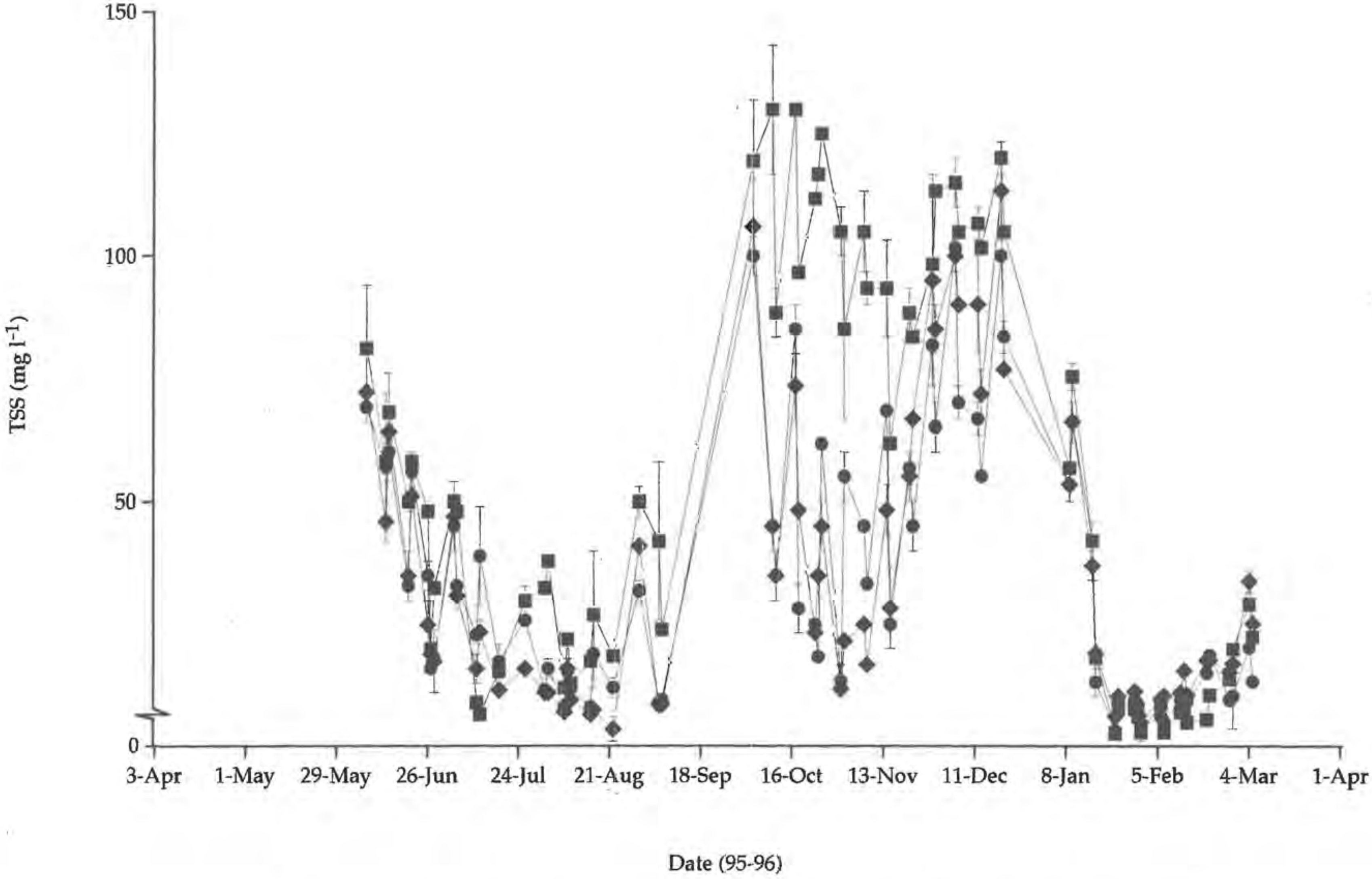
pH of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



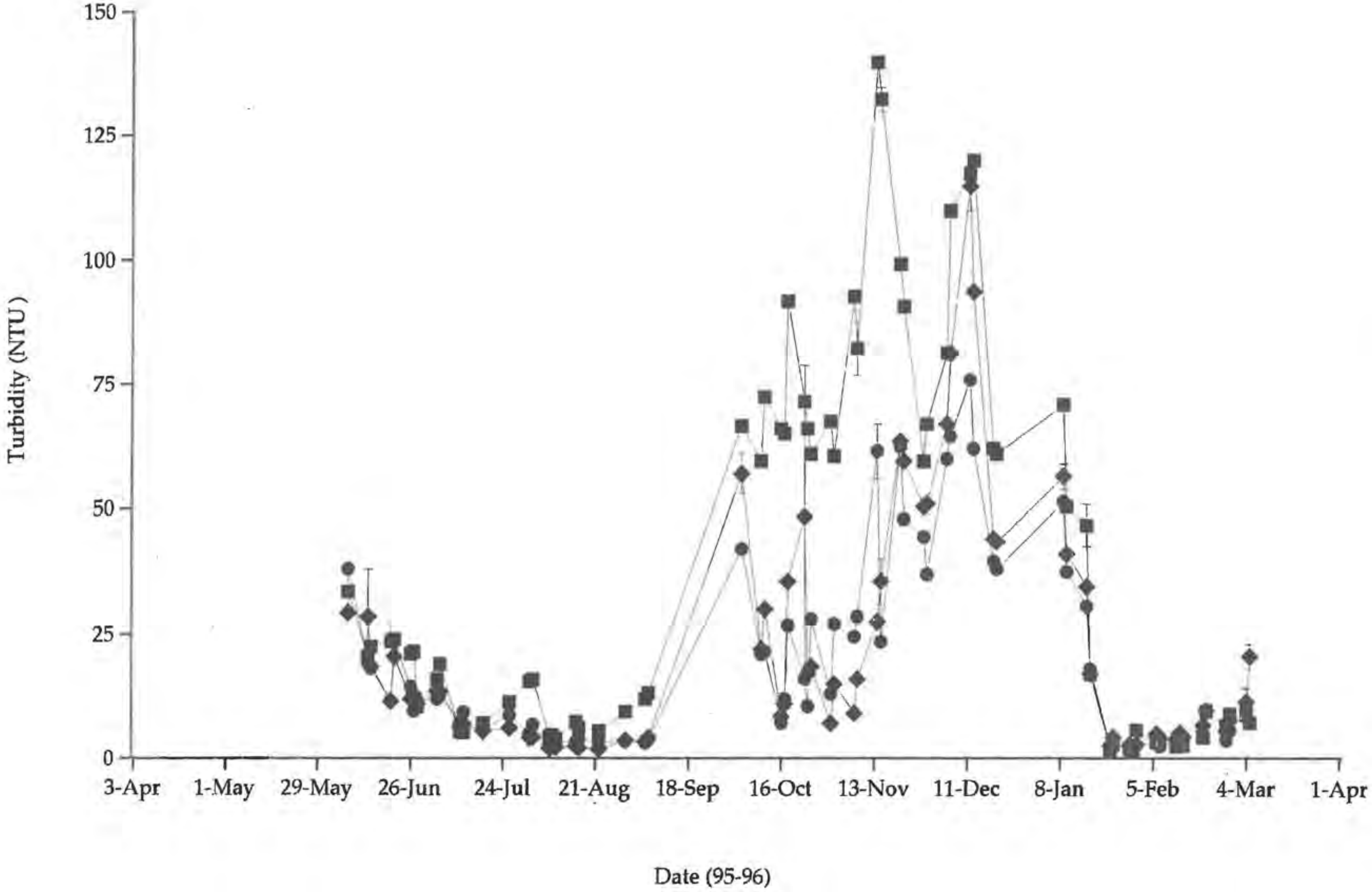
Temperature of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



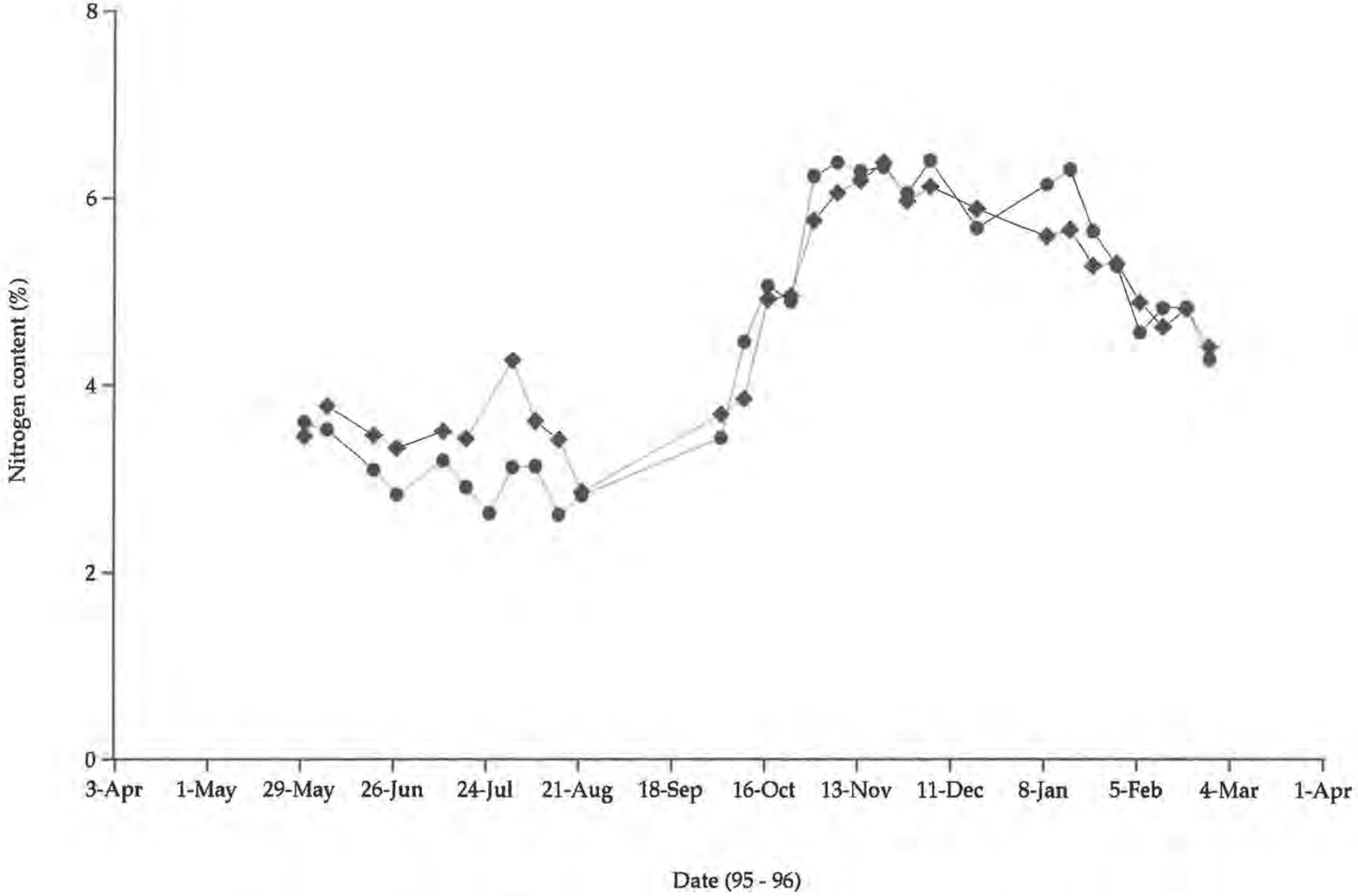
Total dissolved solids of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



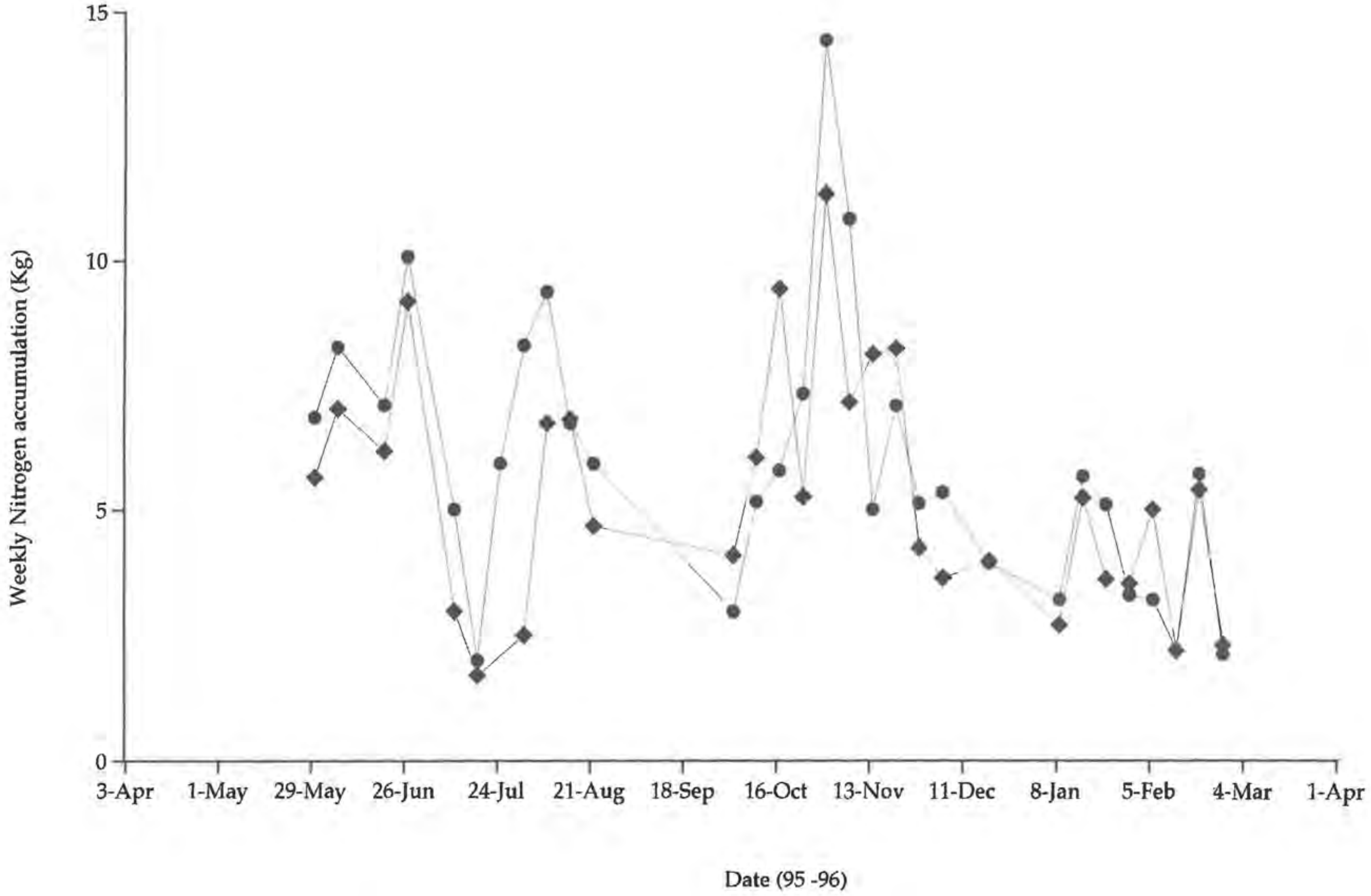
Total suspended solids of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



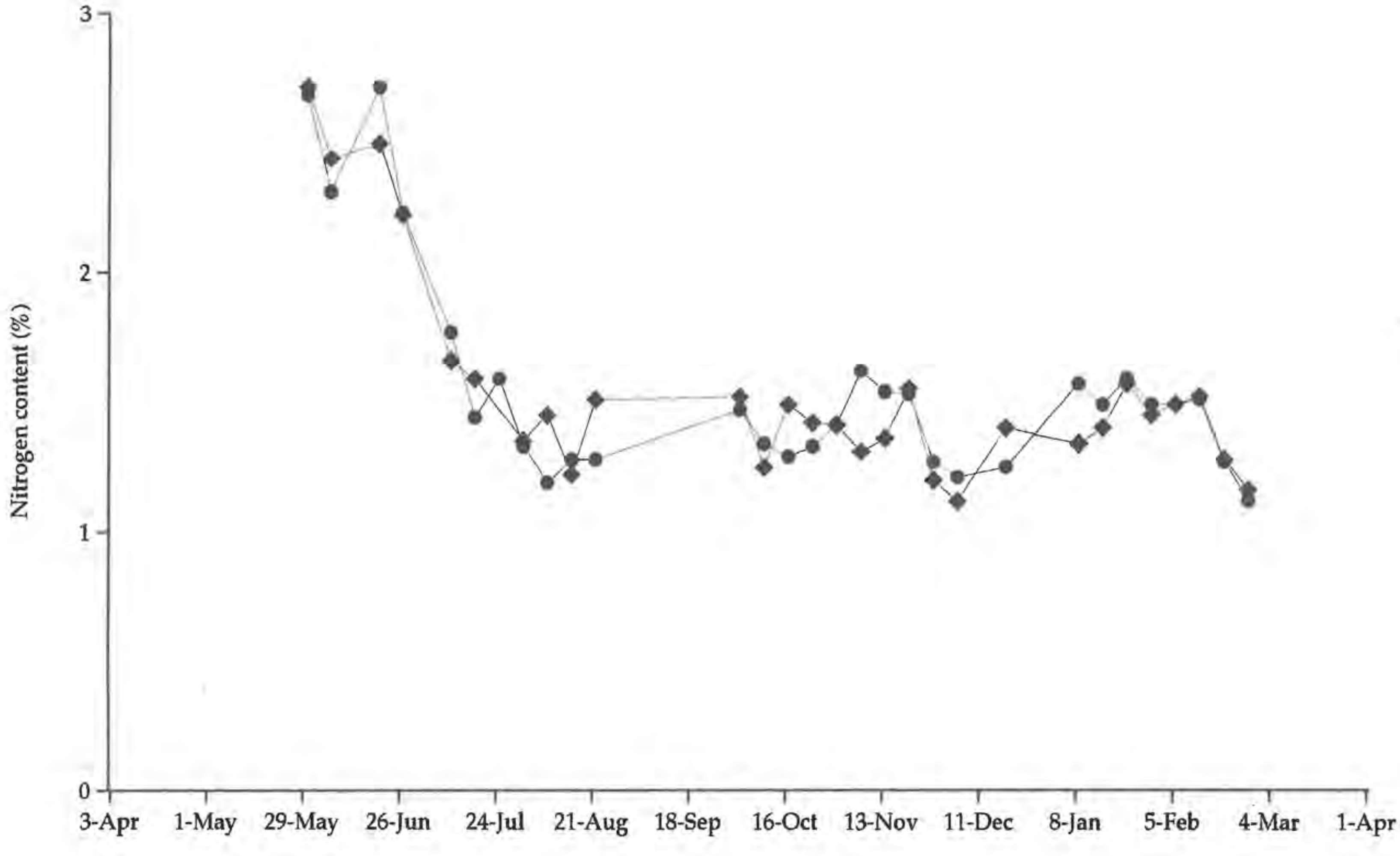
Turbidity of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



Nitrogen content (%) of the biomass of the west (◆) and east (●) sides of the split ATS floway. Values are from weekly samples.

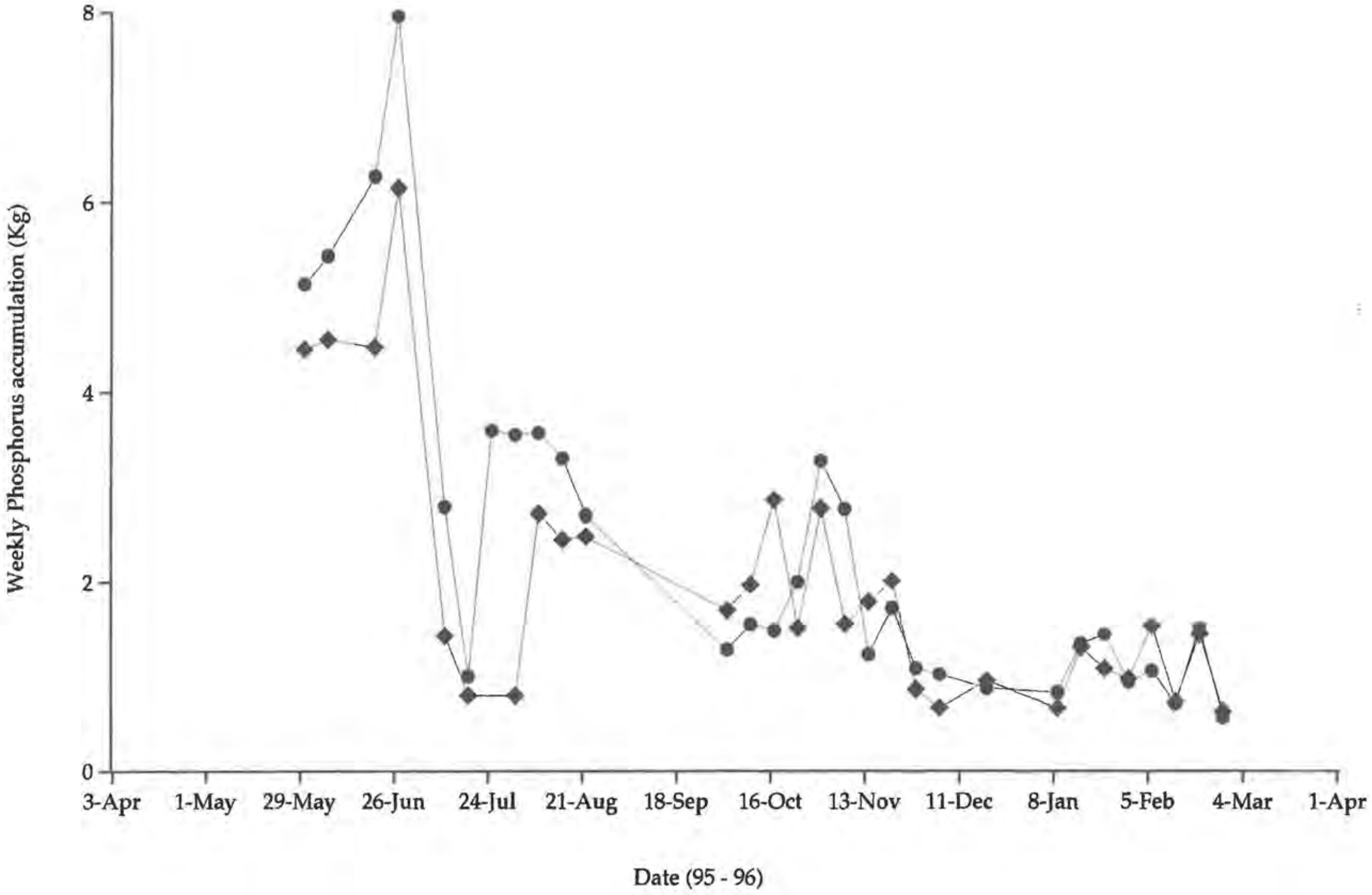


Weekly nitrogen accumulation in the biomass of the west (◆) and east (●) sides of the split ATS floway. Values are from weekly samples.

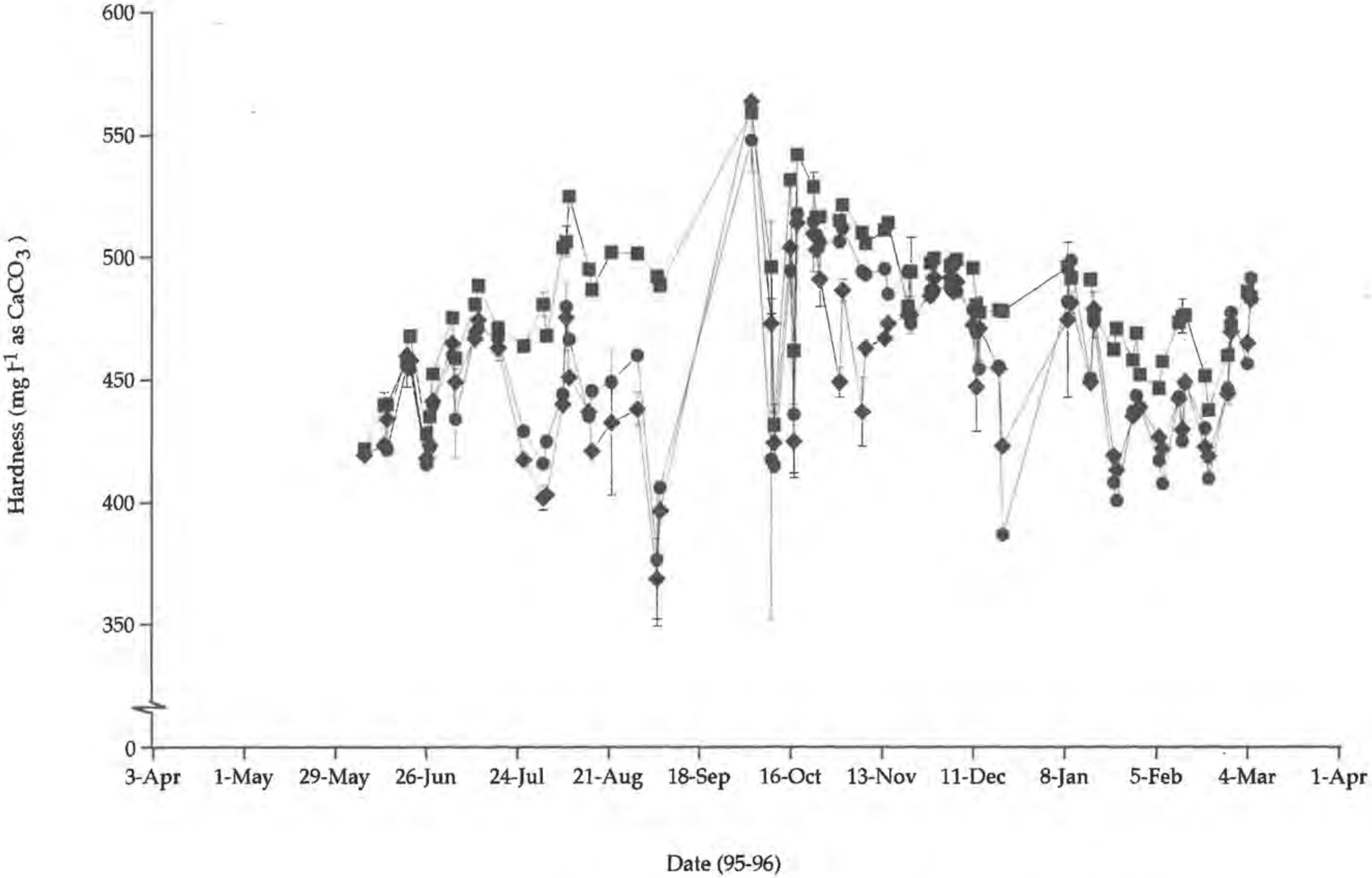


Date (95 - 96)

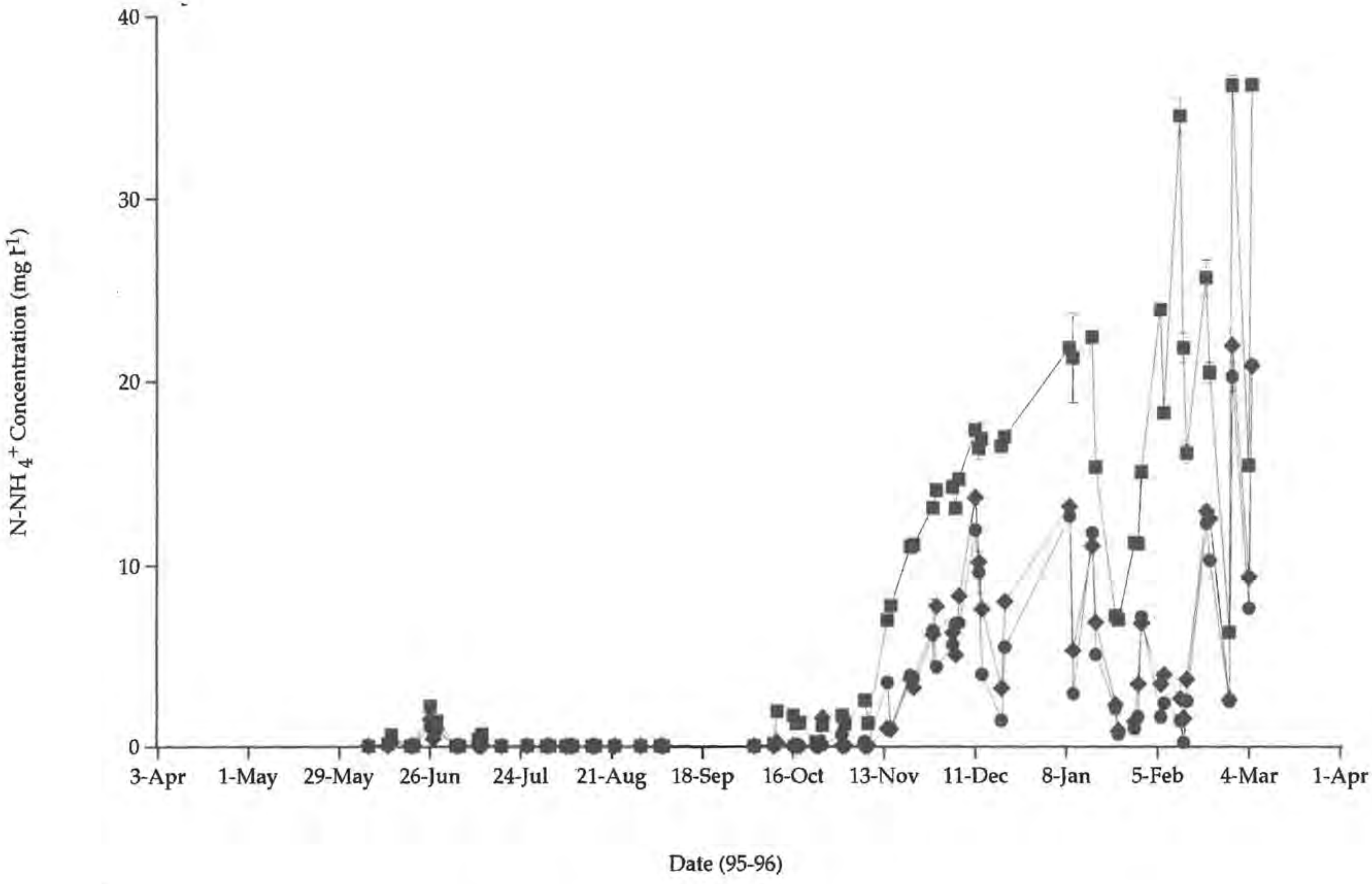
Phosphorus content (%) of the biomass of the west (◆) and east (●) sides of the split ATS floway. Values are from weekly samples.



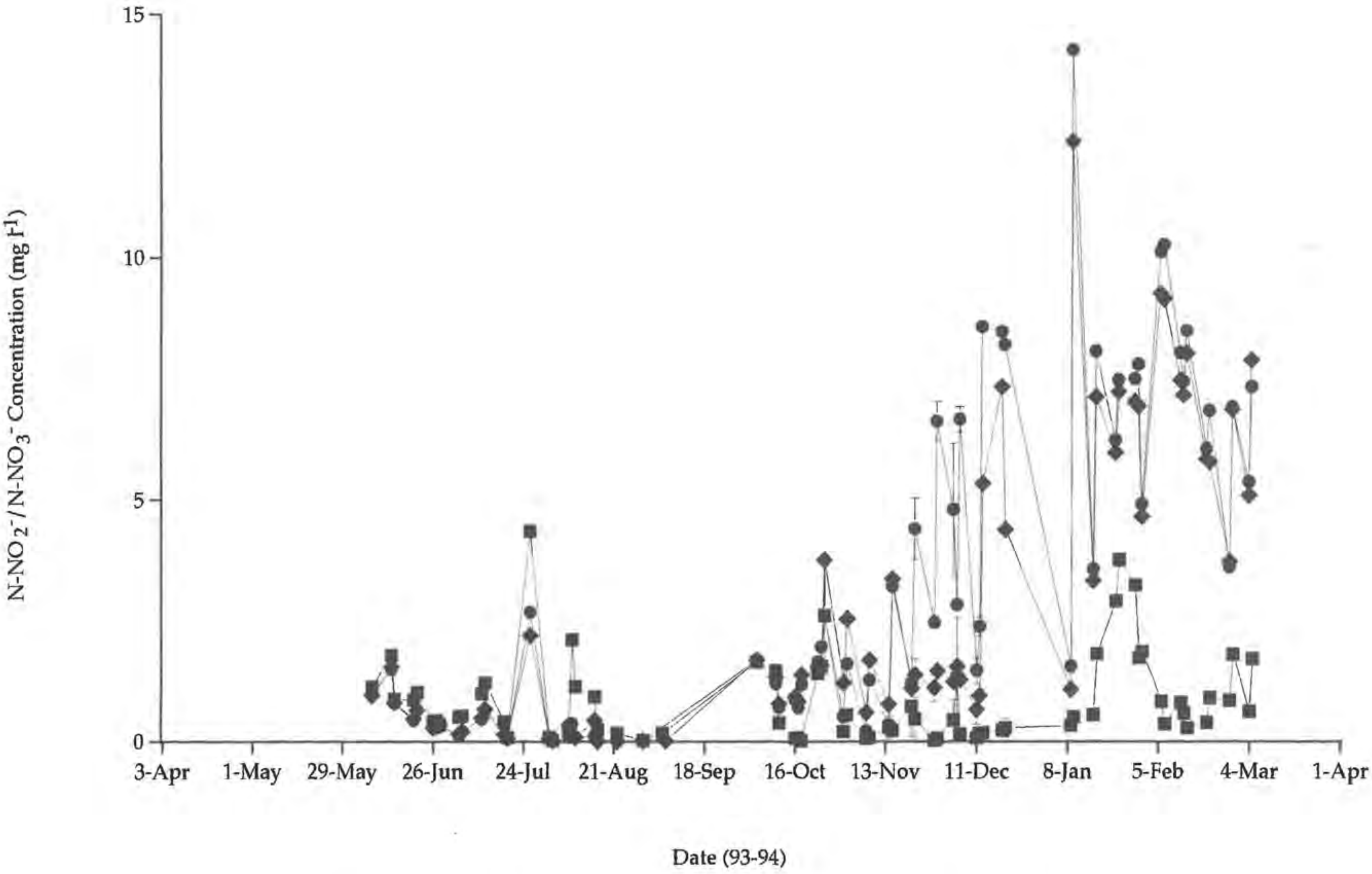
Weekly phosphorus accumulation in the biomass of the west (◆) and east (●) sides of the split ATS floway. Values are from weekly samples.



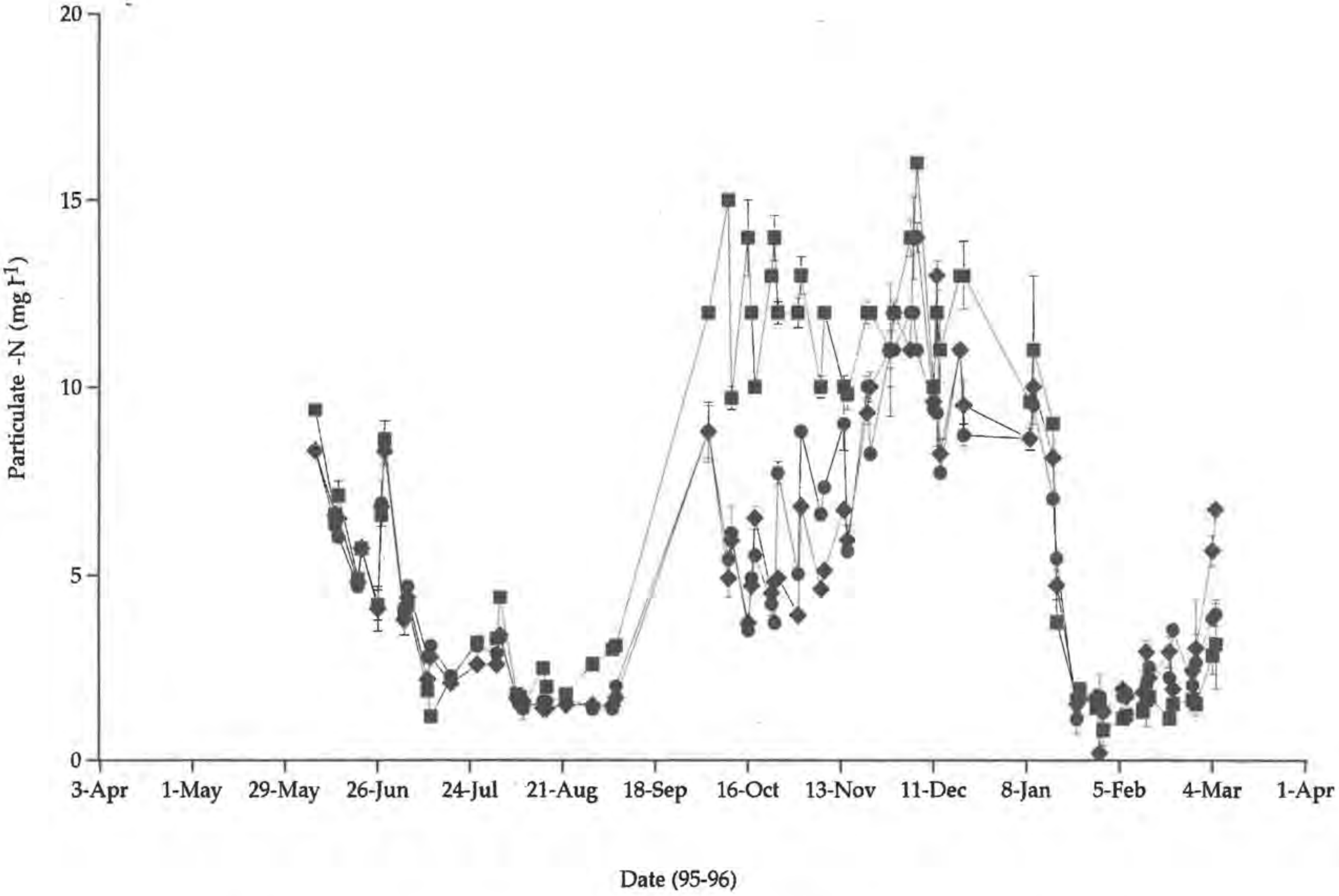
Hardness of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



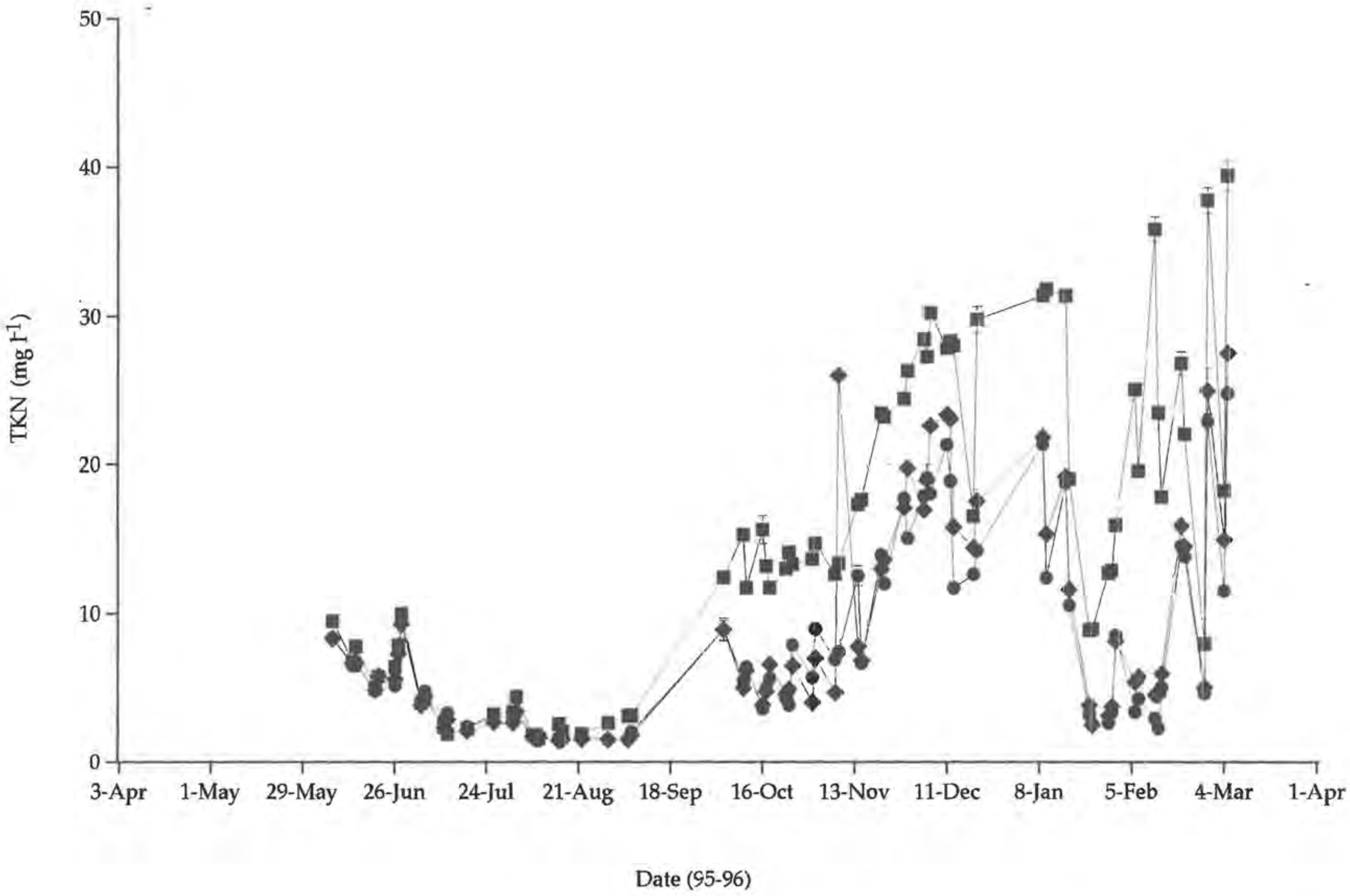
Ammonium concentration of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.. Values are means ± s.d. of two replicate samples.



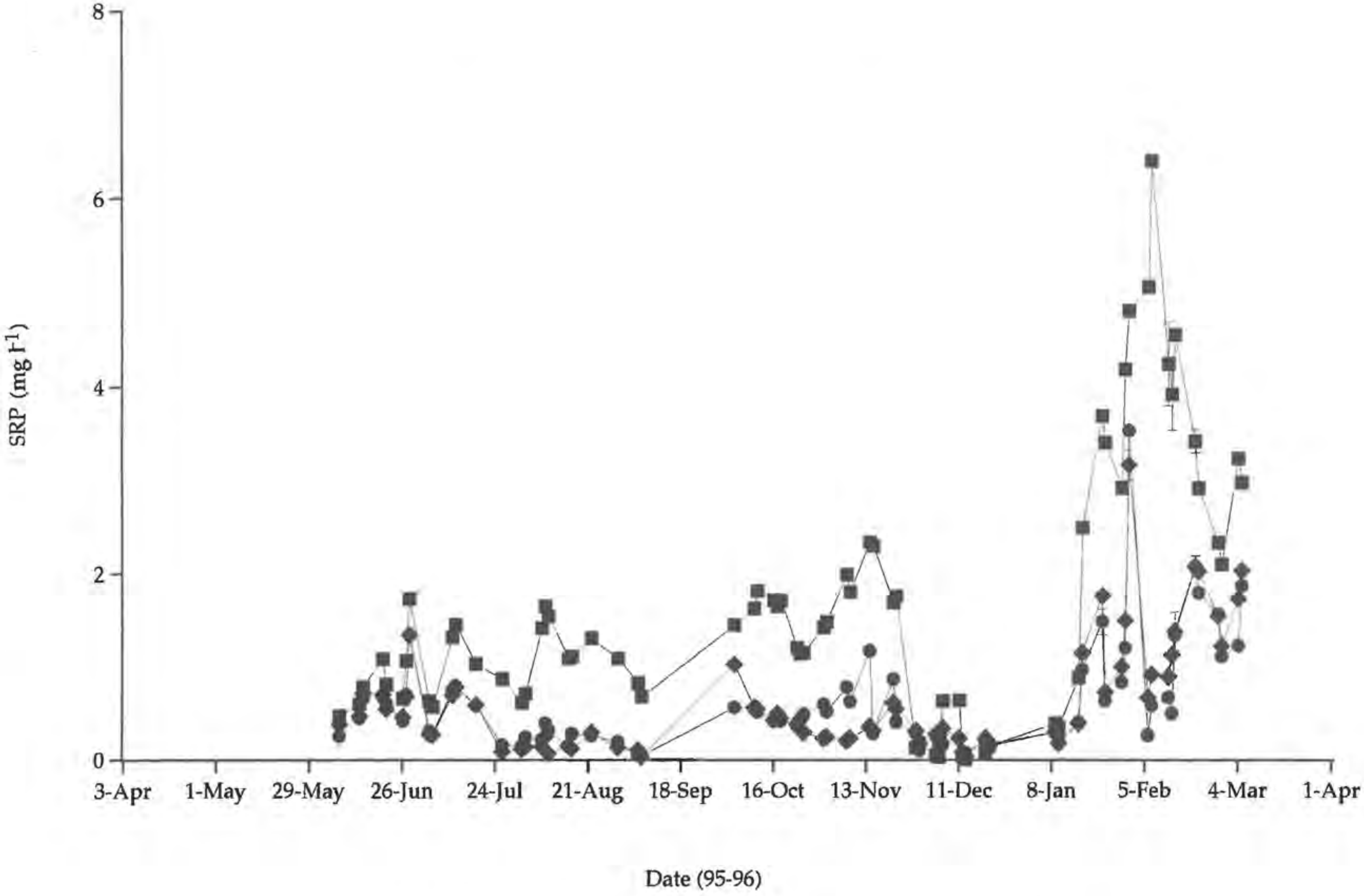
Nitrate/nitrite concentration of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



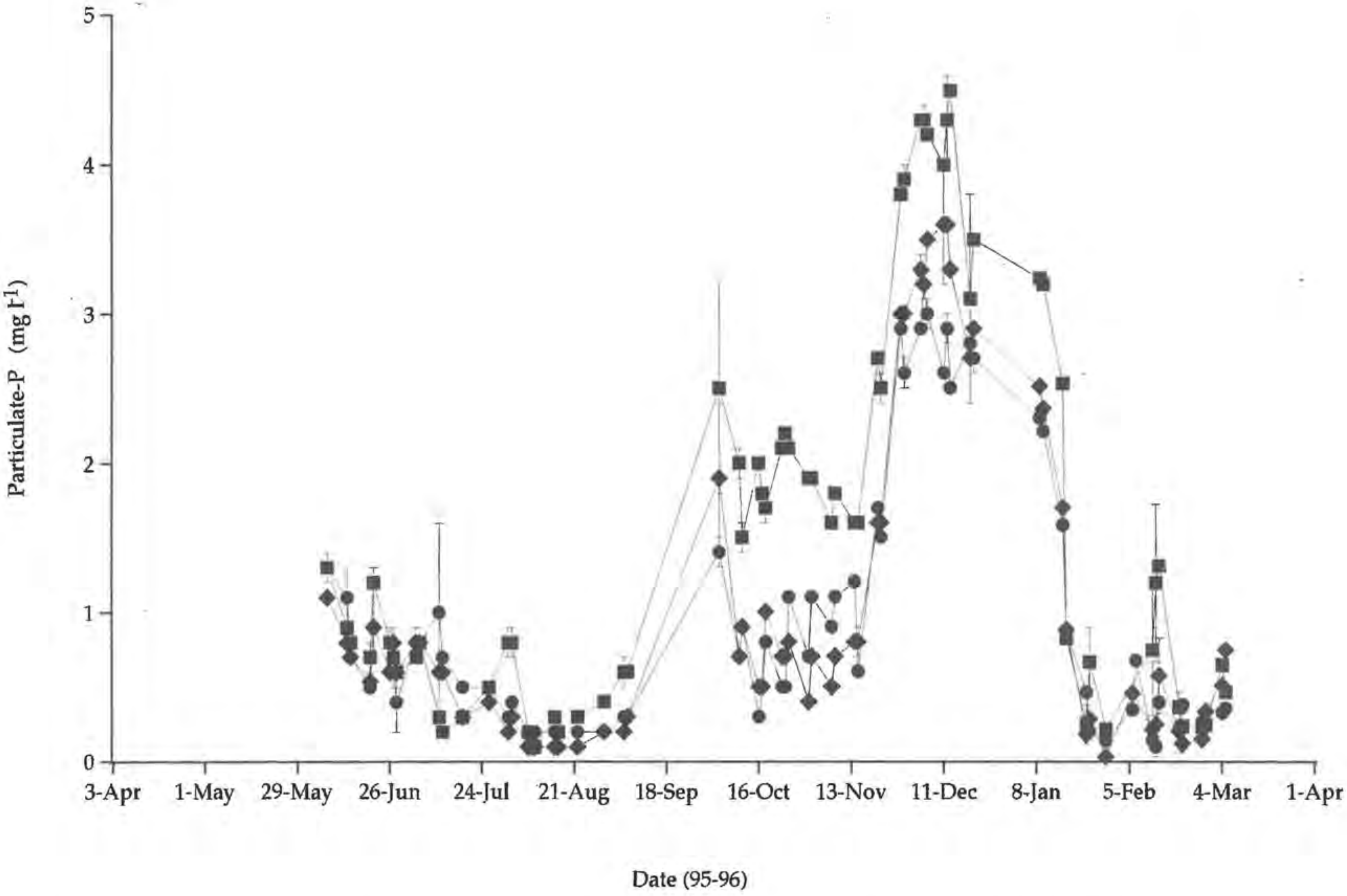
Particulate nitrogen concentration of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



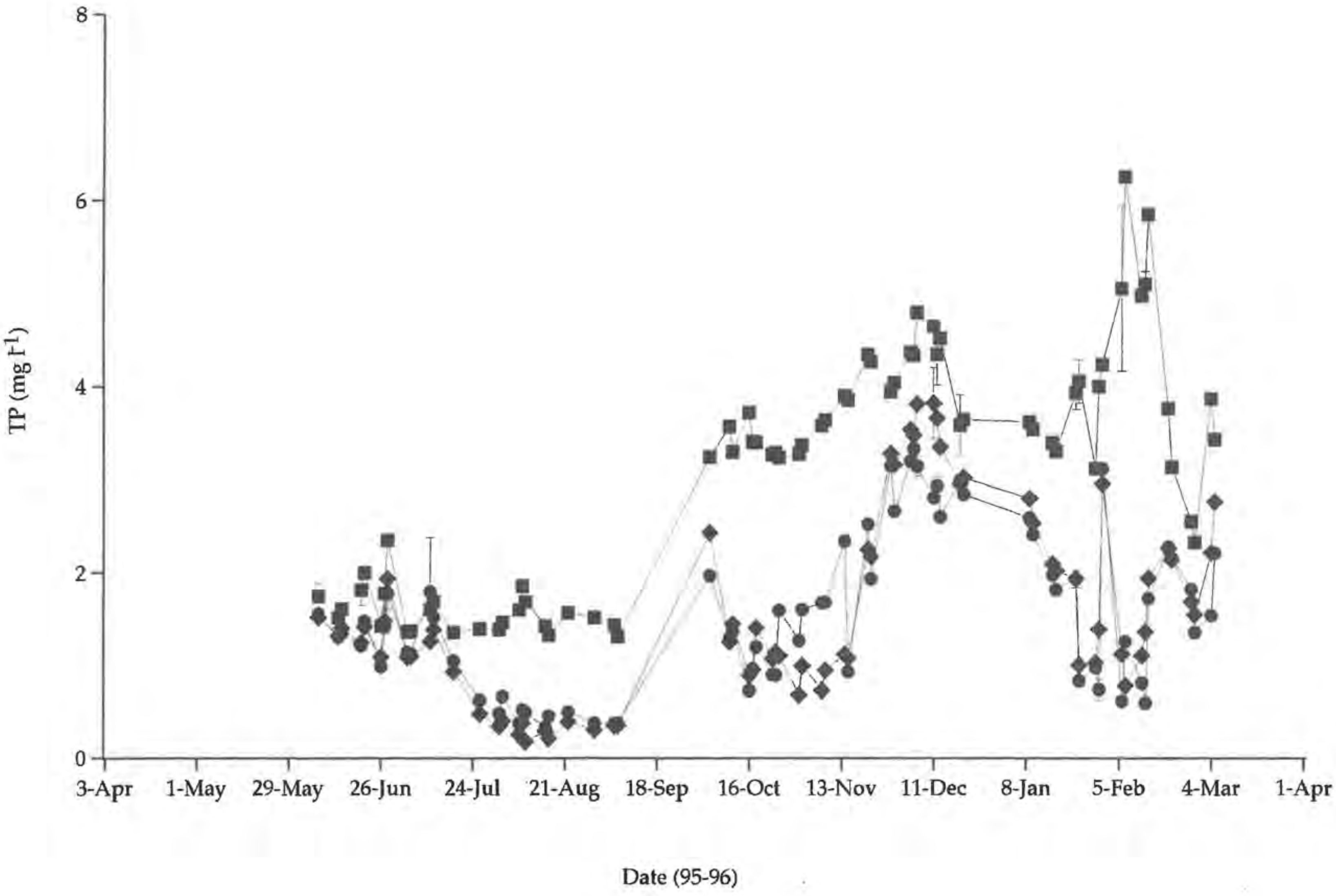
Total kjeldahl nitrogen concentration of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



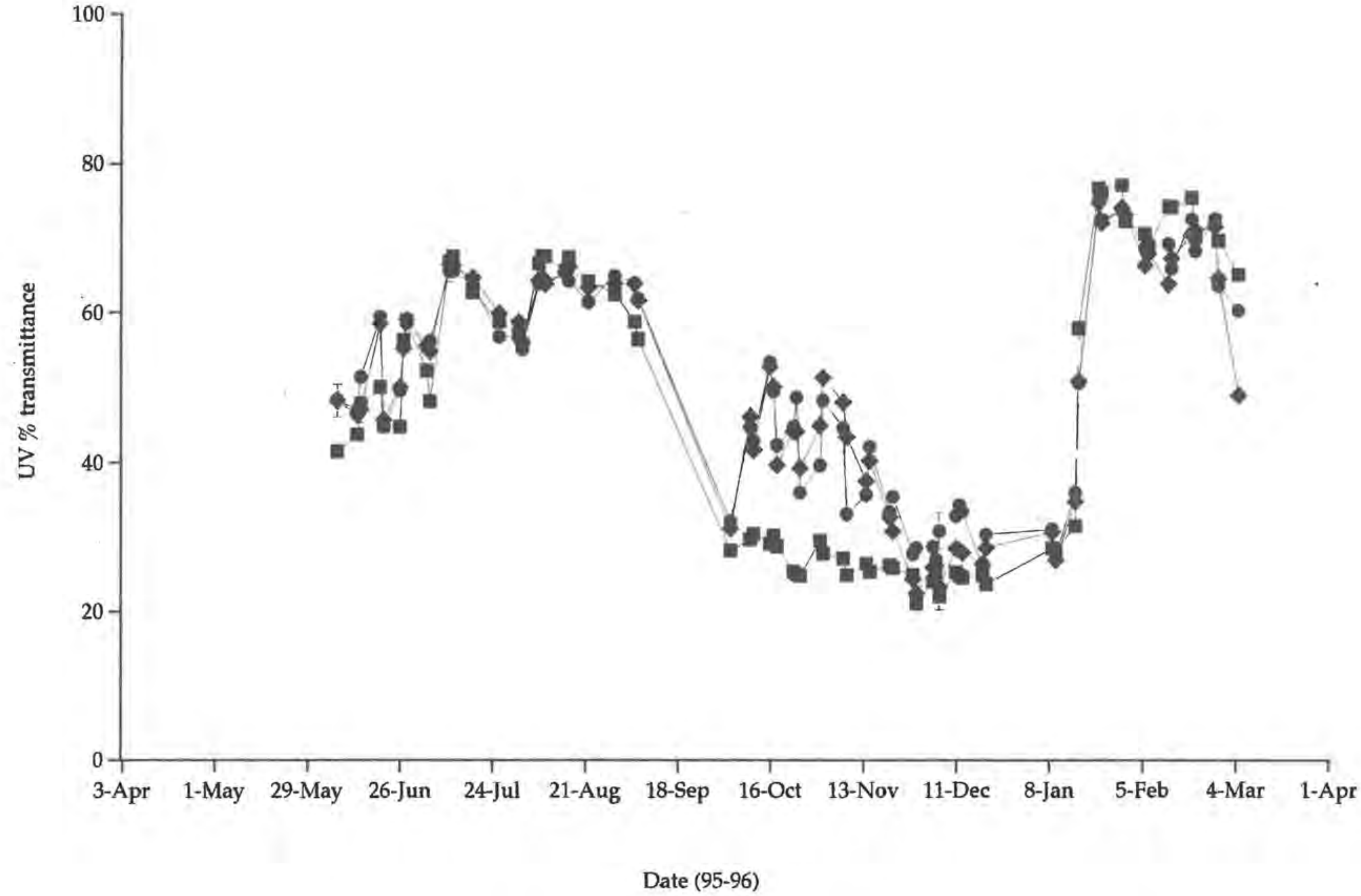
Soluble reactive phosphorus concentration of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



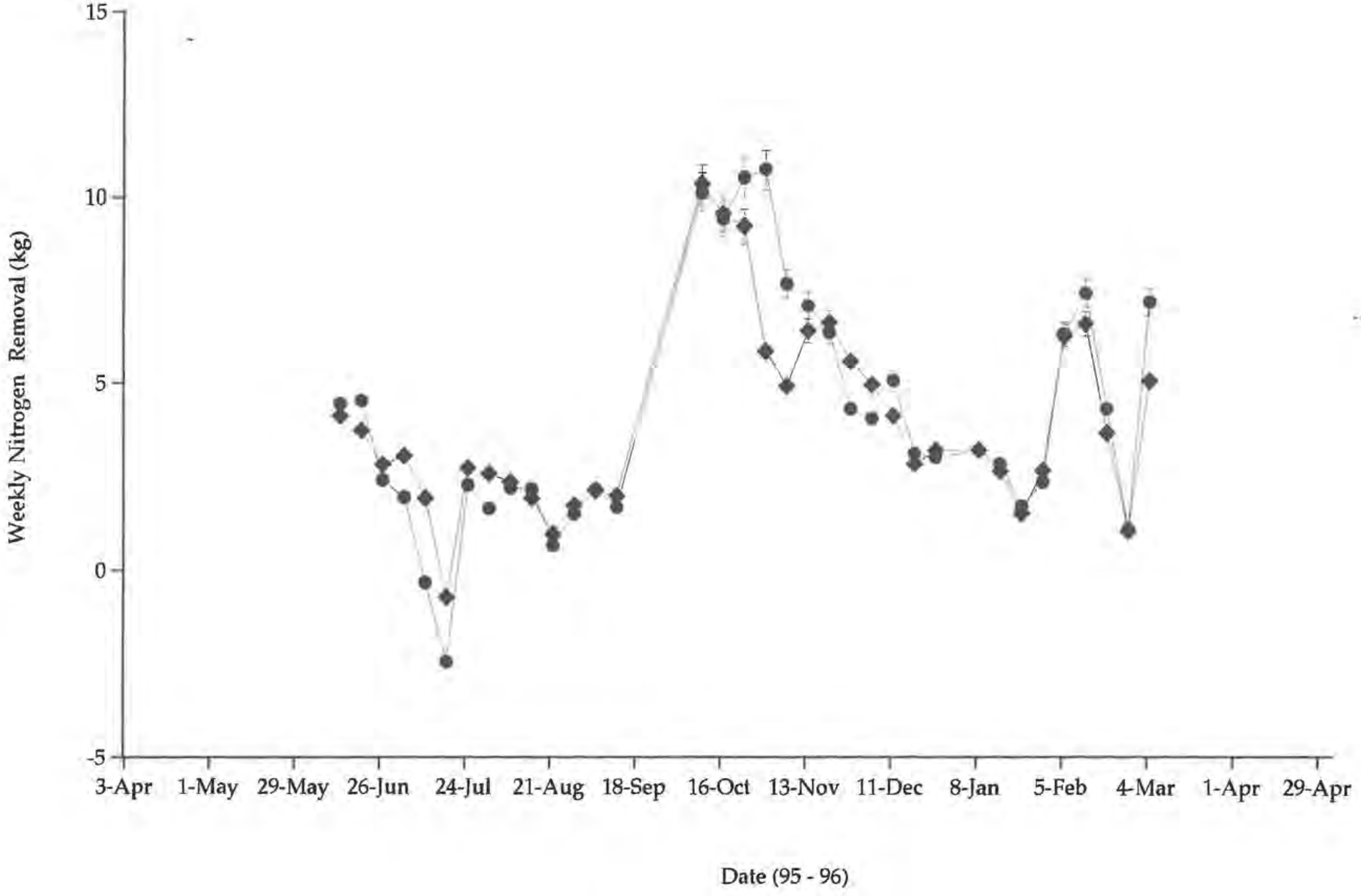
Particulate phosphorus concentration of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.



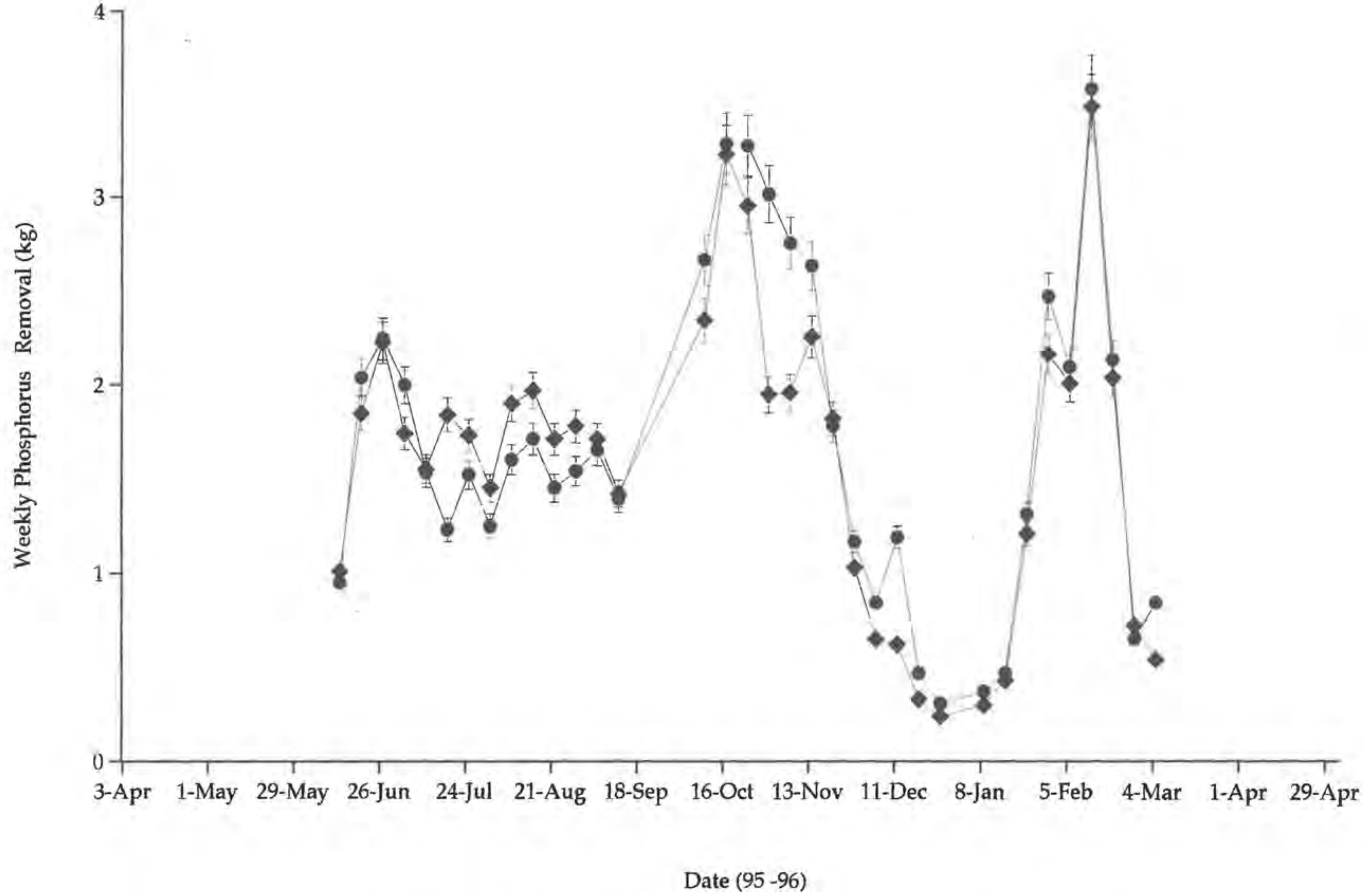
Total phosphorus concentration of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.. Values are means ± s.d. of two replicate samples.



UV % transmittance of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway. Values are means ± s.d. of two replicate samples.

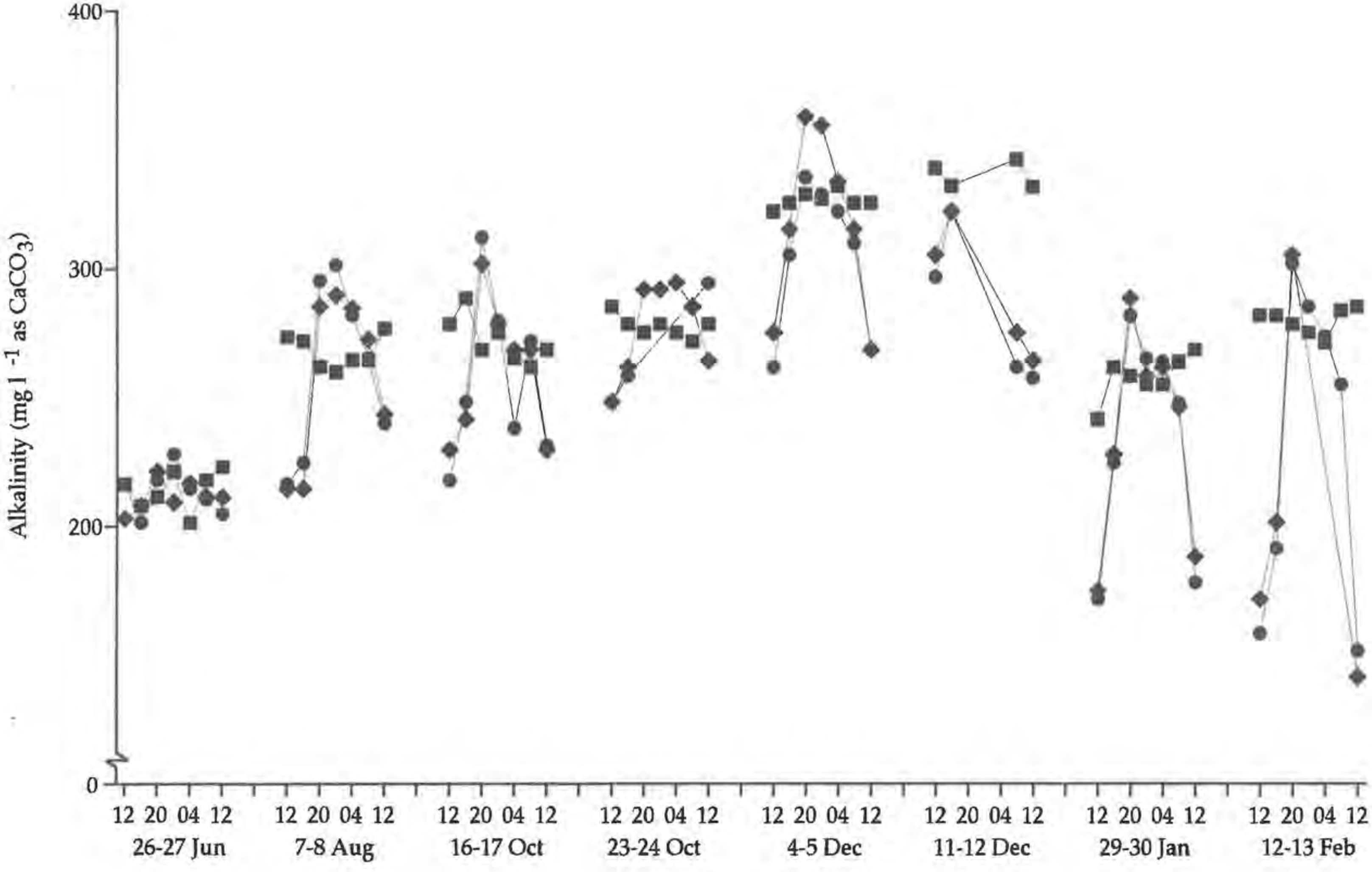


Weekly nitrogen removal of the west (◆) and east (●) sides of the split ATS floway. Values are means ± s.d. of water samples taken on day one and day seven of each week.

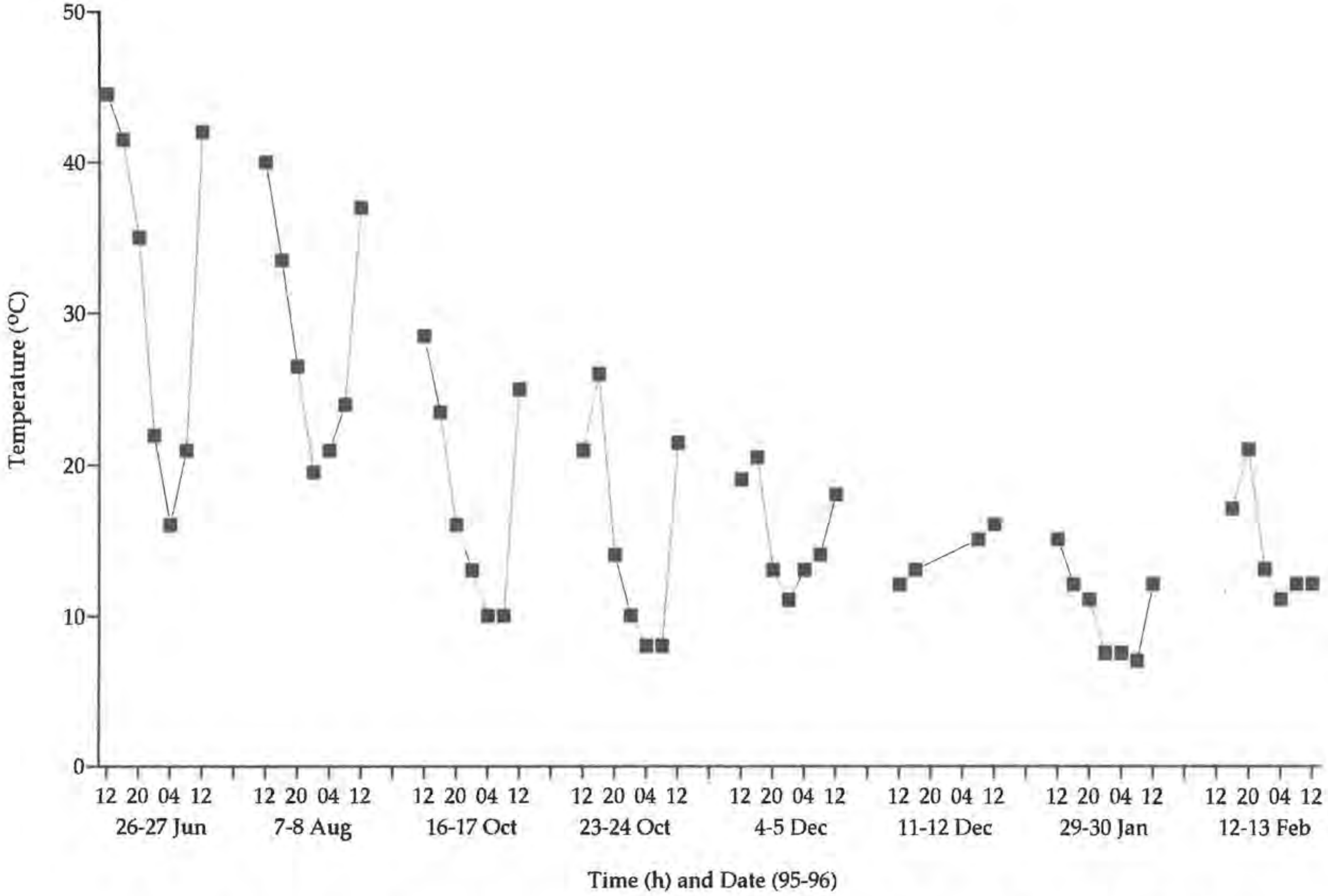


Weekly phosphorus removal of the west (◆) and east (●) sides of the split ATS floway. Values are means ± s.d. of water samples taken on day one and day seven of each week.

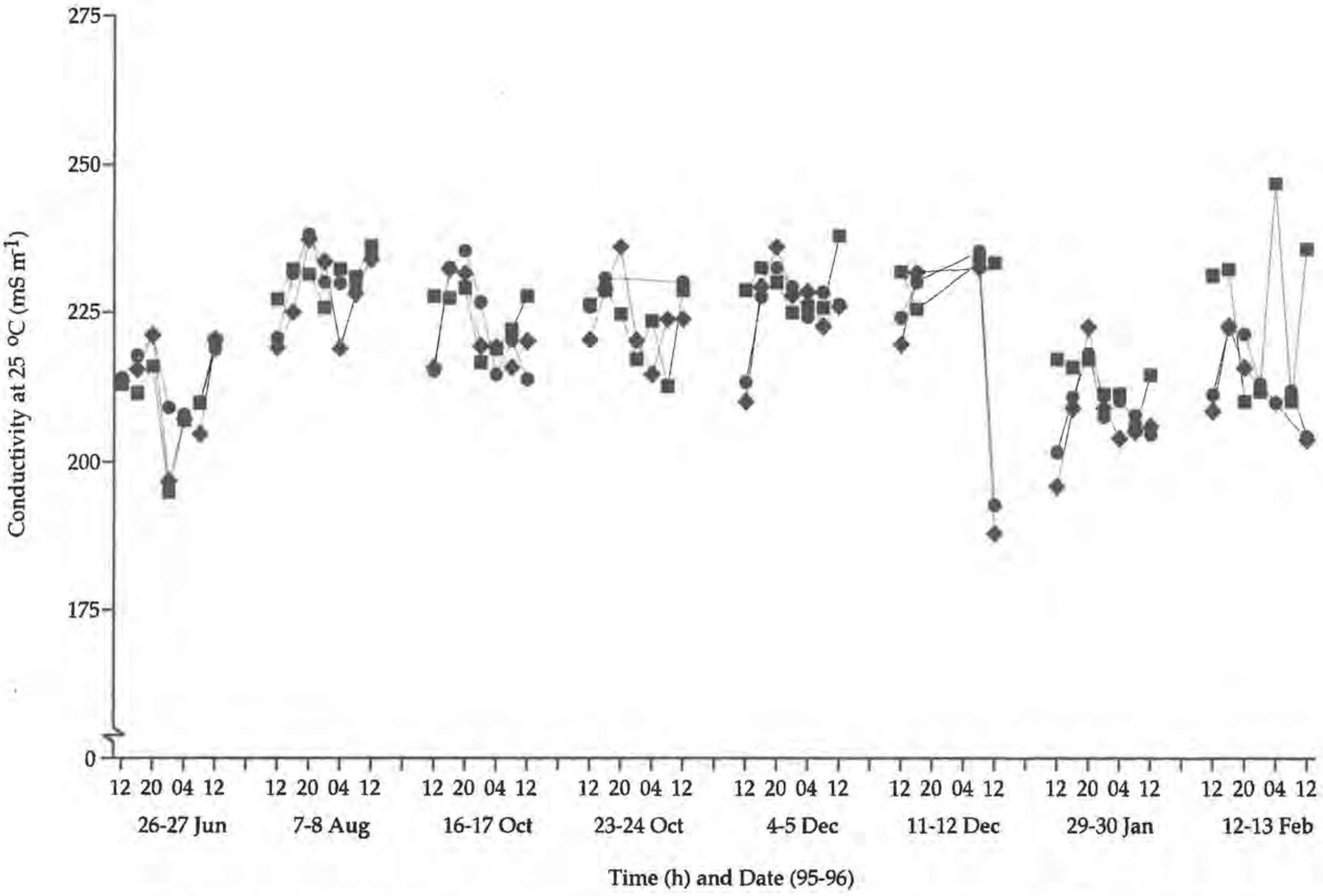
Appendix 2



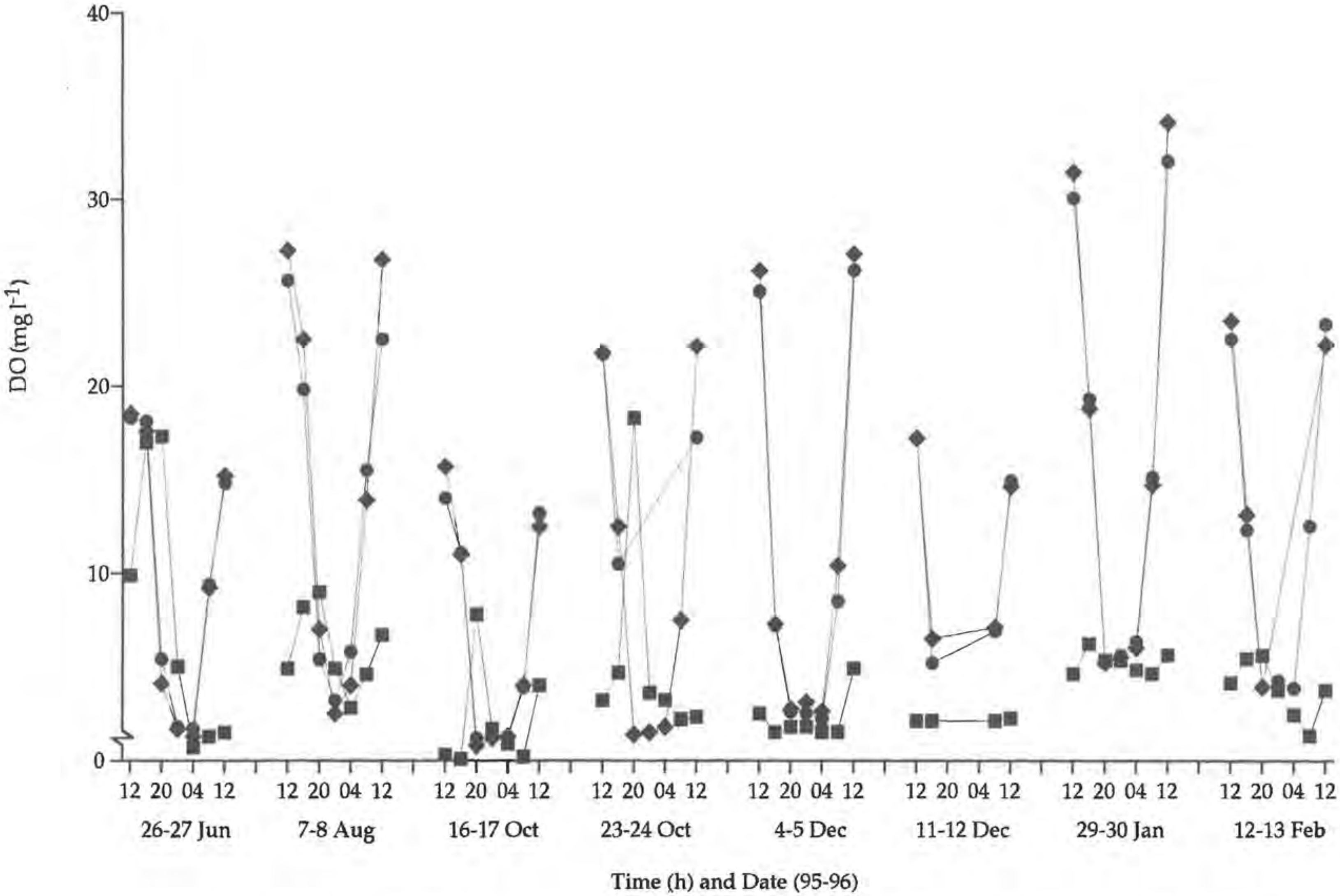
24 hour variation of alkalinity of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



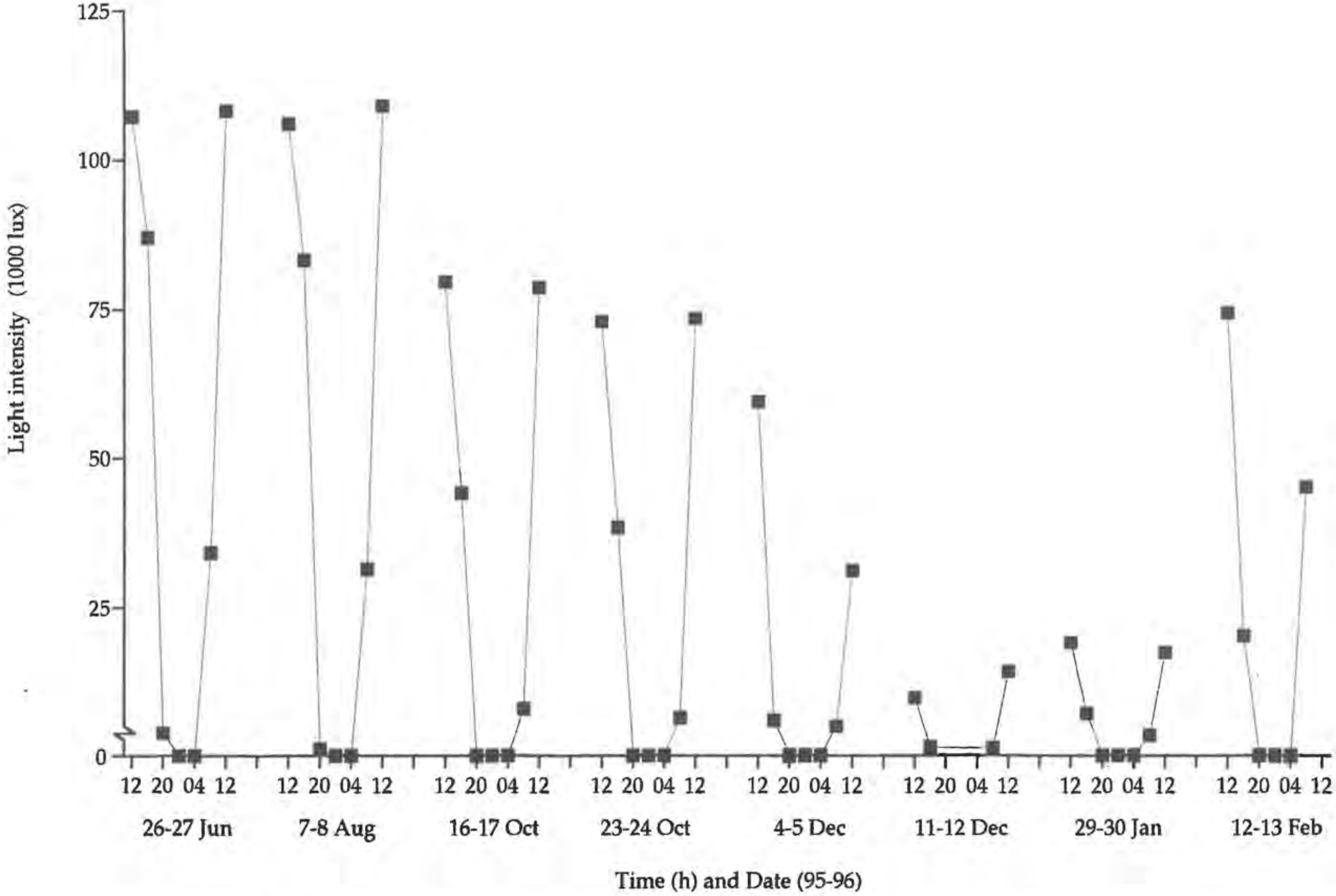
24 hour variation of ambient temperature during the diurnal studies of the split ATS floway.



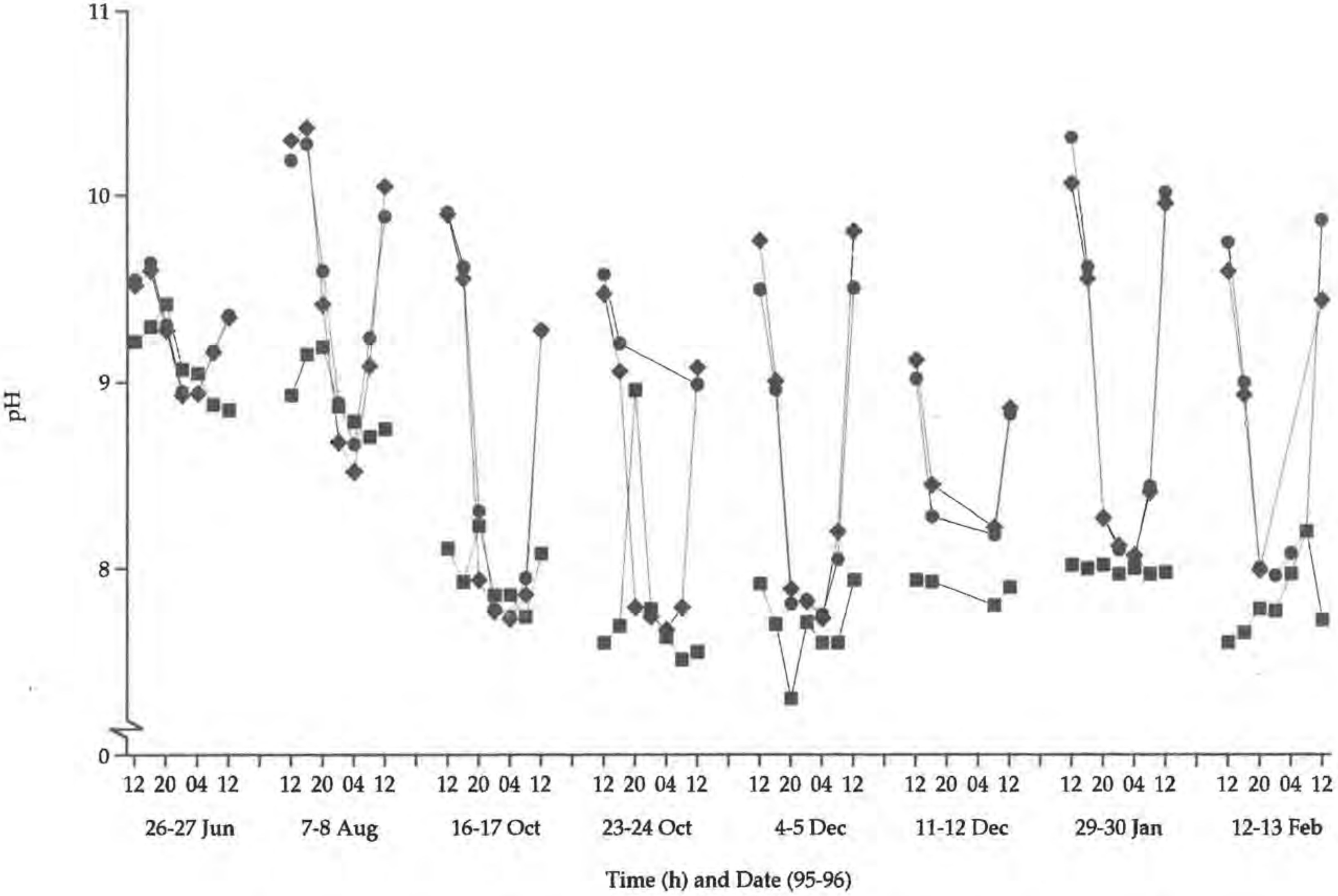
24 hour variation of conductivity of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



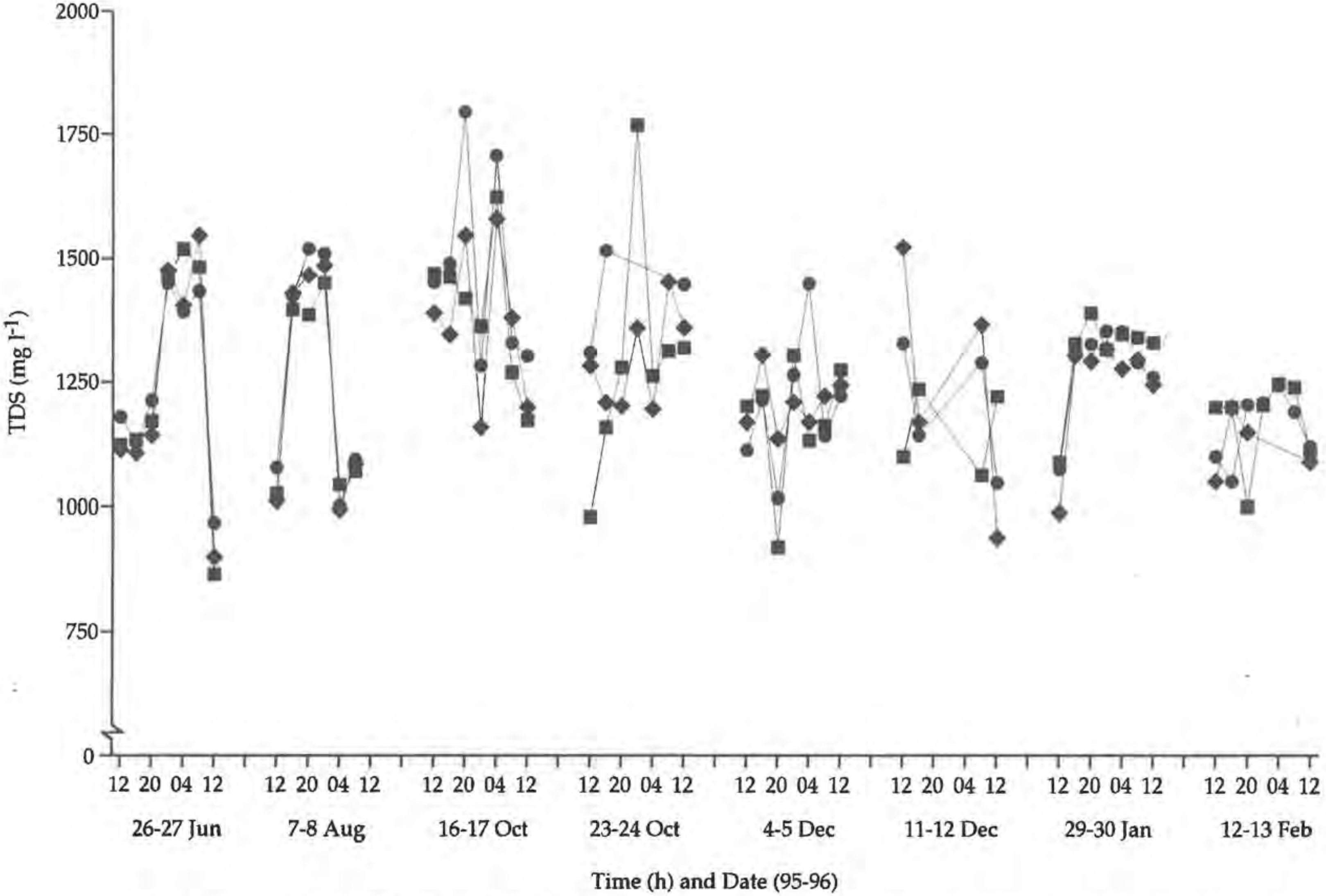
24 hour variation of dissolved oxygen of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



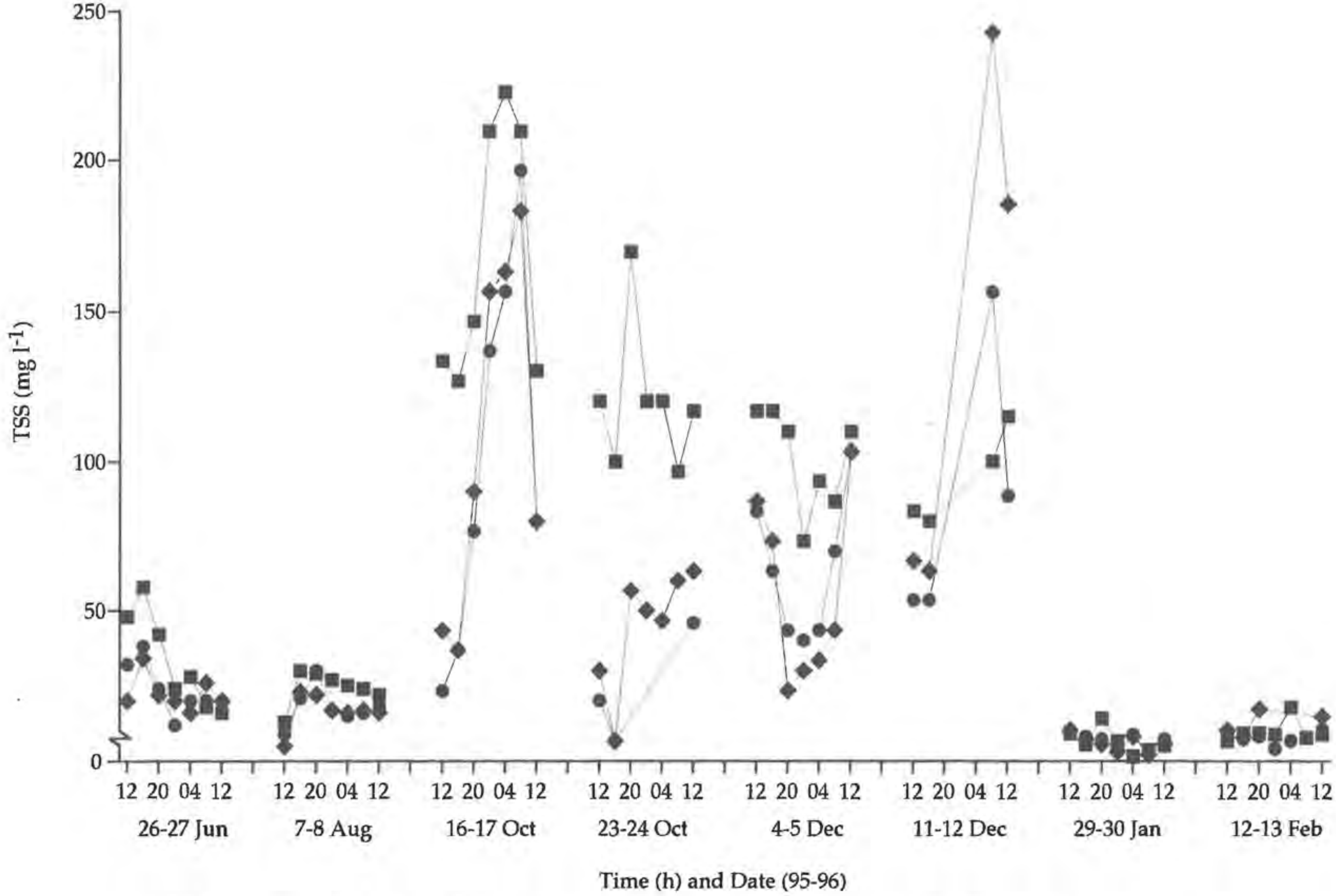
24 hour variation of light intensity of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



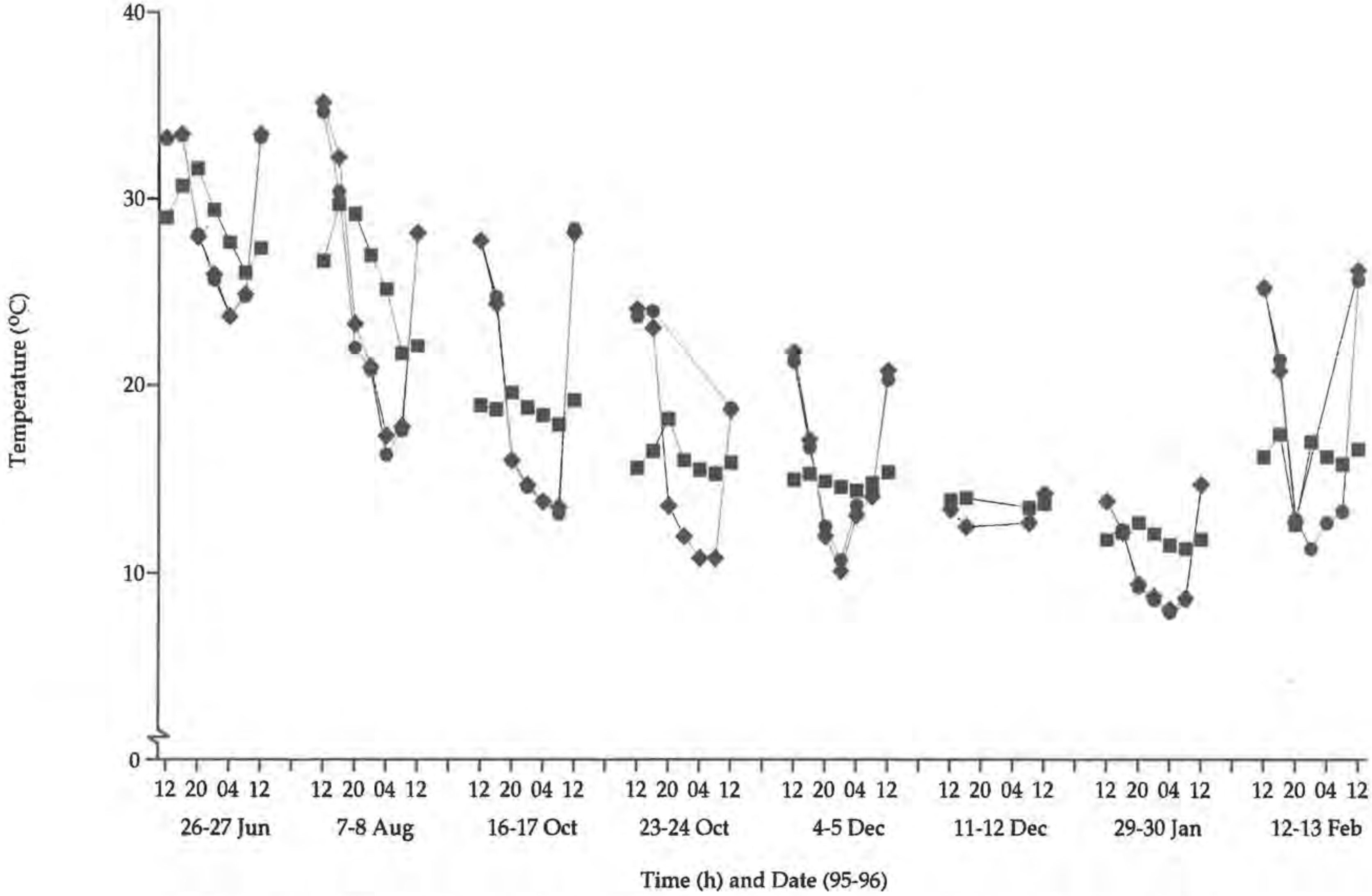
24 hour variation of pH of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



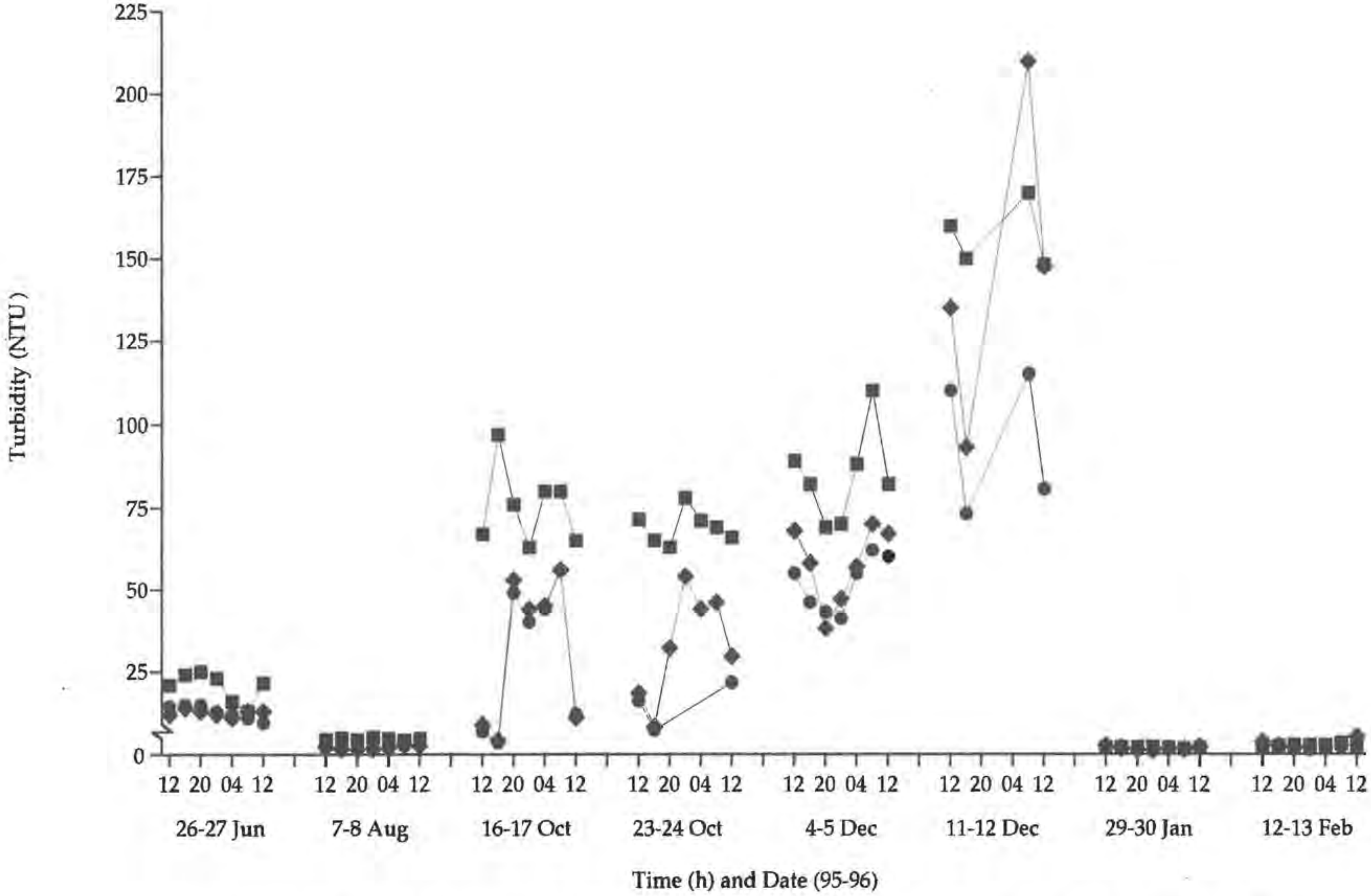
24 hour variation of total dissolved solids of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



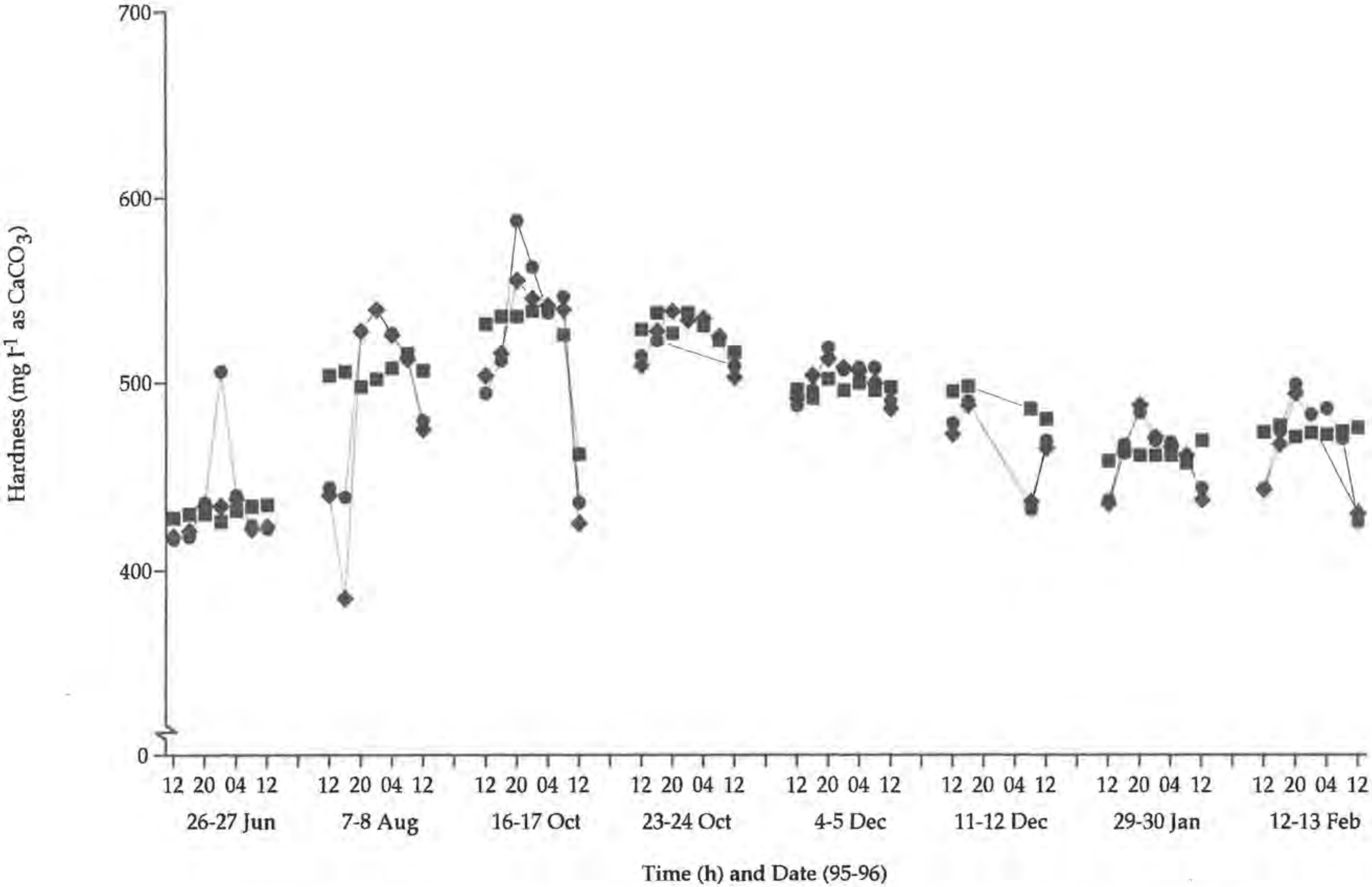
24 hour variation of total suspended solids of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



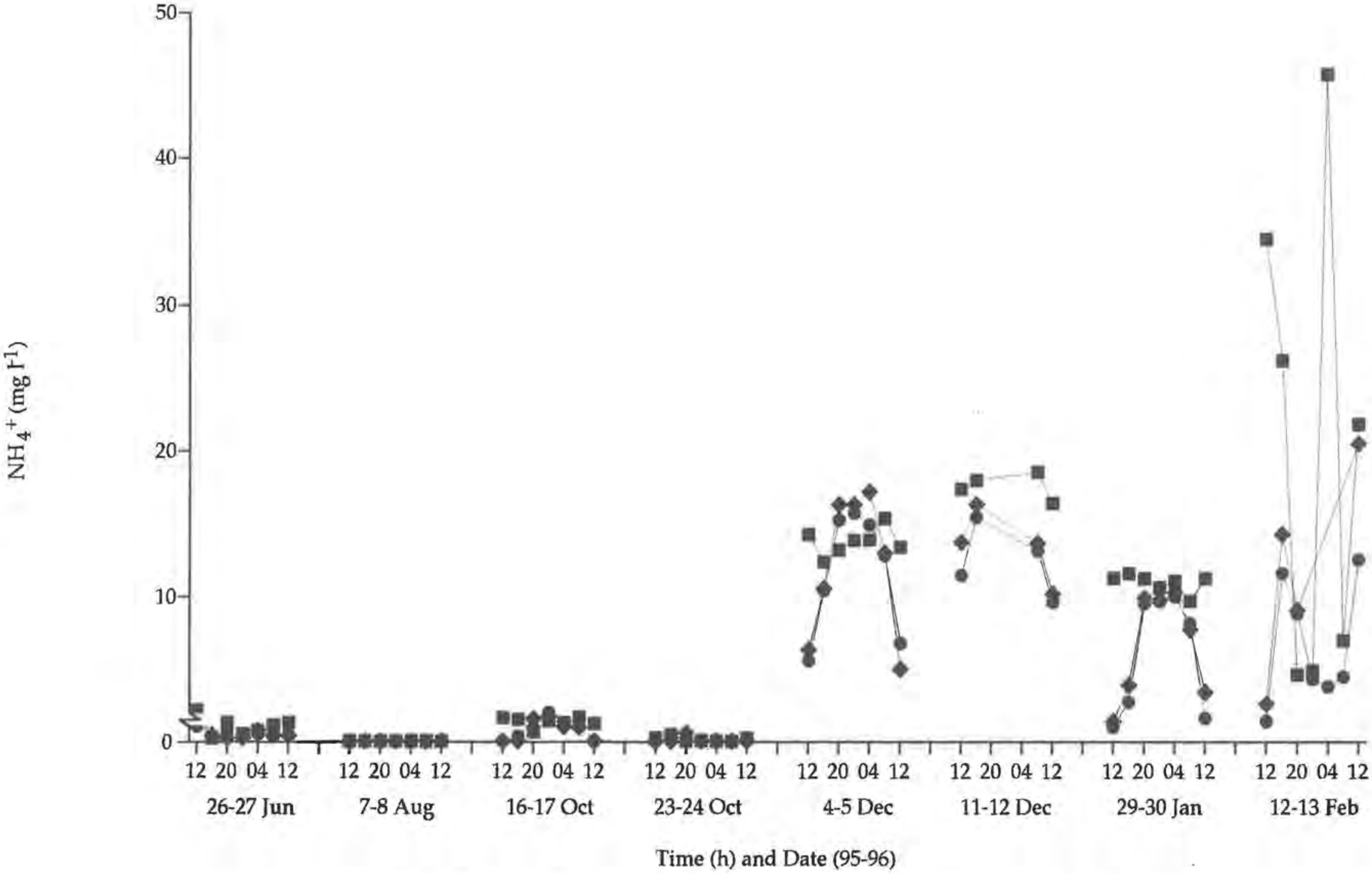
24 hour variation of temperature of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



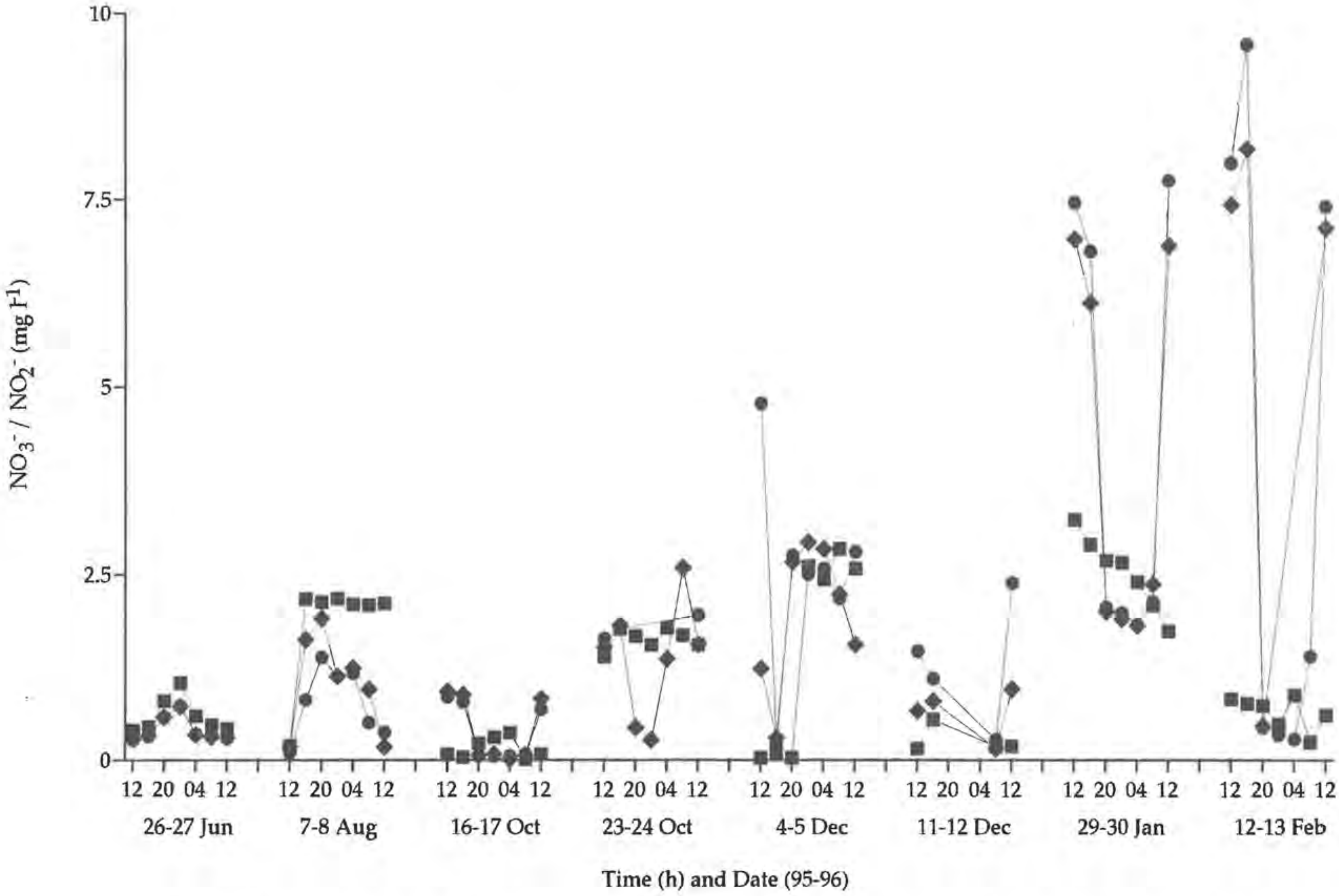
24 hour variation of turbidity of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



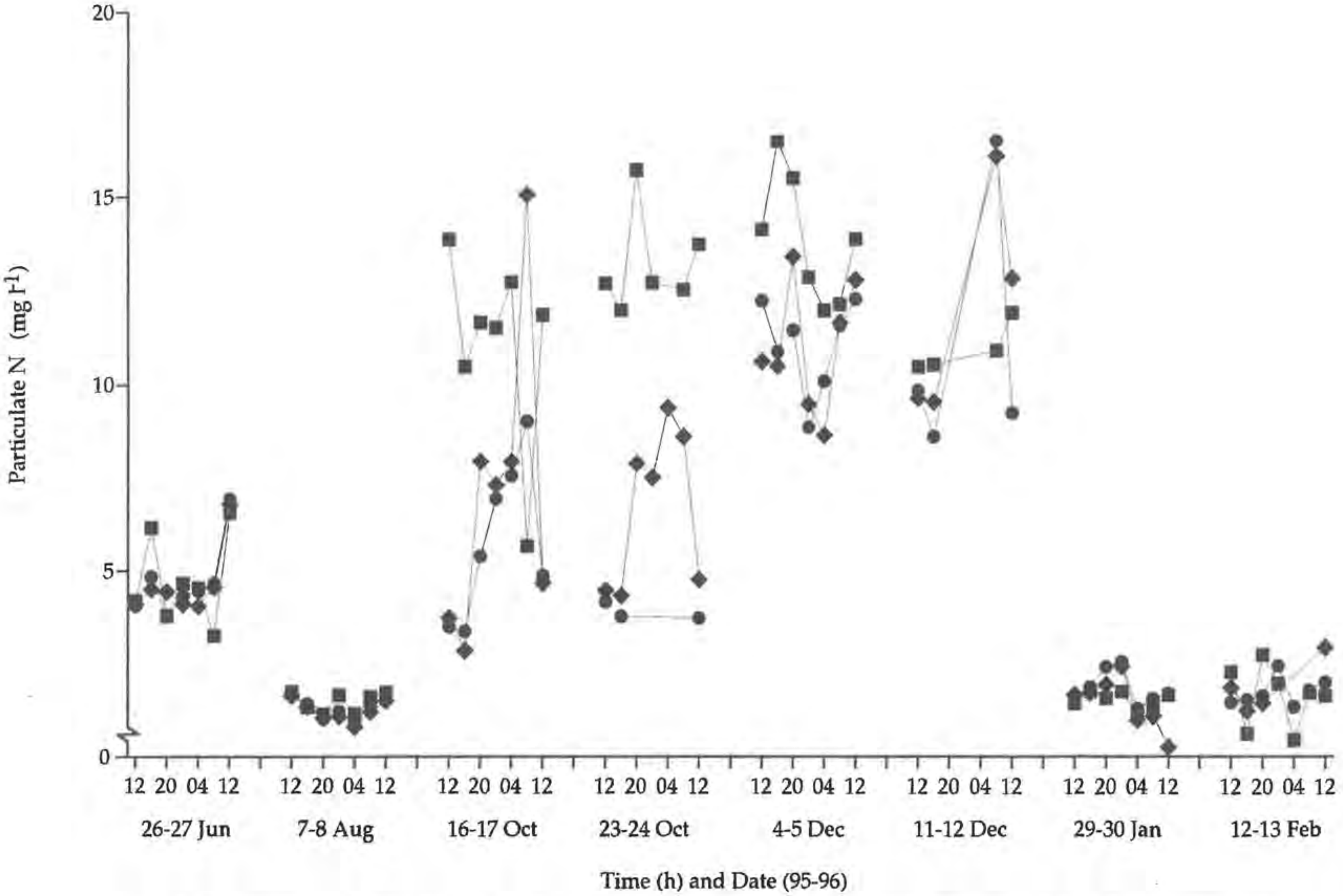
24 hour variation of hardness of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



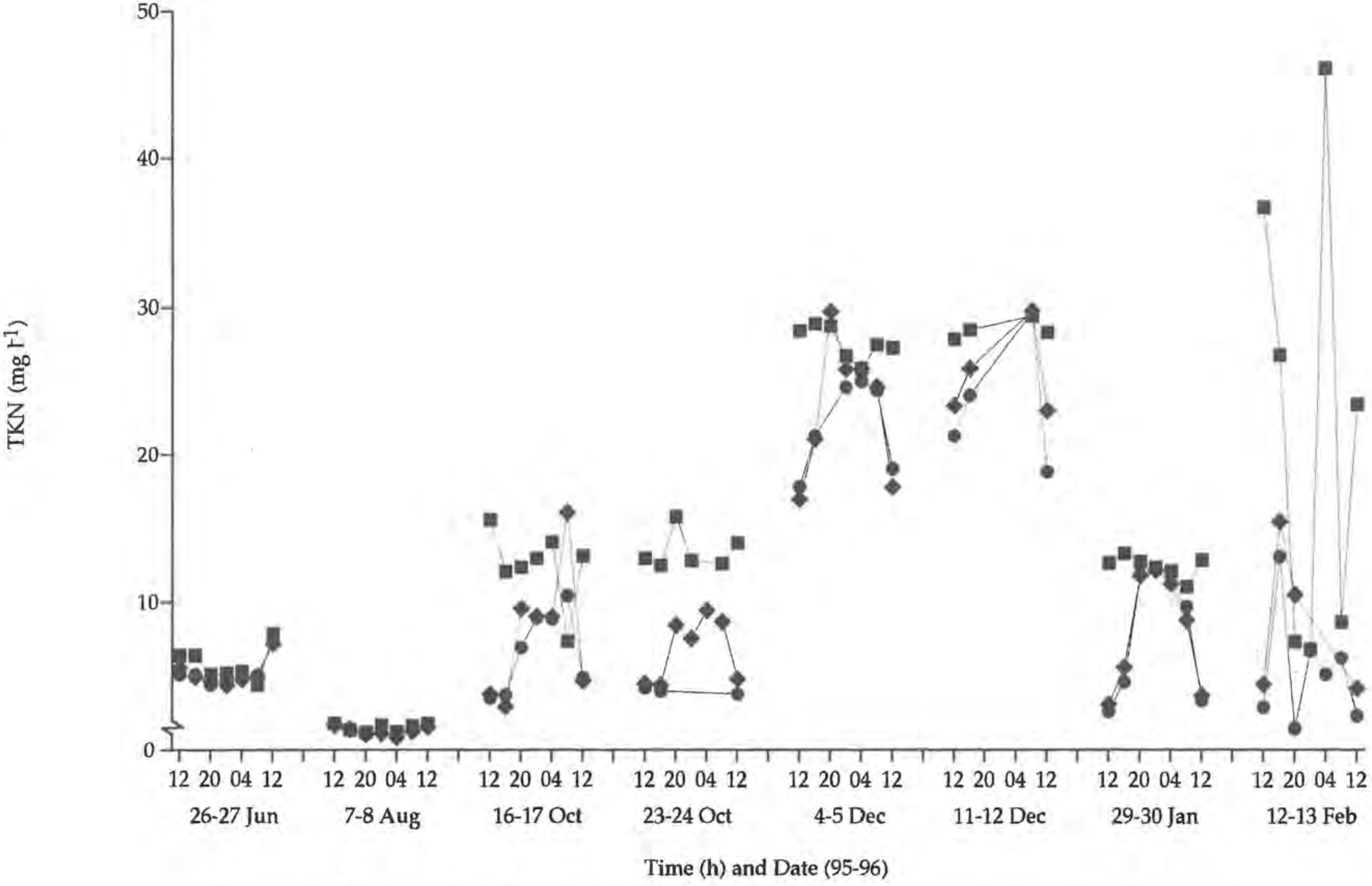
24 hour variation of ammonium of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



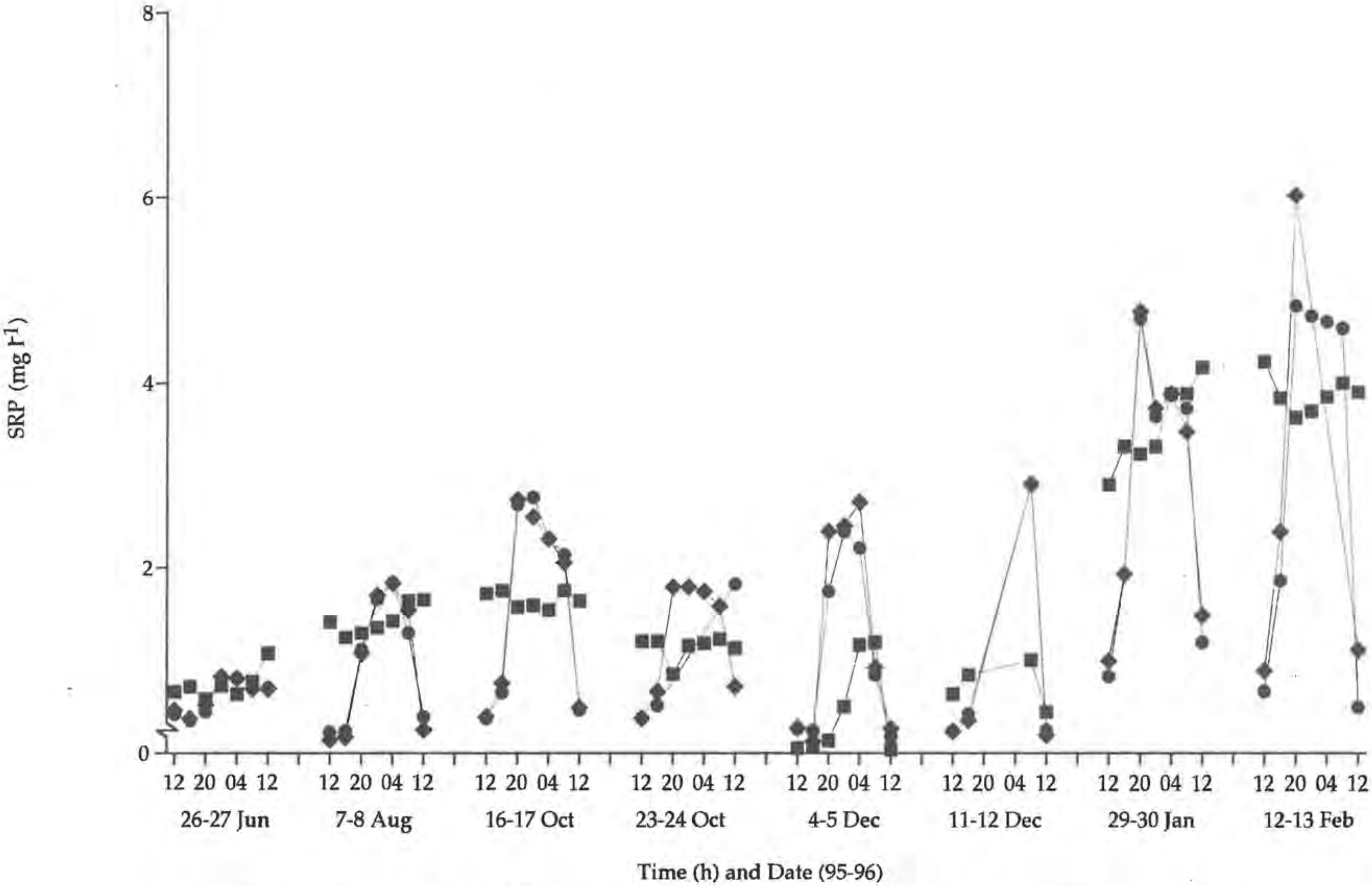
24 hour variation of nitrate/nitrite of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



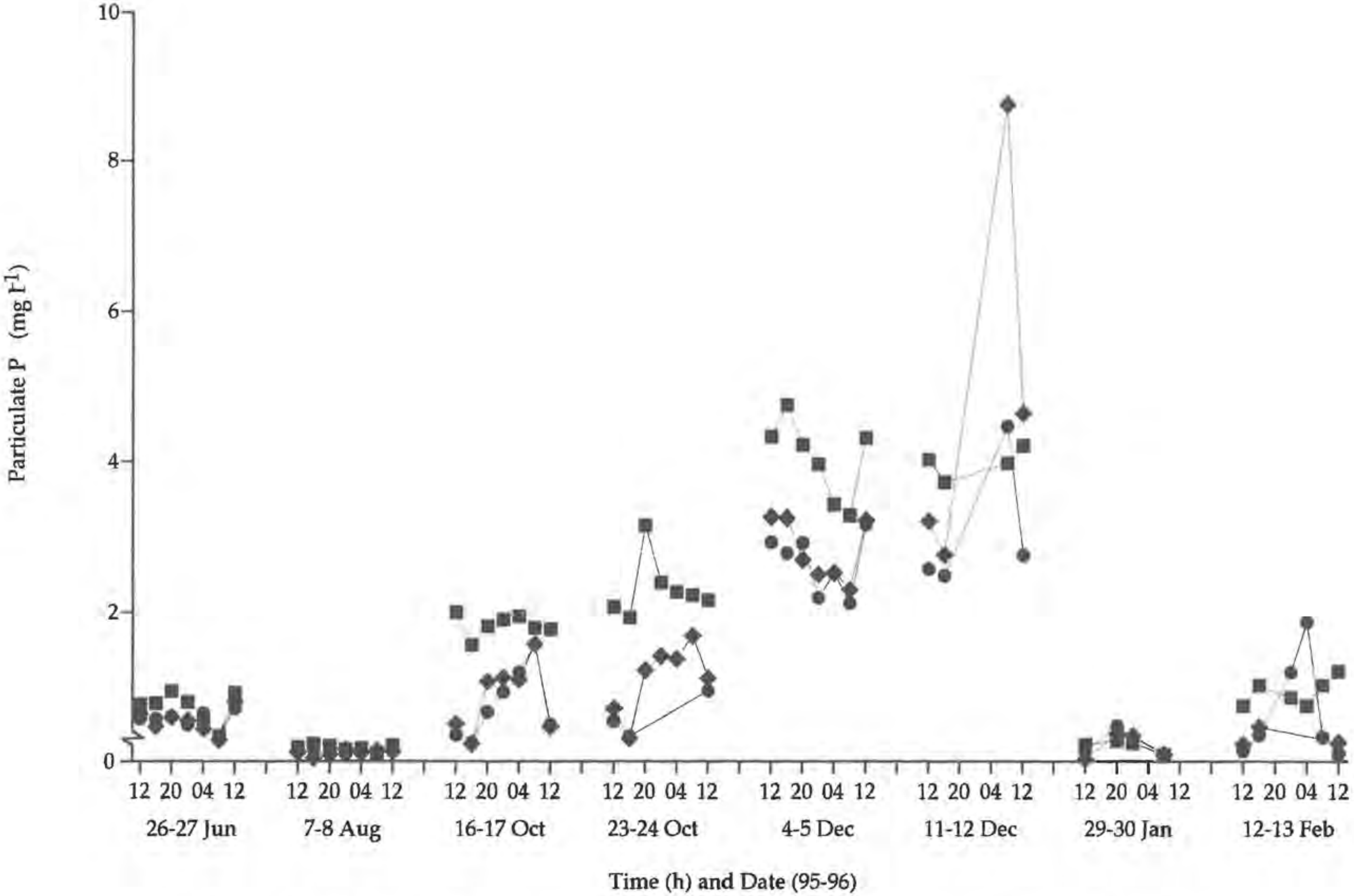
24 hour variation of particulate nitrogen of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



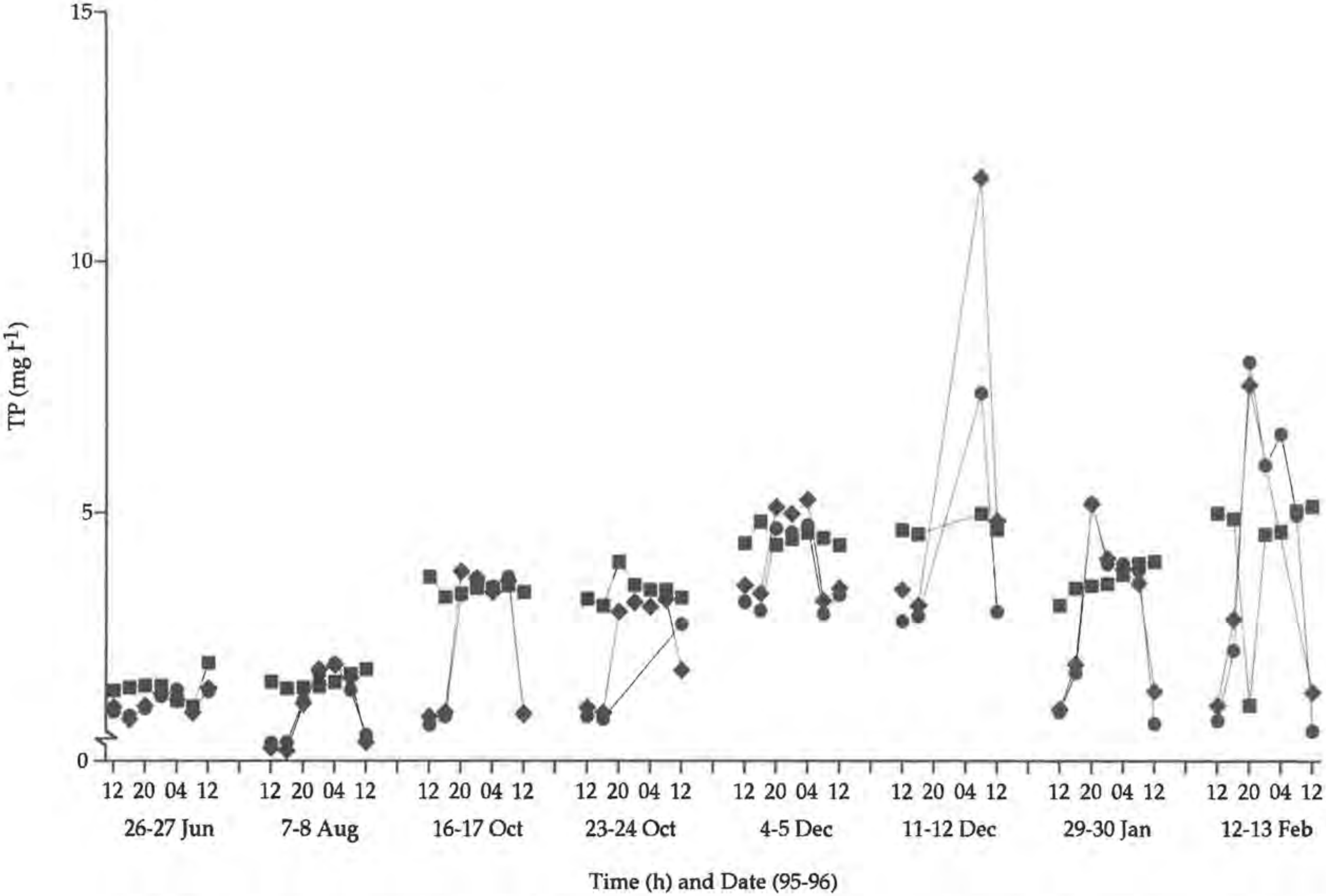
24 hour variation of total kjeldahl nitrogen of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



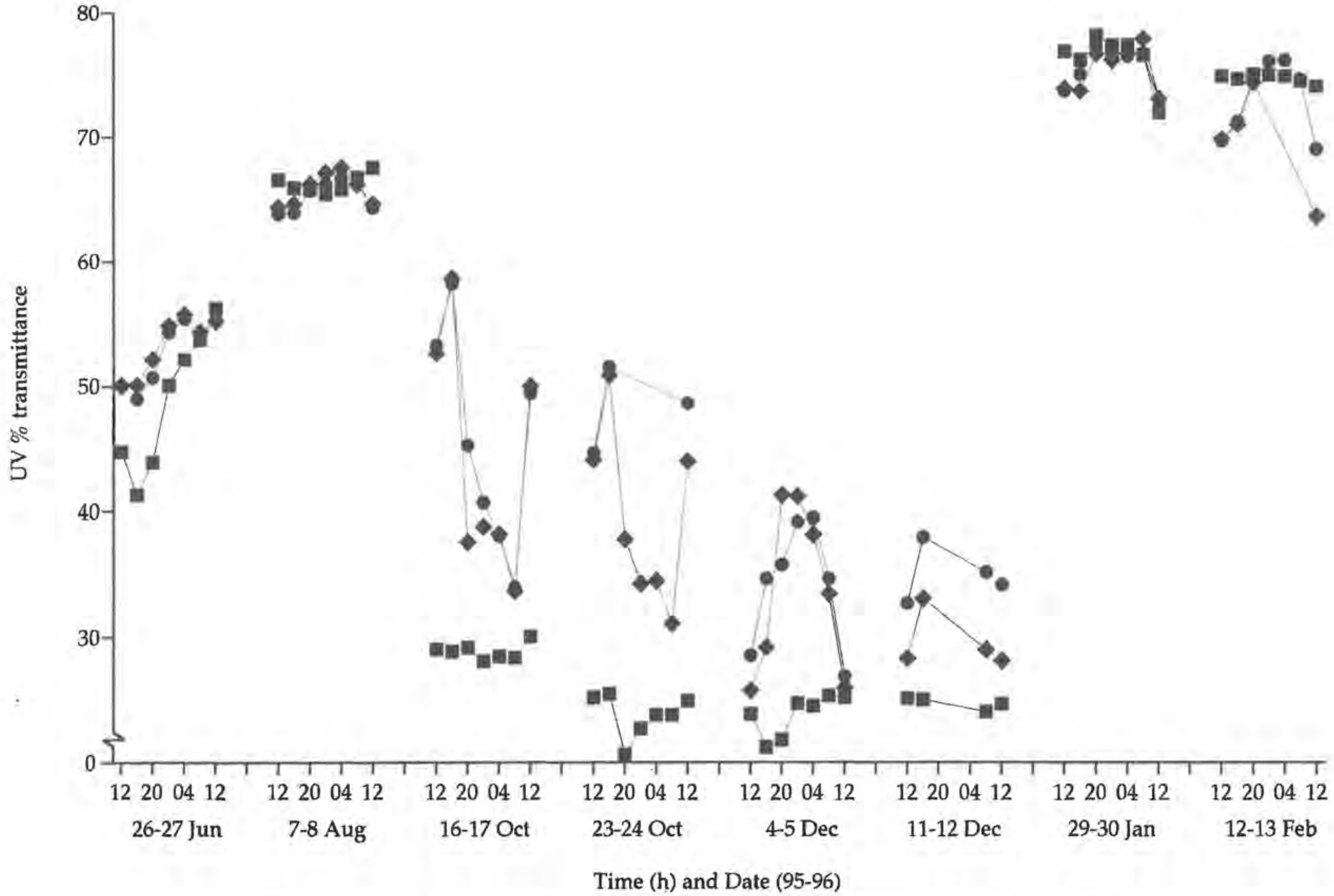
24 hour variation of soluble reactive phosphorus of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



24 hour variation of particulate phosphorus of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



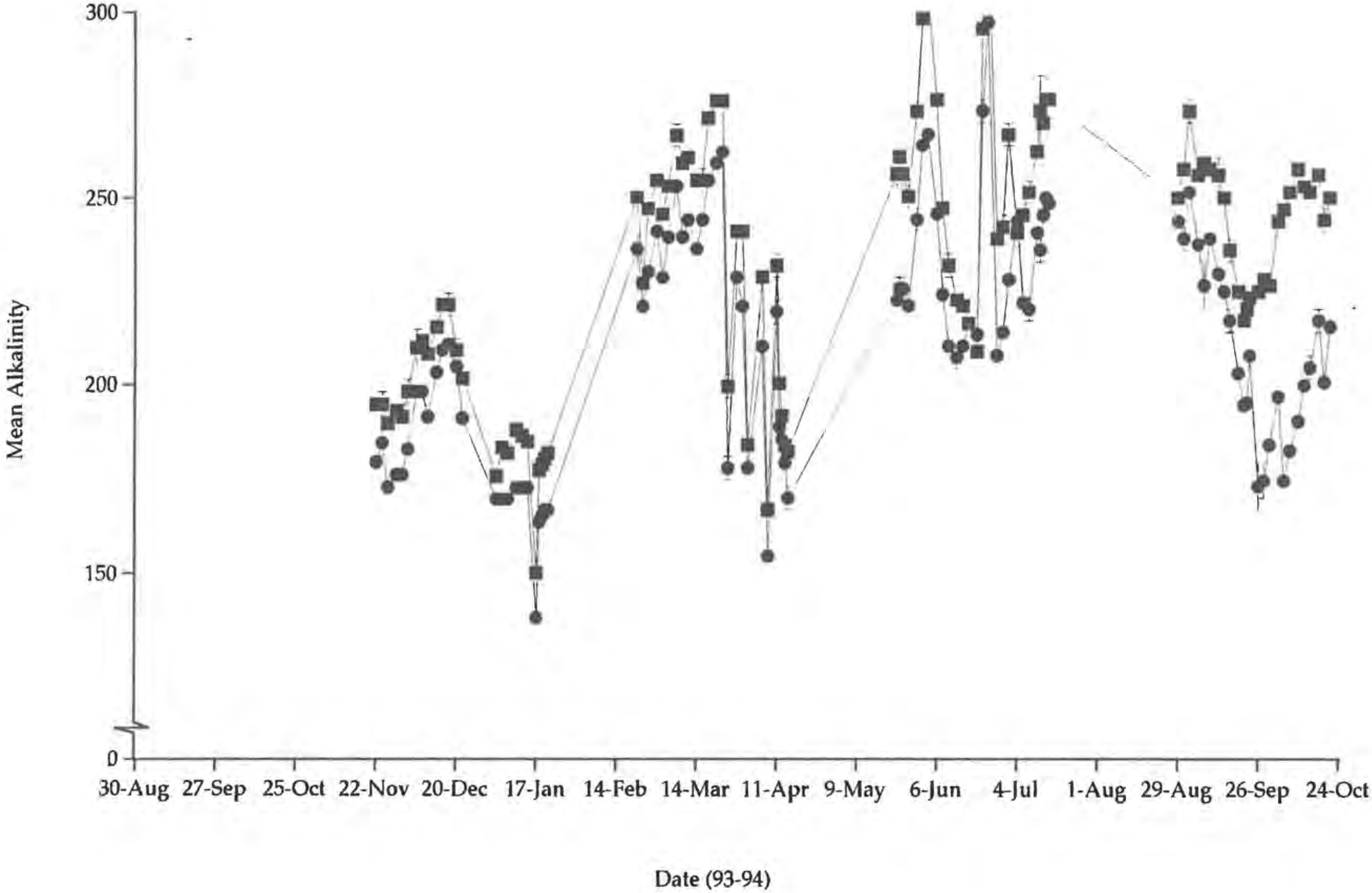
24 hour variation of total phosphorus of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.



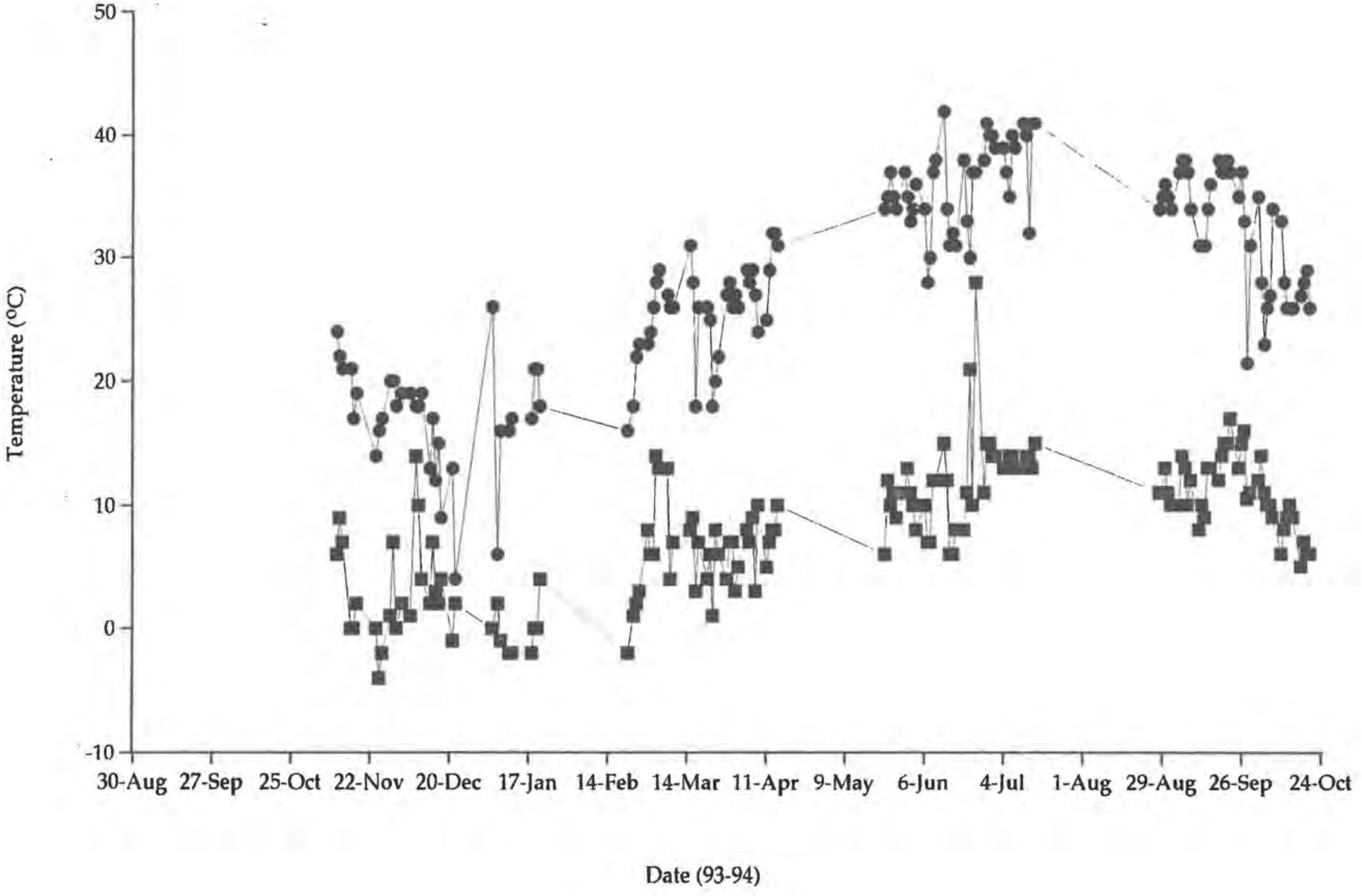
24 hour variation of UV % transmittance of influent (■), west effluent (◆) and east effluent (●) of the split ATS floway.

Appe

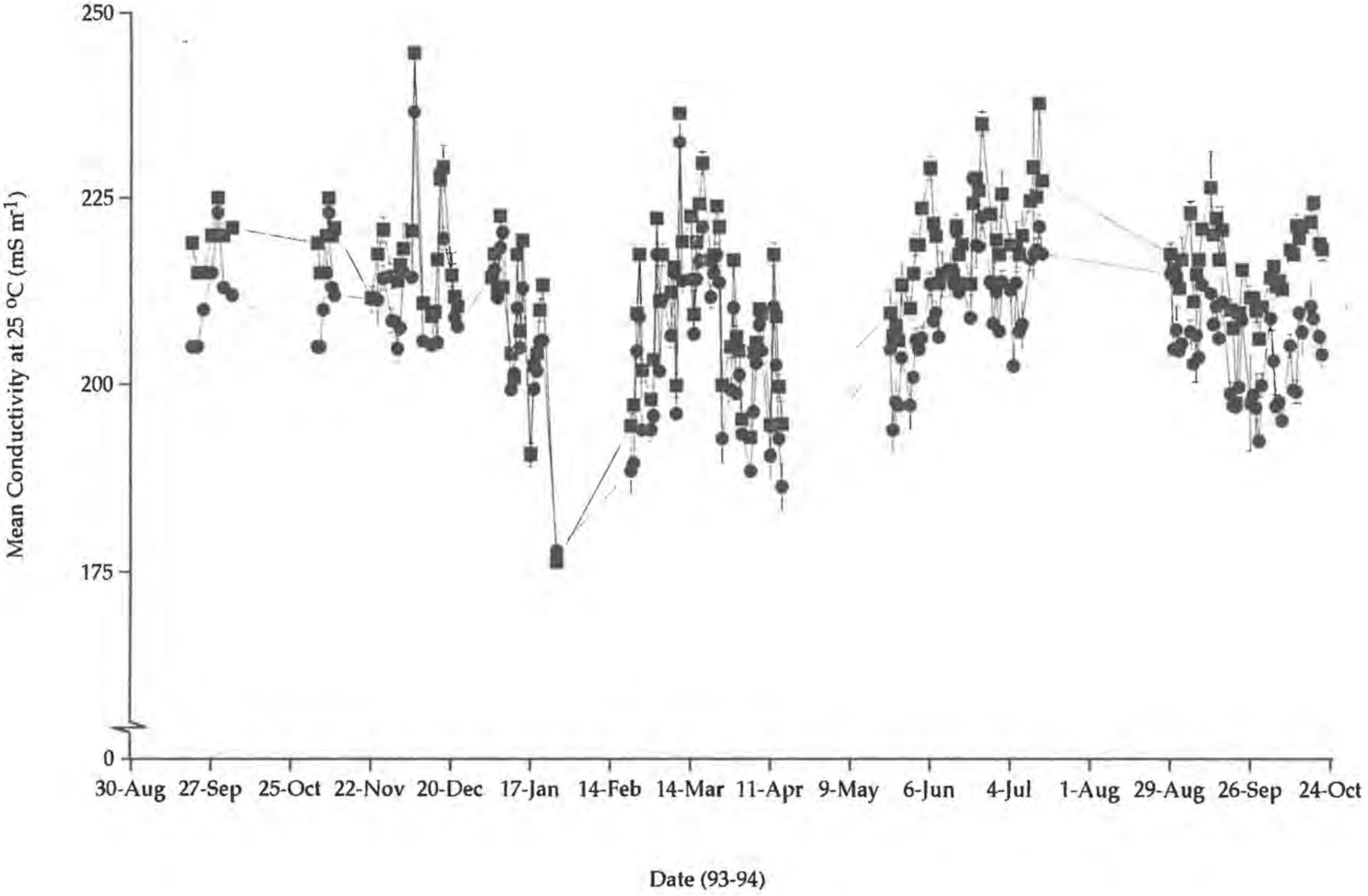
Appendix 3



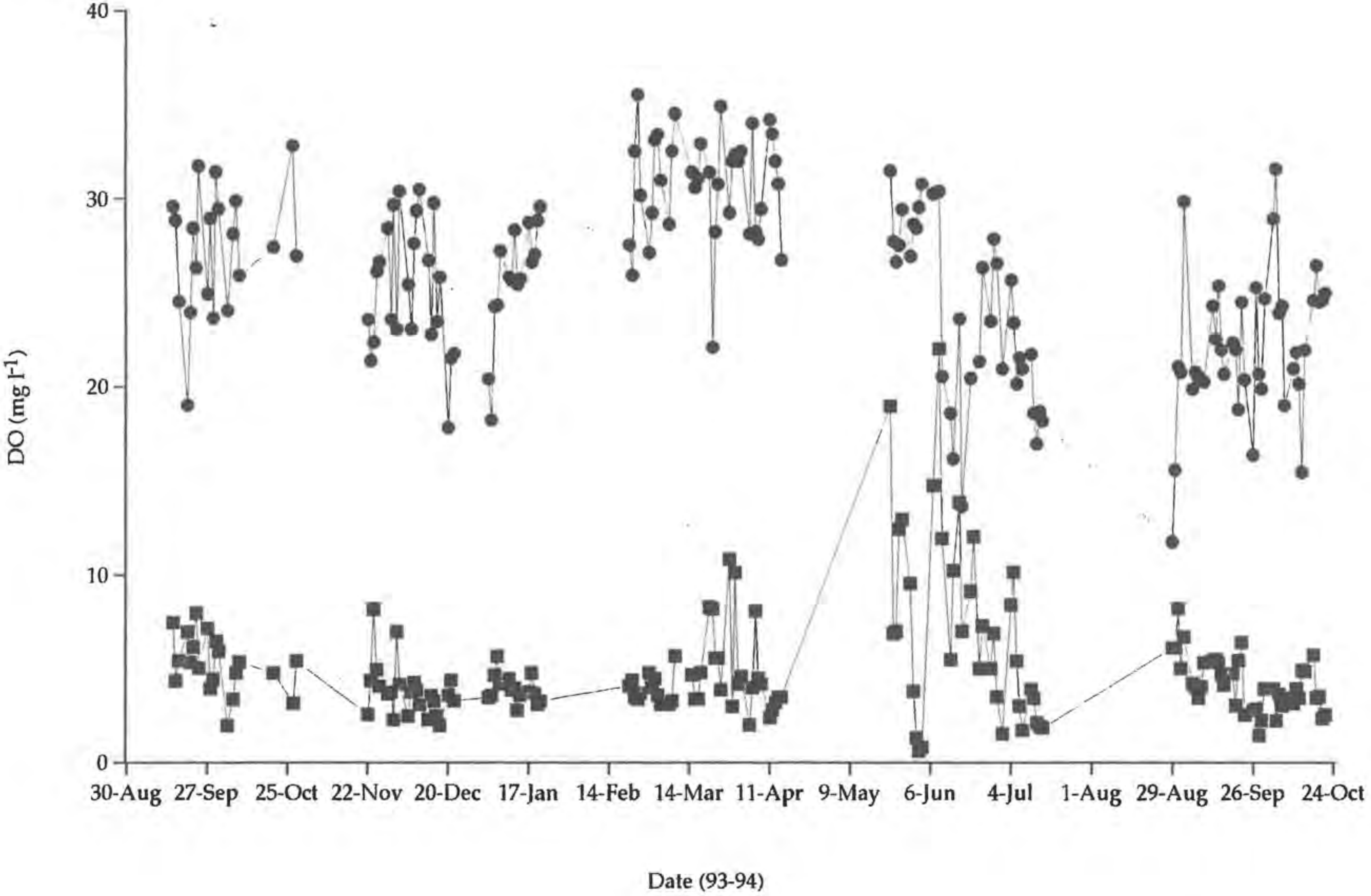
Alkalinity of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



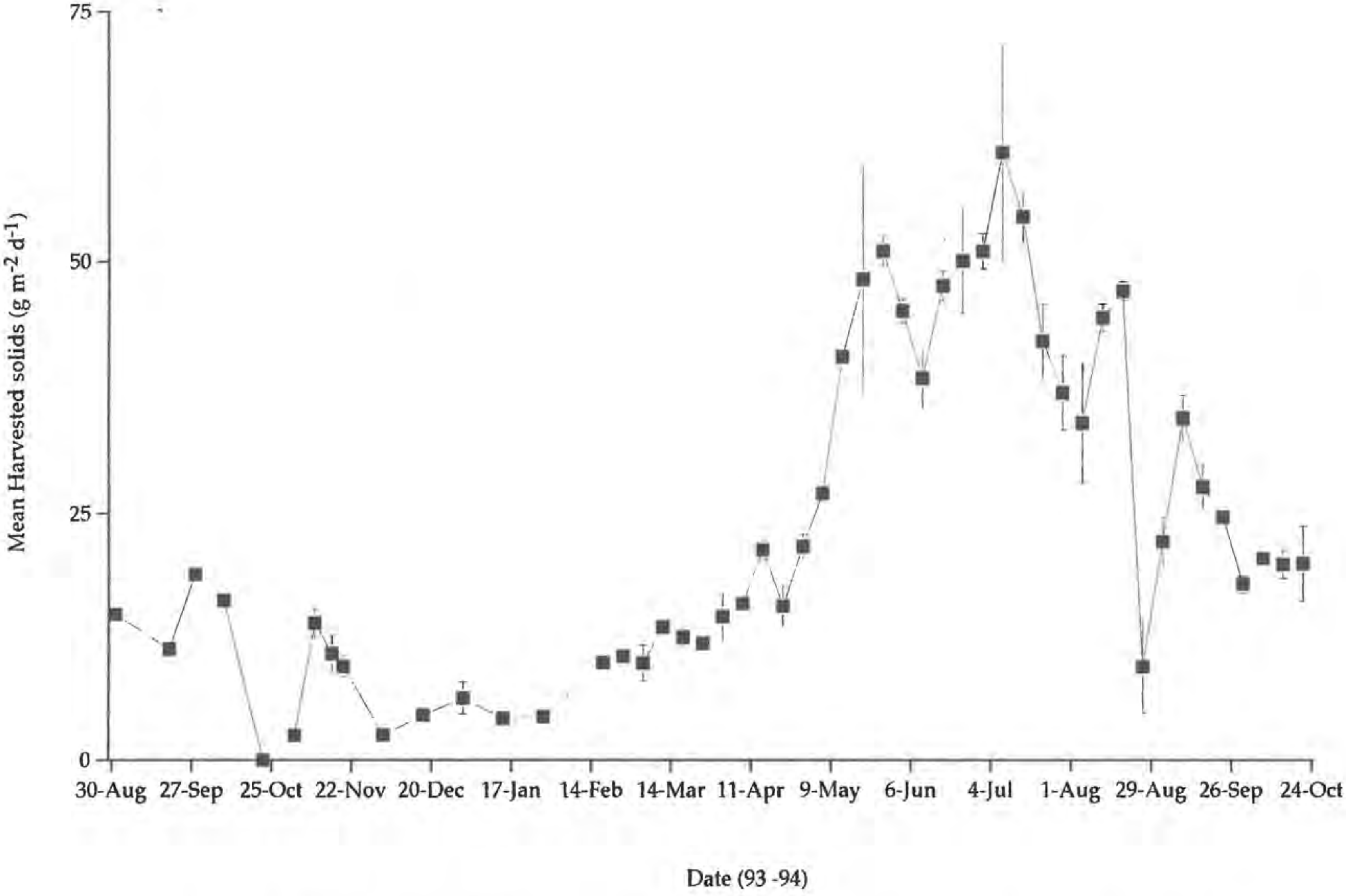
Minimum (■) and maximum (●) ambient temperature .



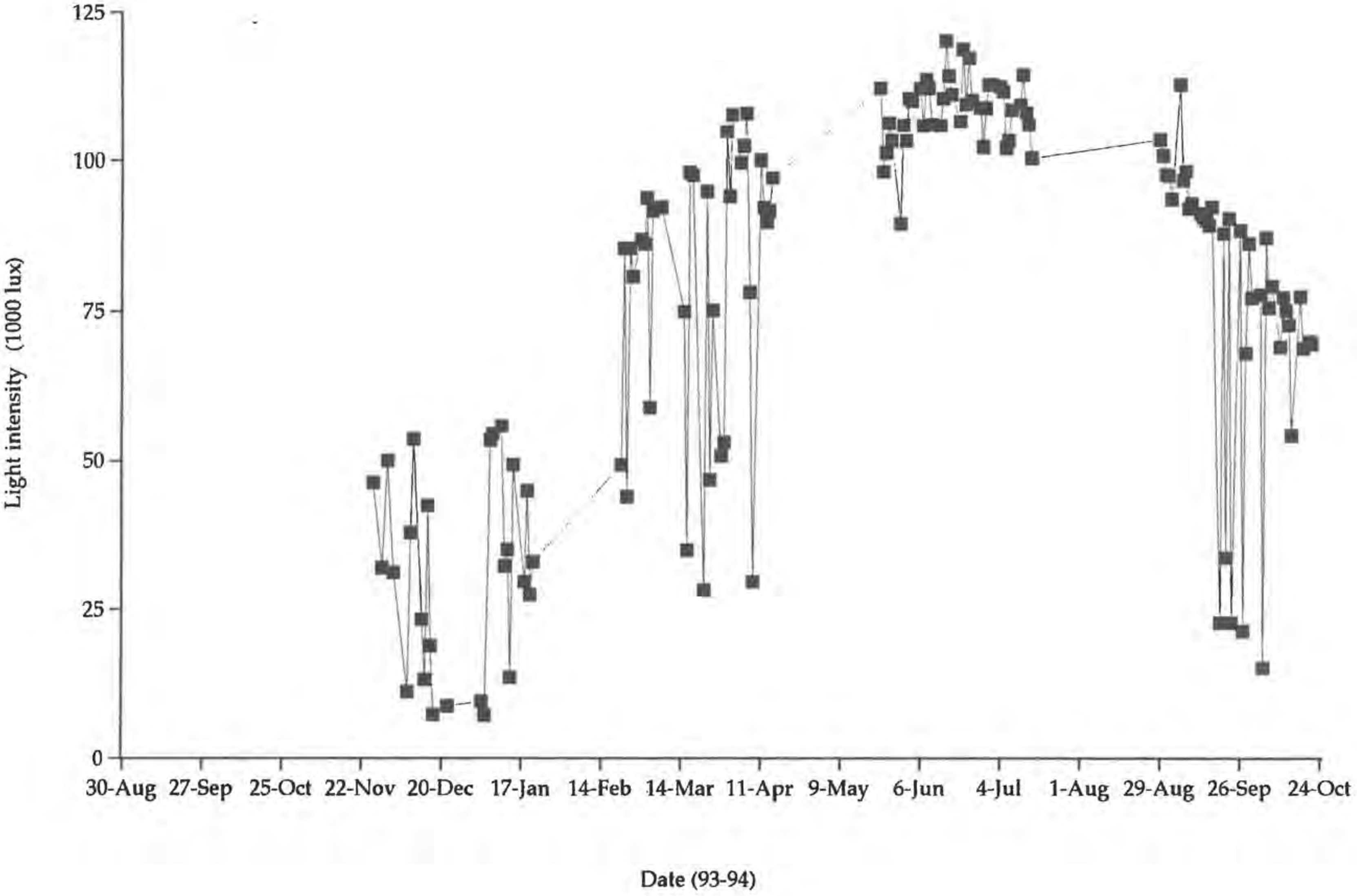
Conductivity of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



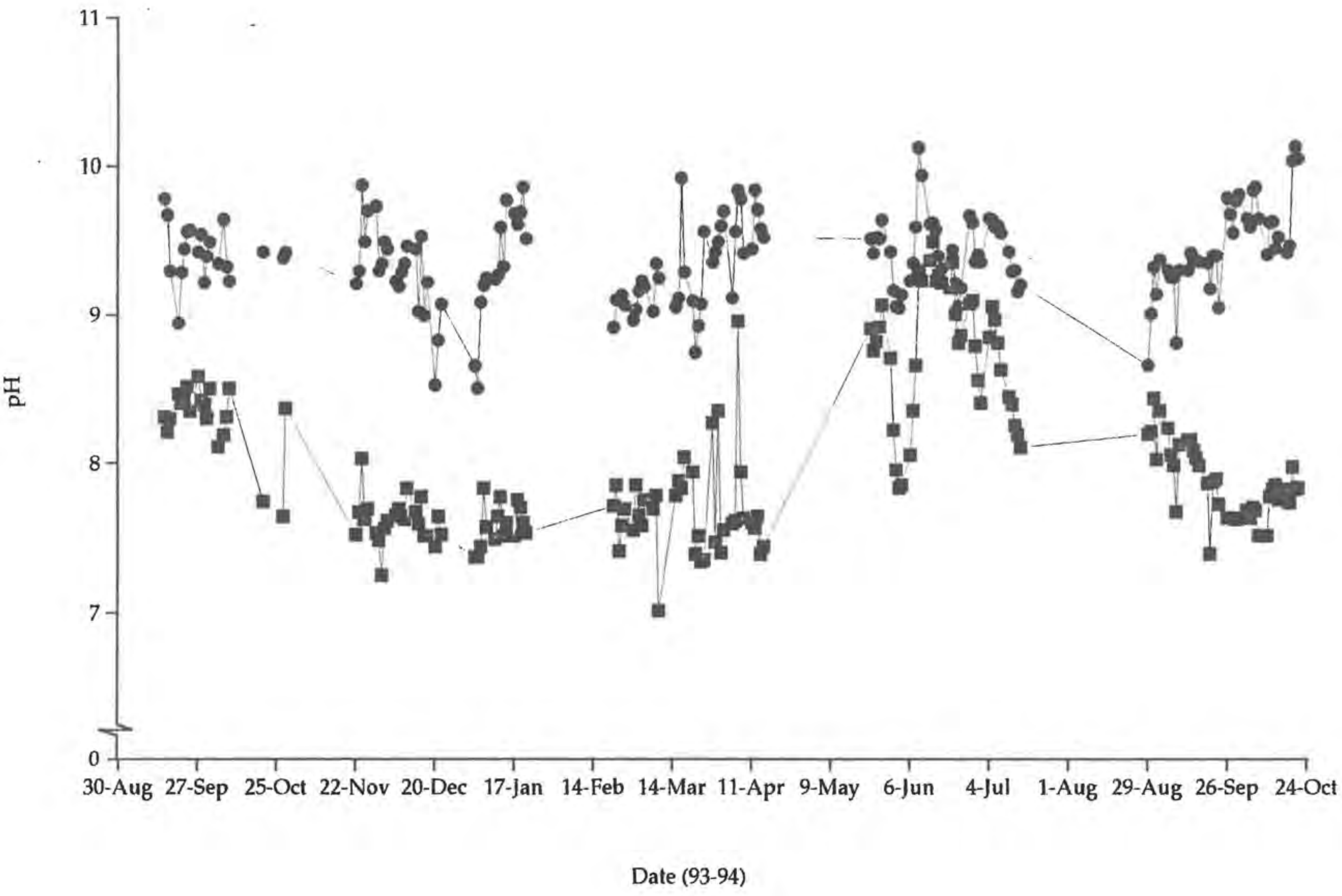
Dissolved Oxygen of influent (■) and effluent (●) of the ATS/UV system.



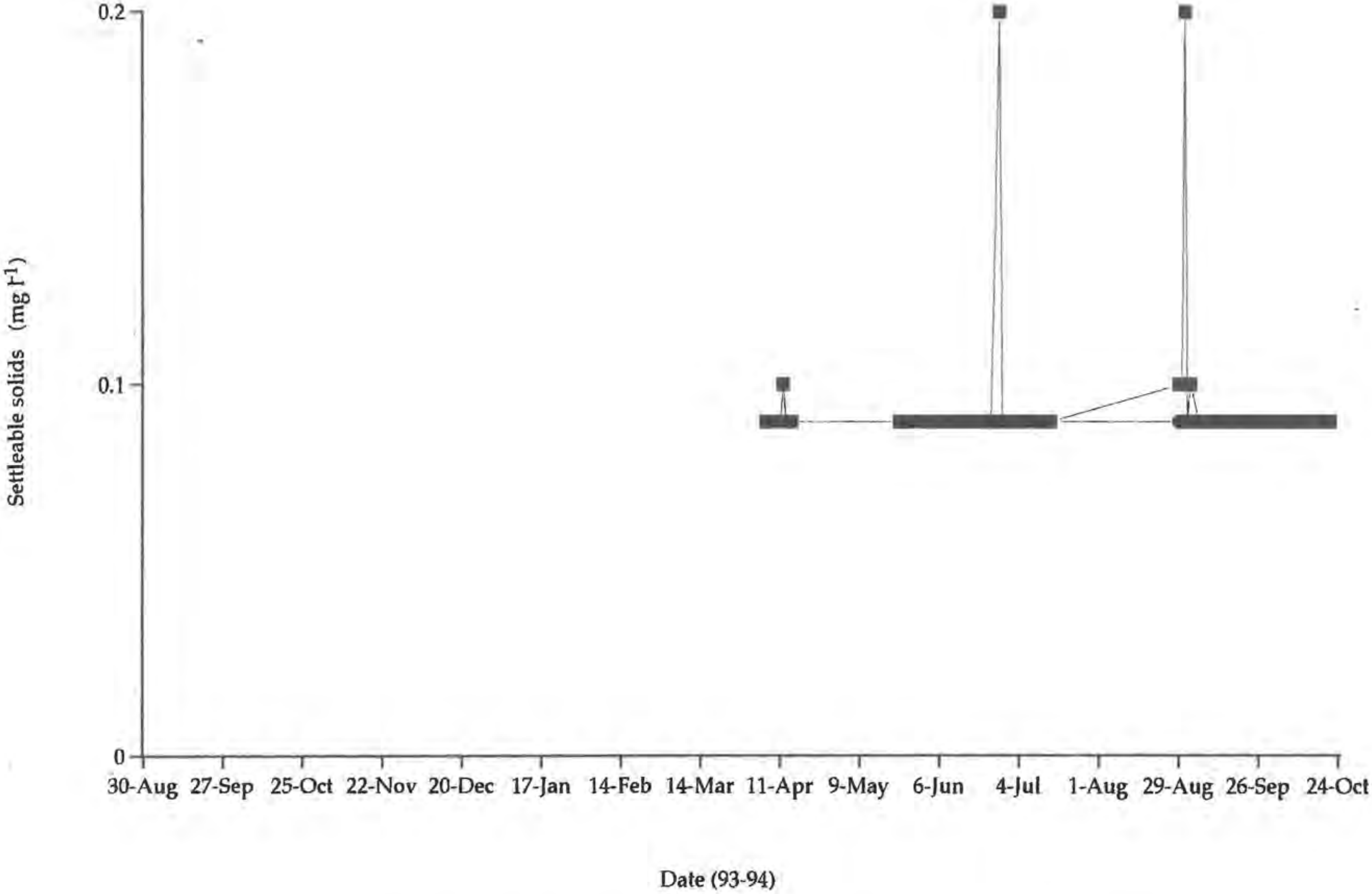
Harvested solids from the ATS. Values are means ± s.d. of two composite samples, each from five sites.



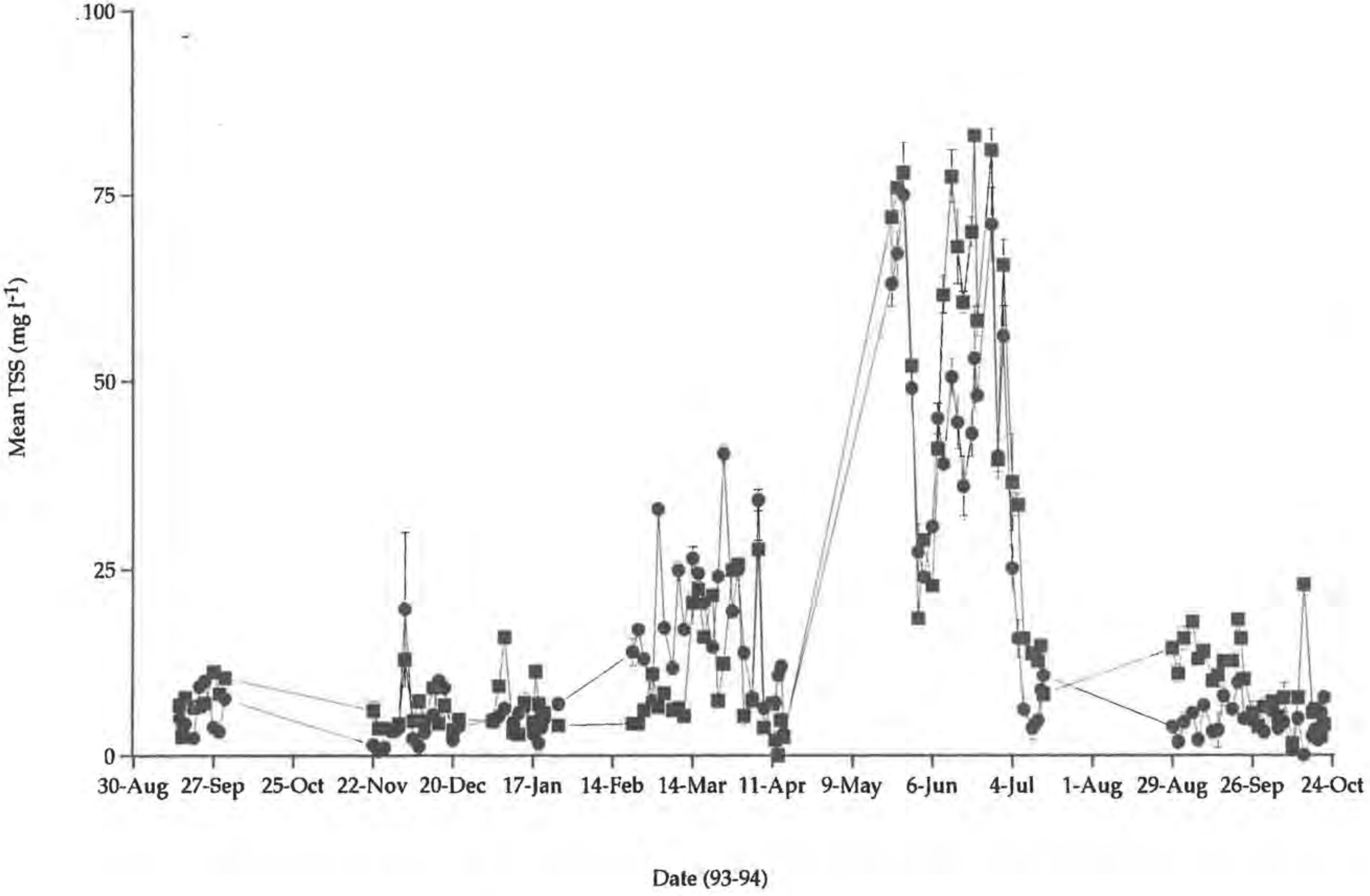
Light intensity measured at time of sampling (11.00 am) .



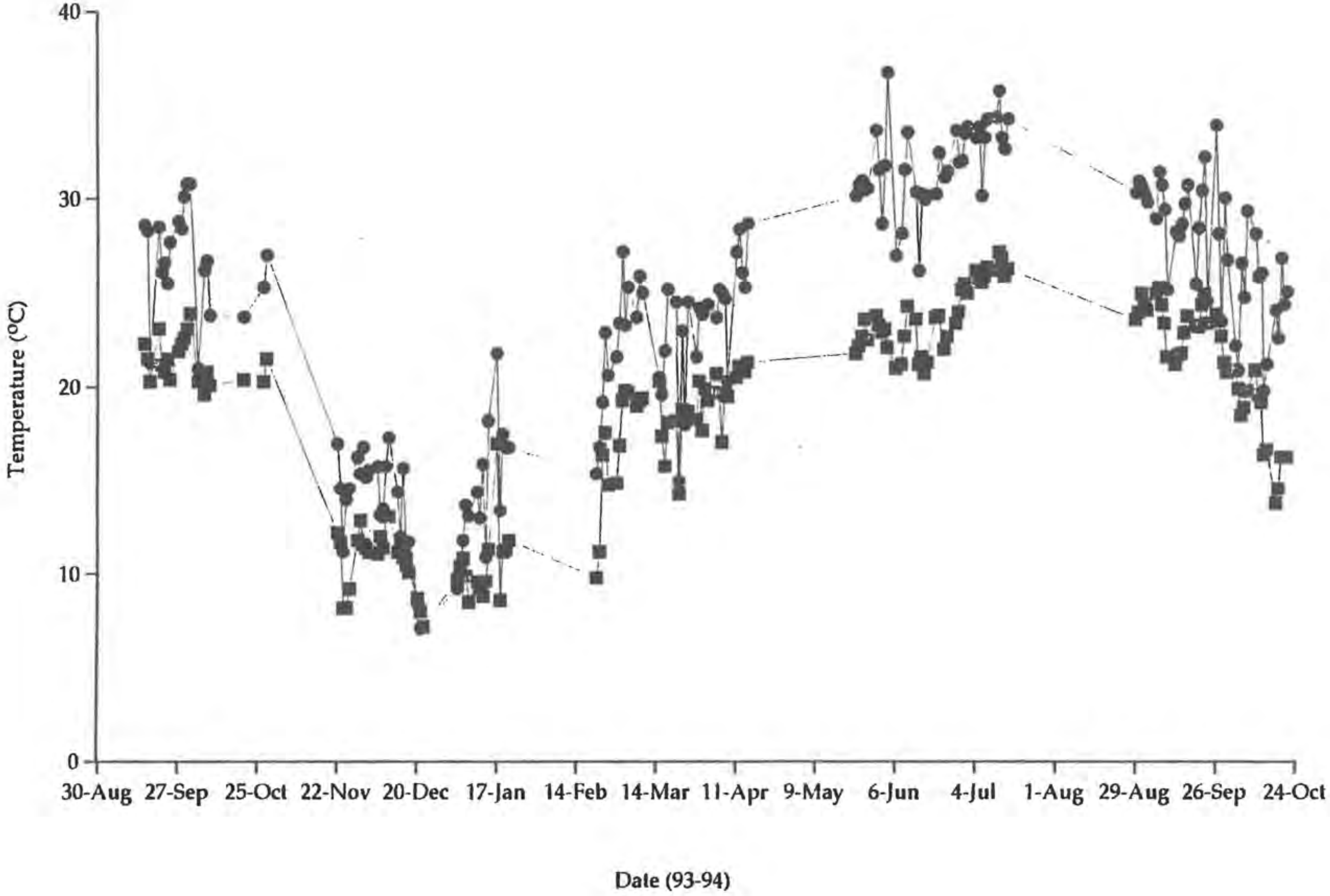
pH of influent (■) and effluent (●) of the ATS/UV system.



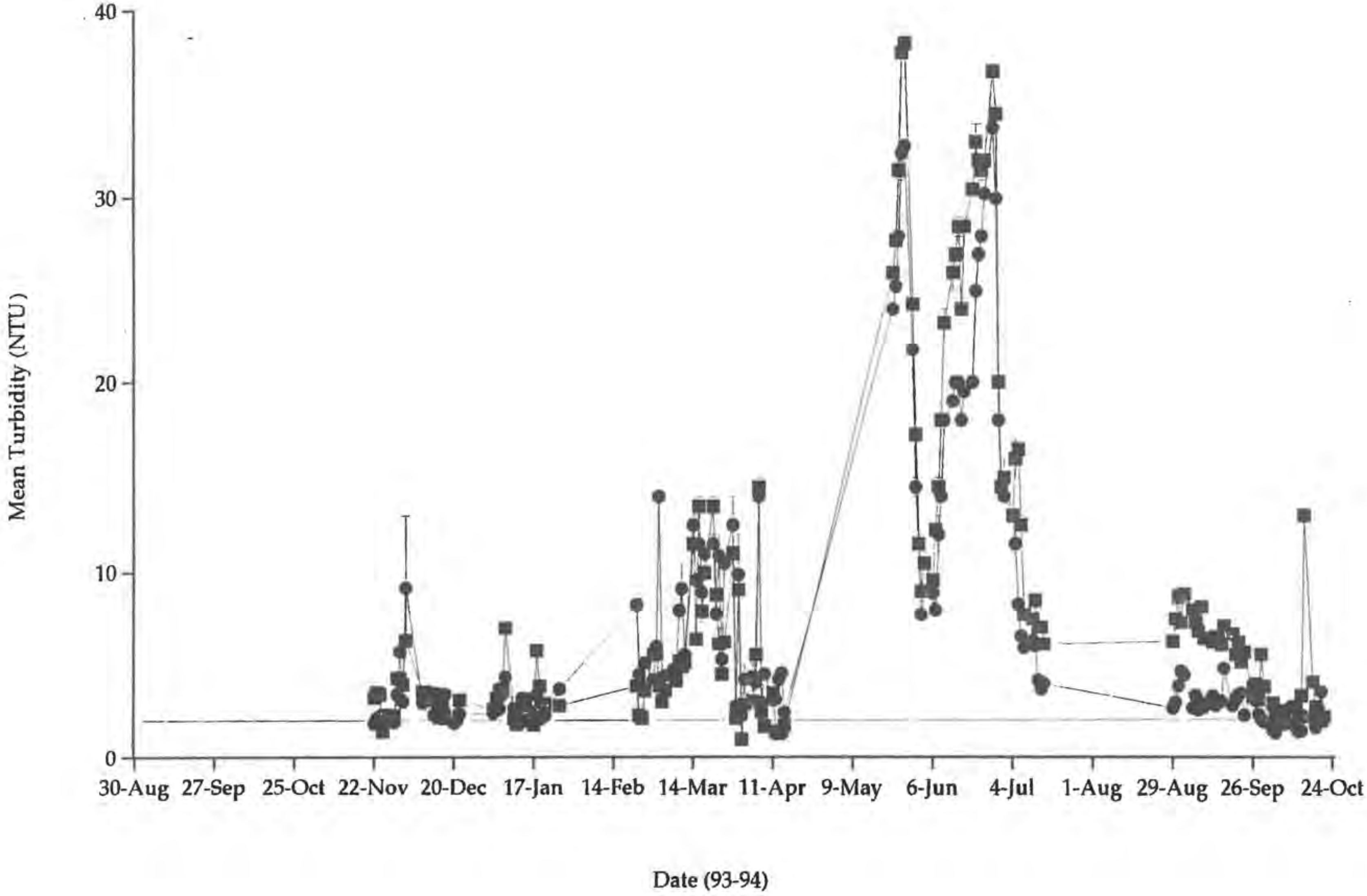
Settleable solidsof influent (■) and effluent (●) of the ATS/UV system .



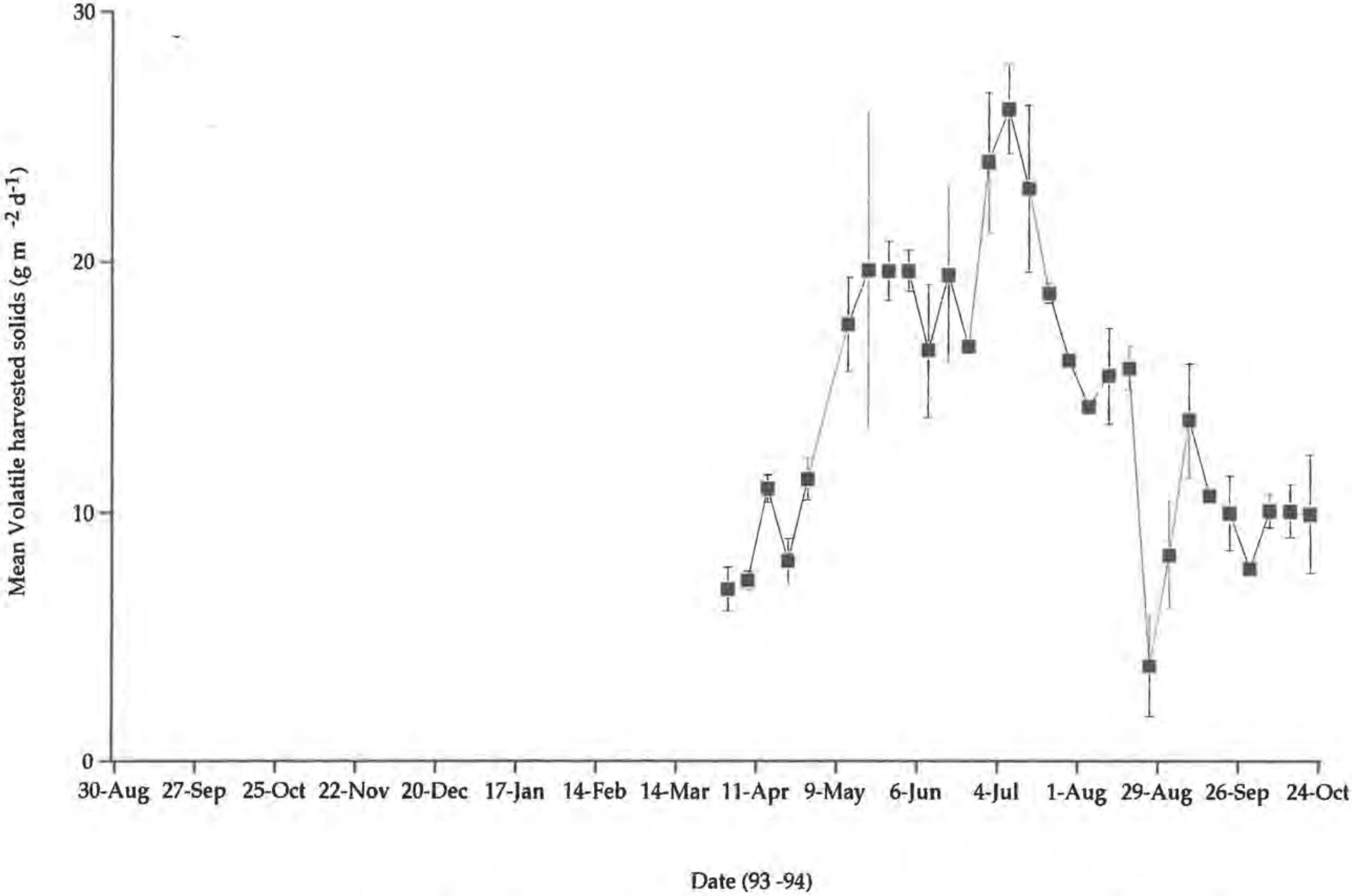
Total suspended solids of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



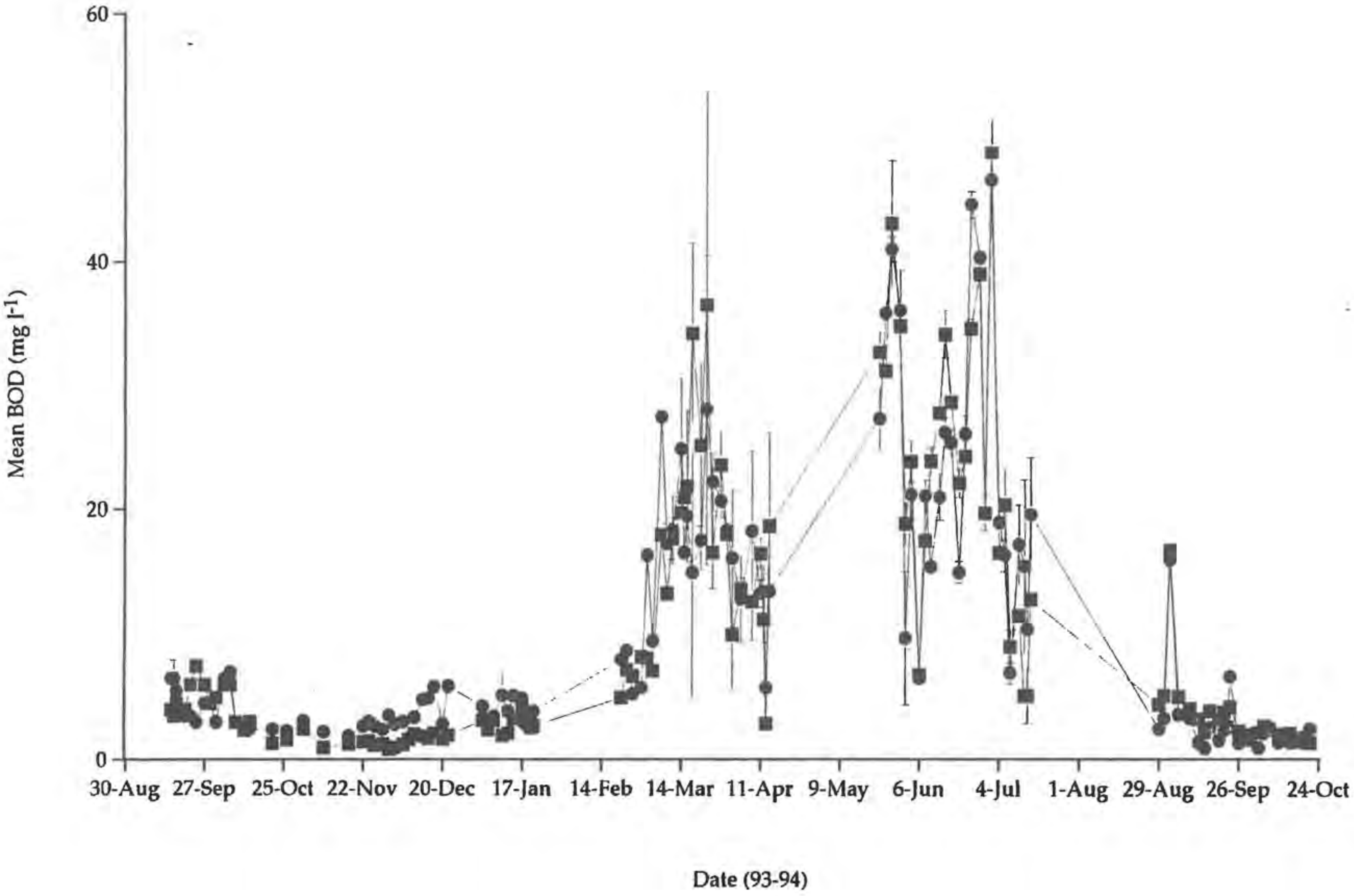
Temperature of influent (■) and effluent (●) of the ATS/UV system .



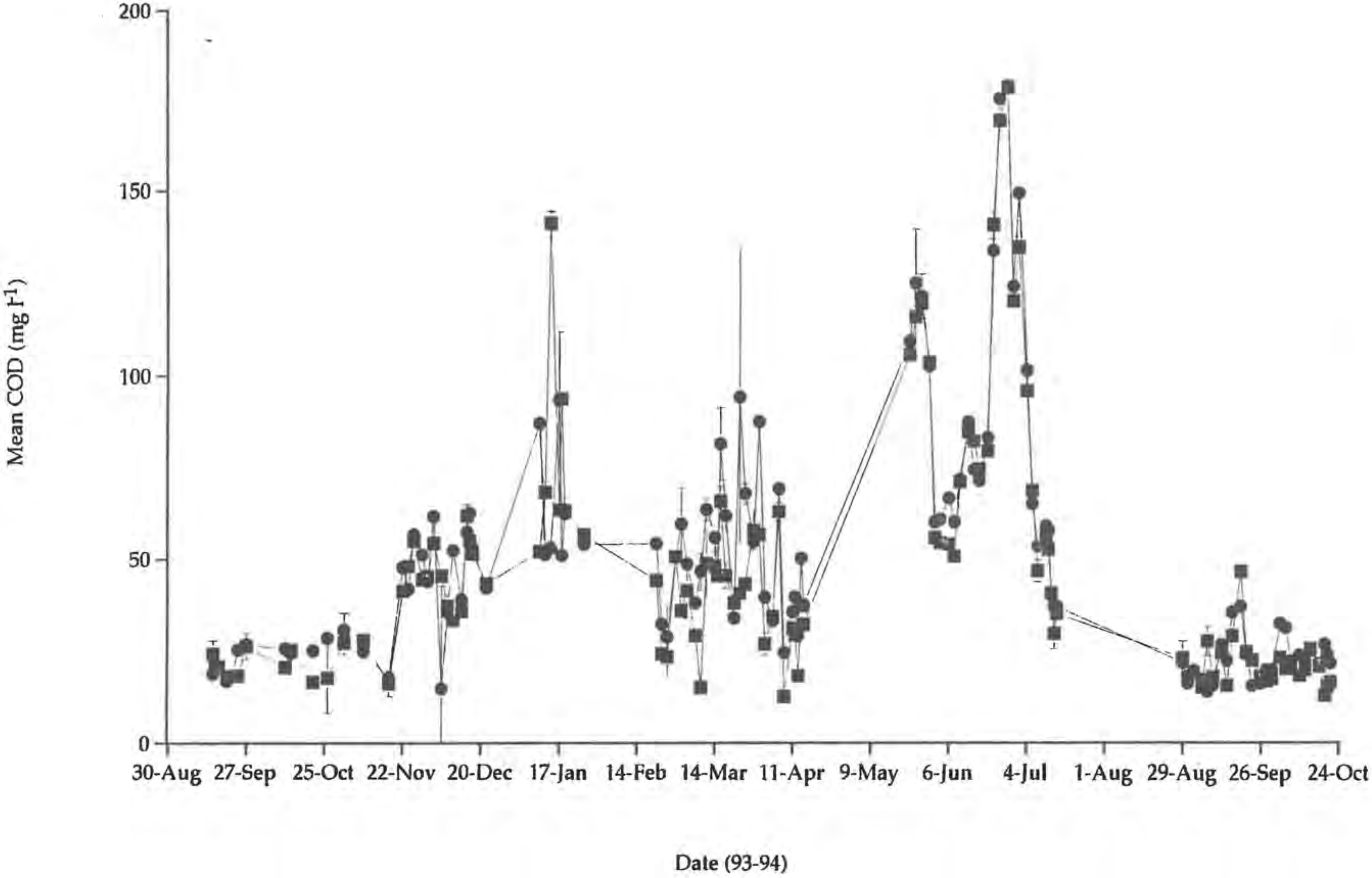
Turbidity of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



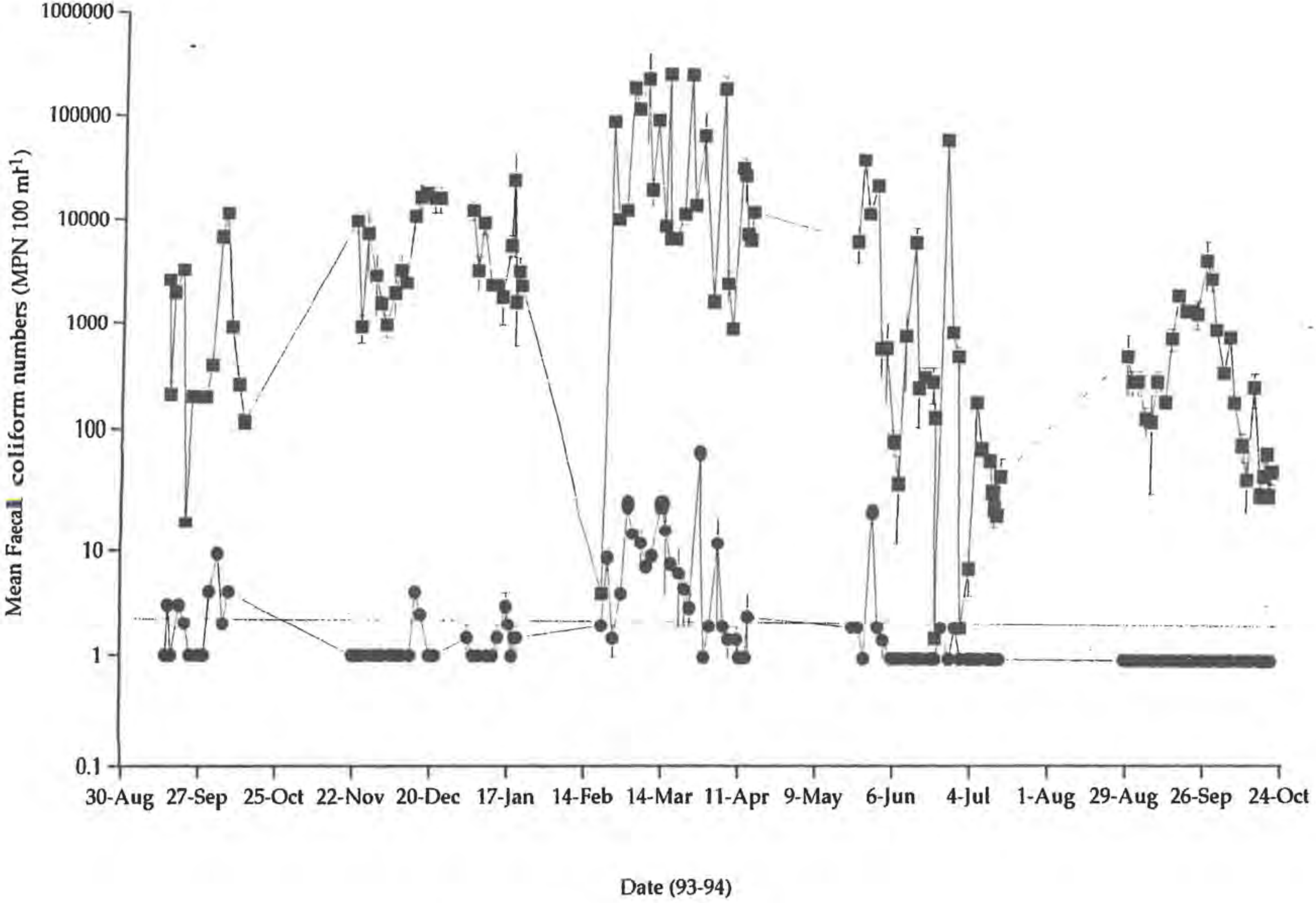
Volatile harvested solids from the ATS. Values are means ± s.d. of two composite samples, each from five sites.



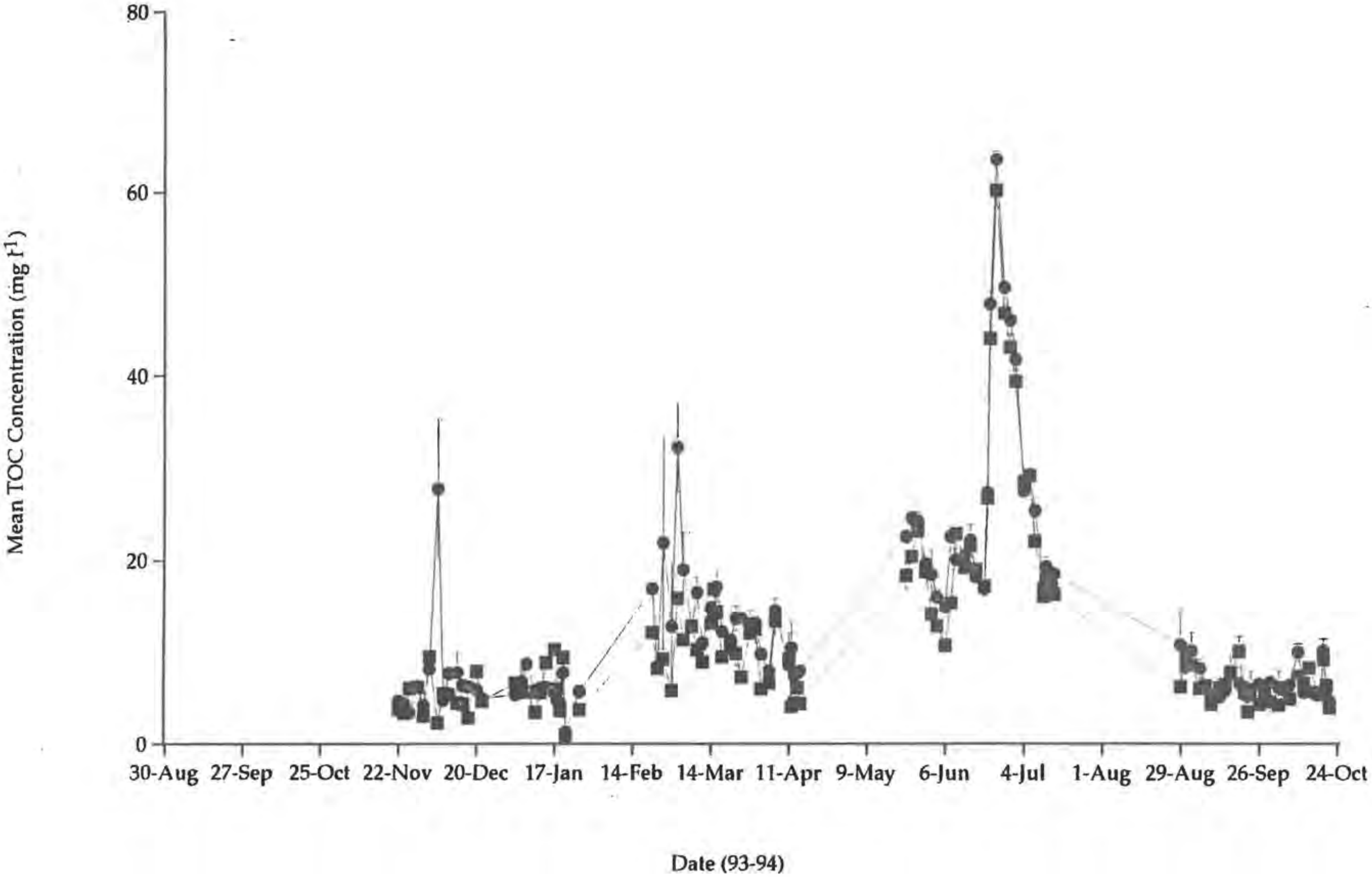
Biochemical oxygen demand of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



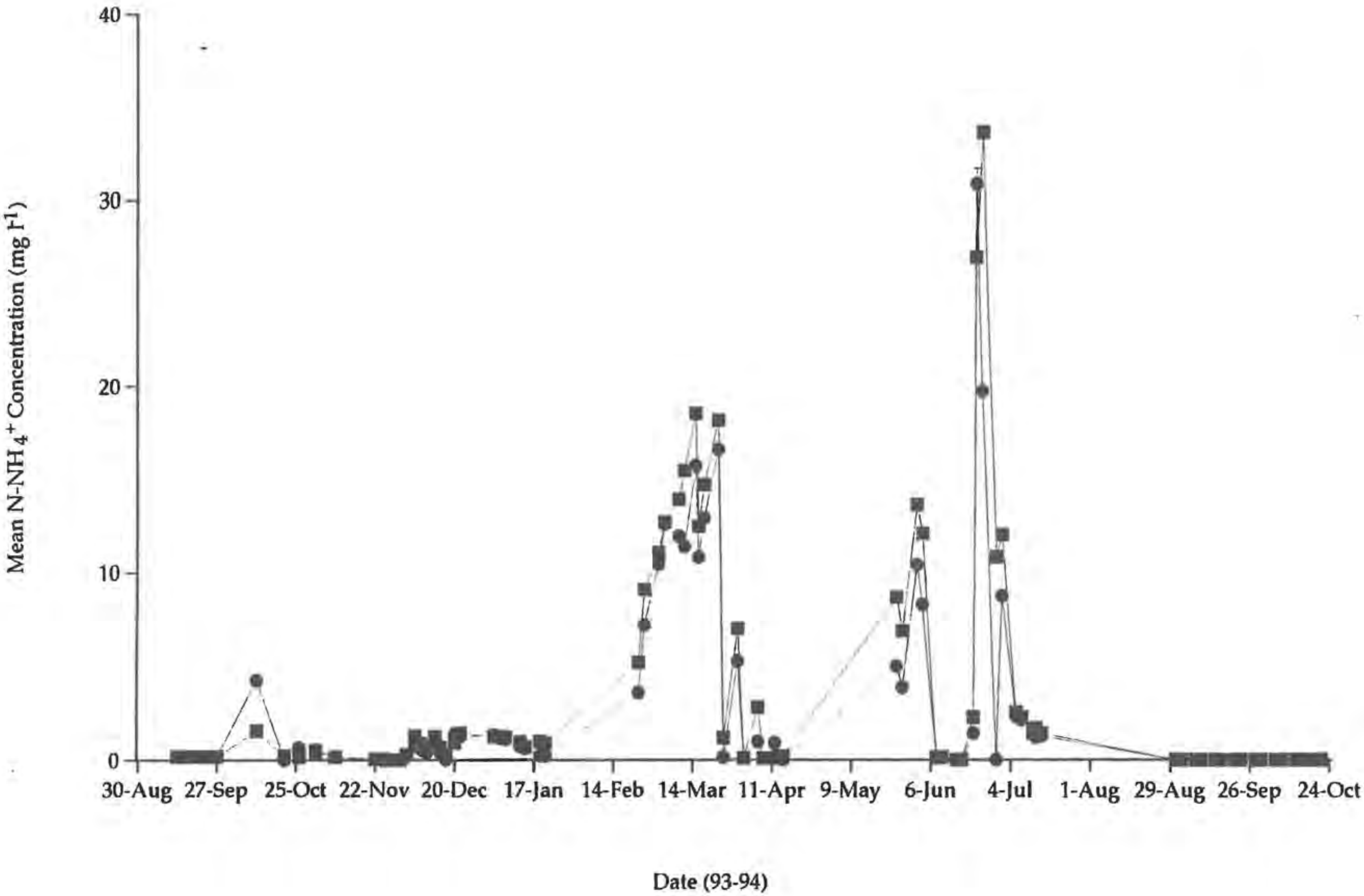
Chemical oxygen demand of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



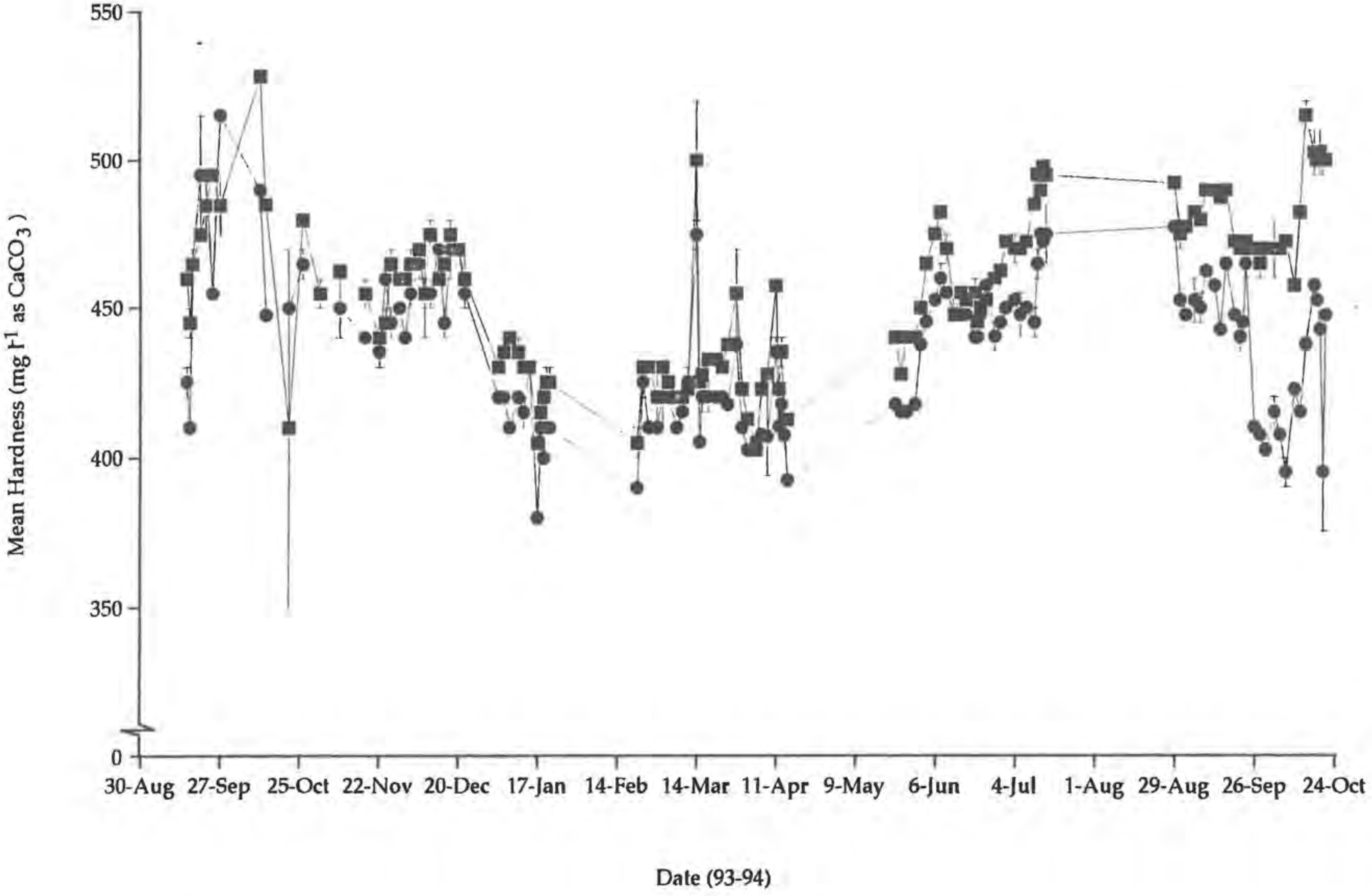
Faecal coliform numbers of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



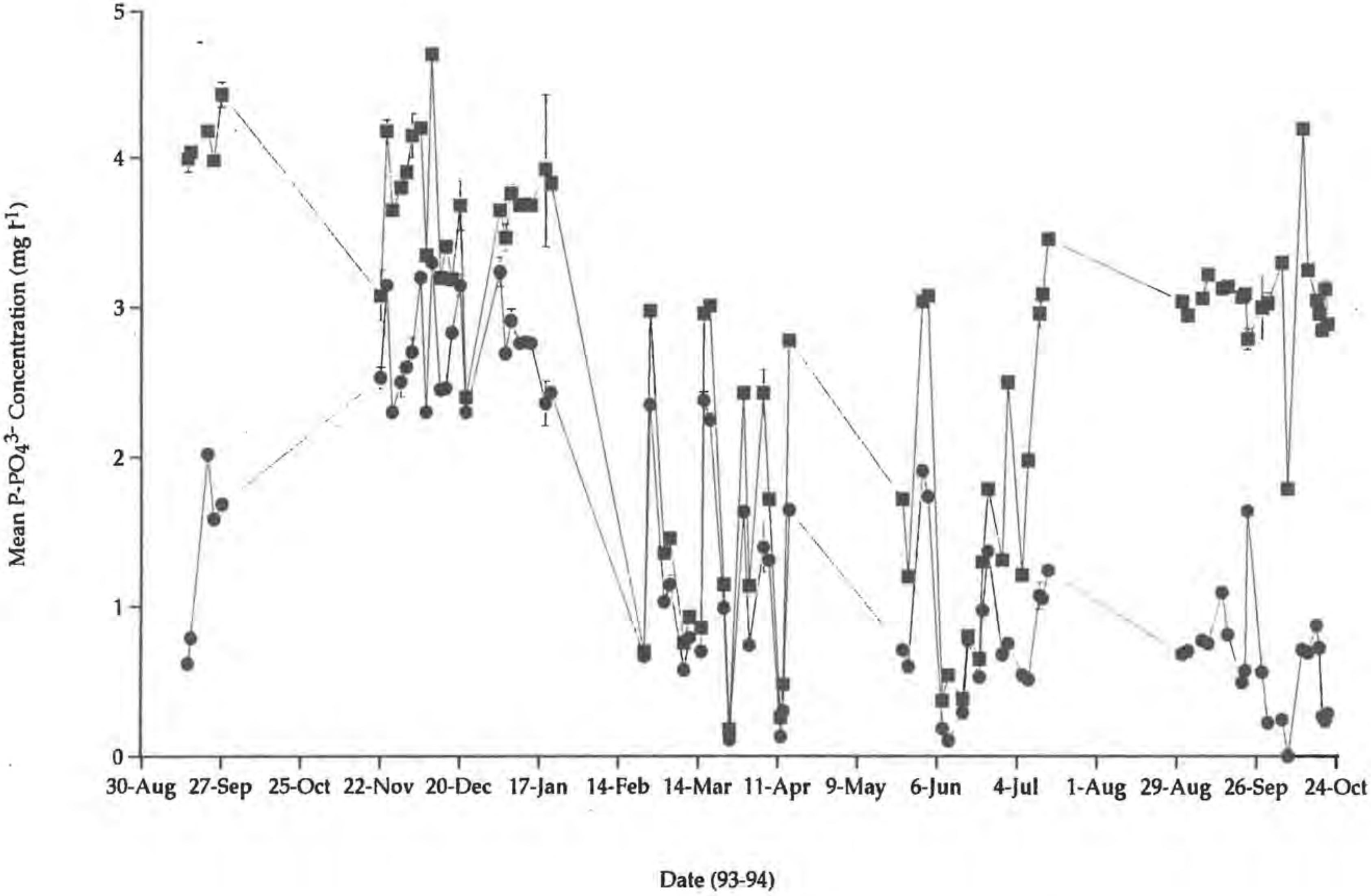
Total organic carbon concentration of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



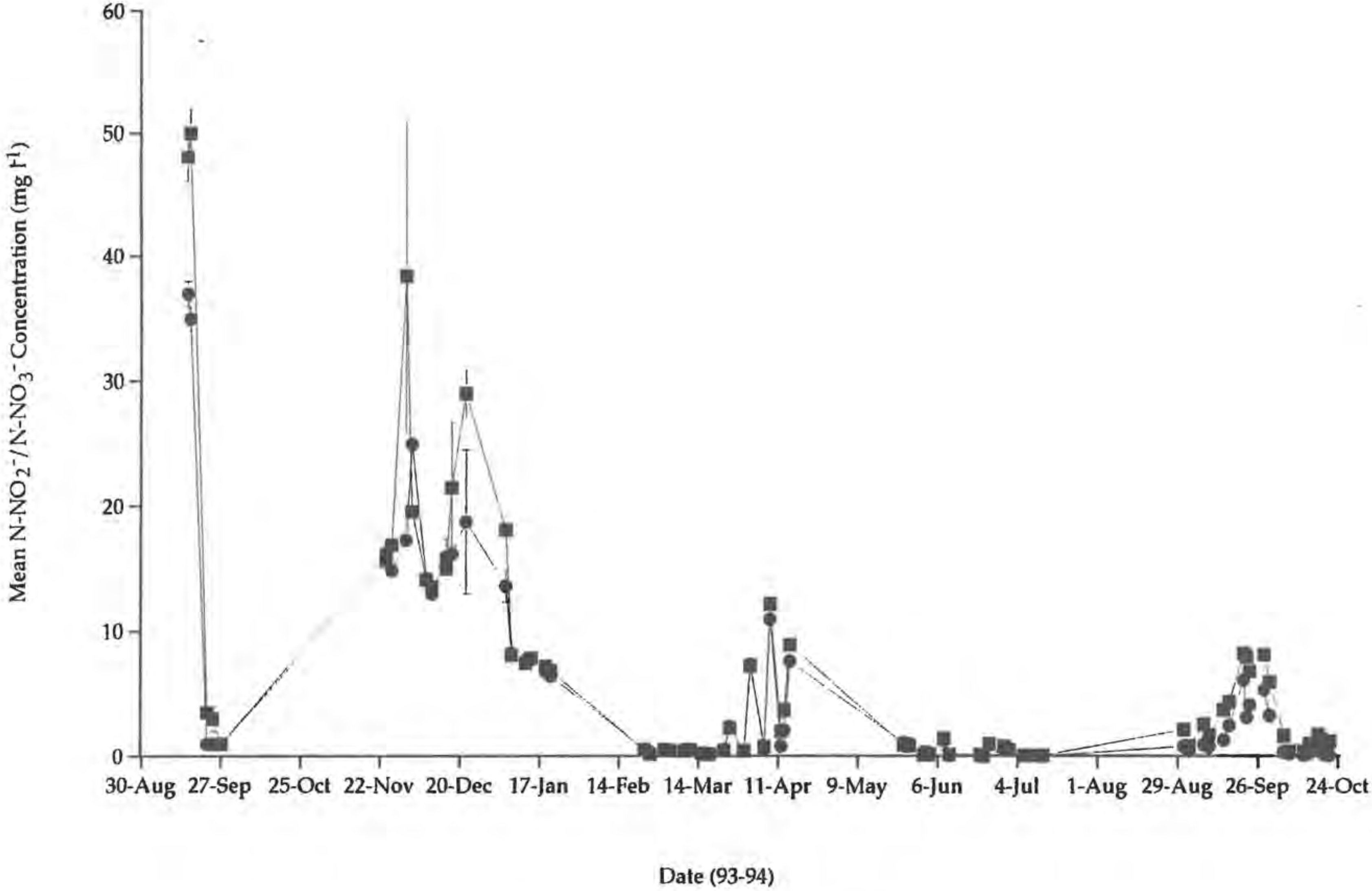
Ammonium-nitrogen concentration of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



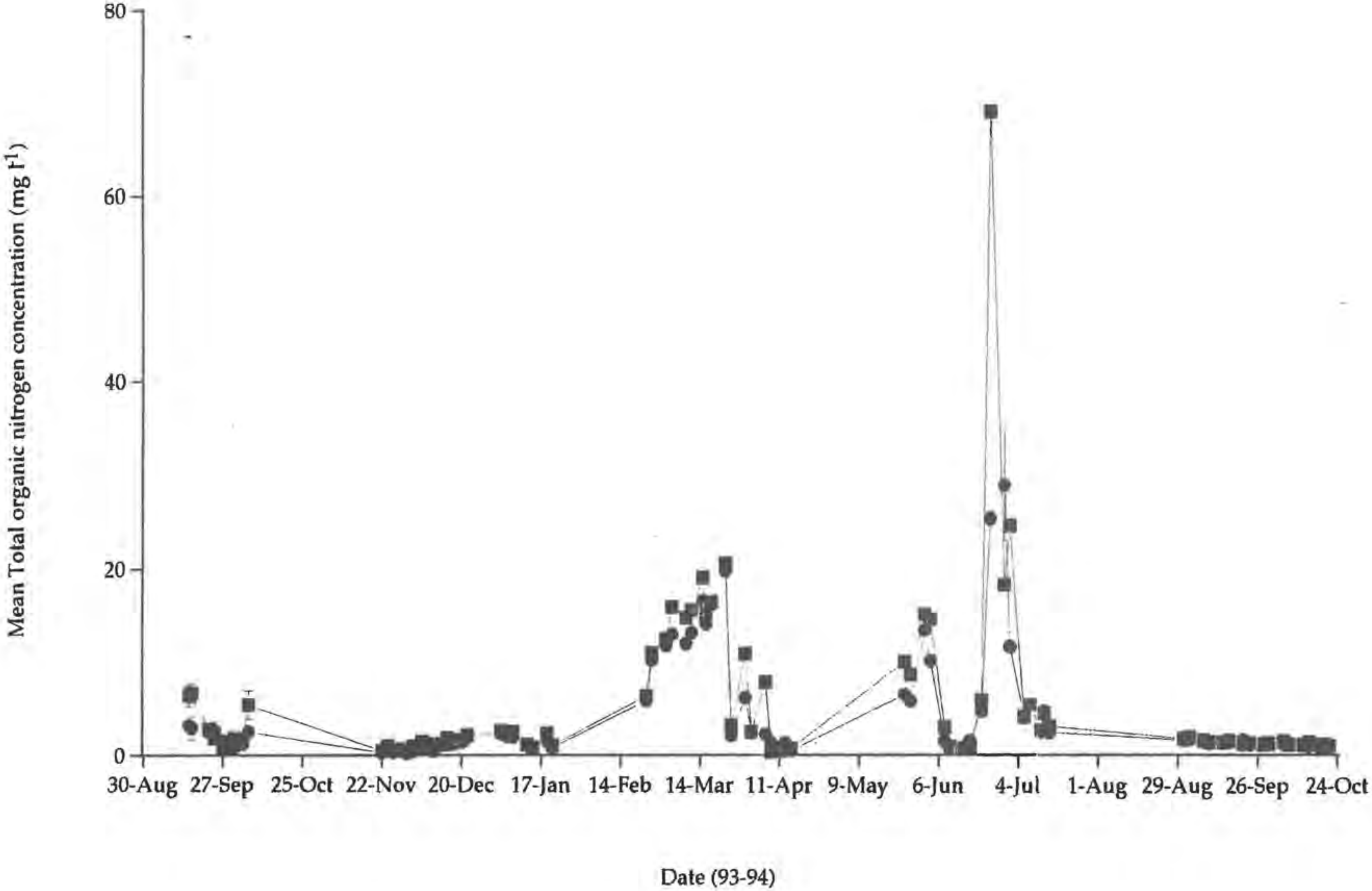
Hardness of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



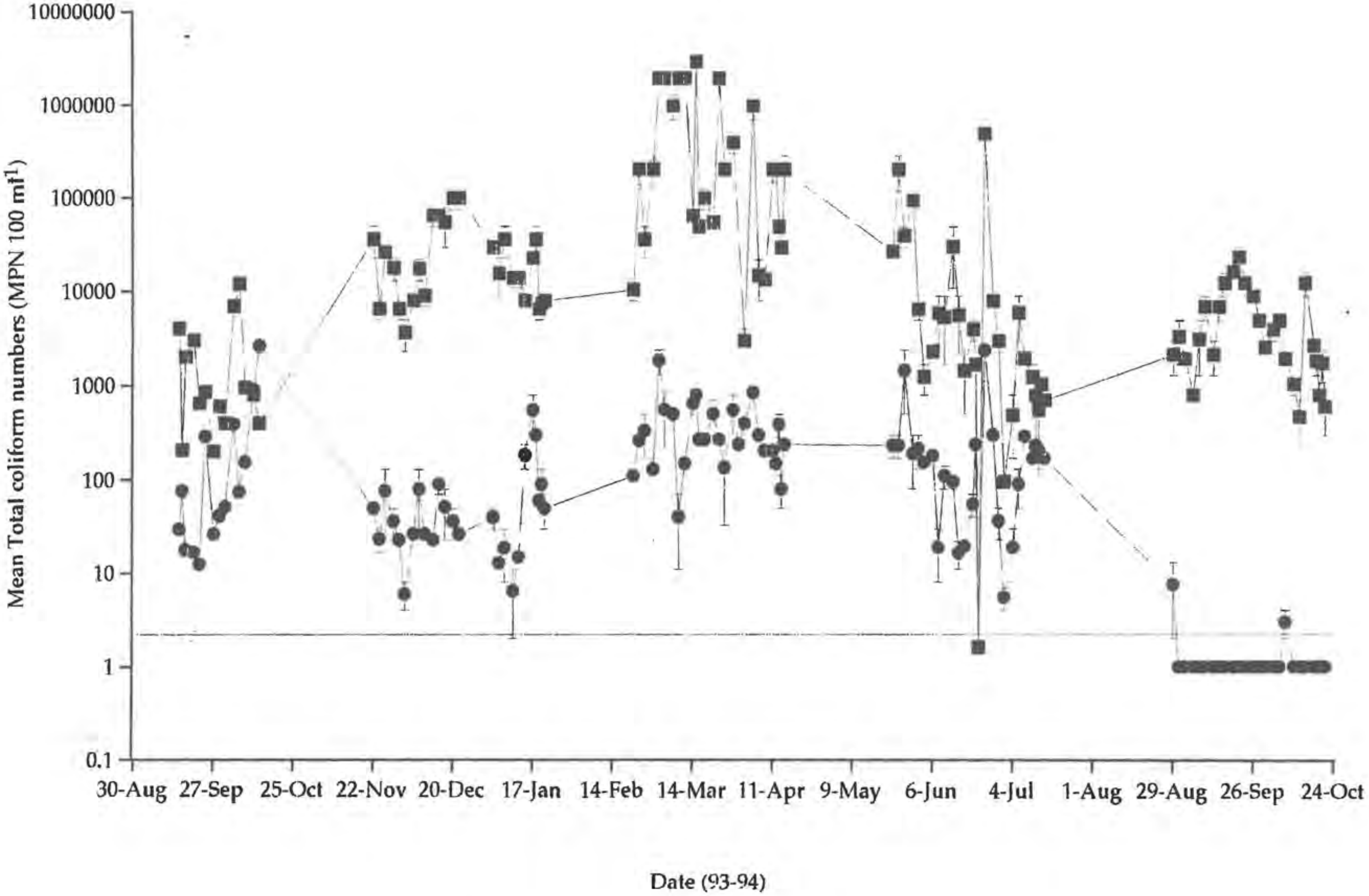
Soluble reactive phosphorus concentration of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



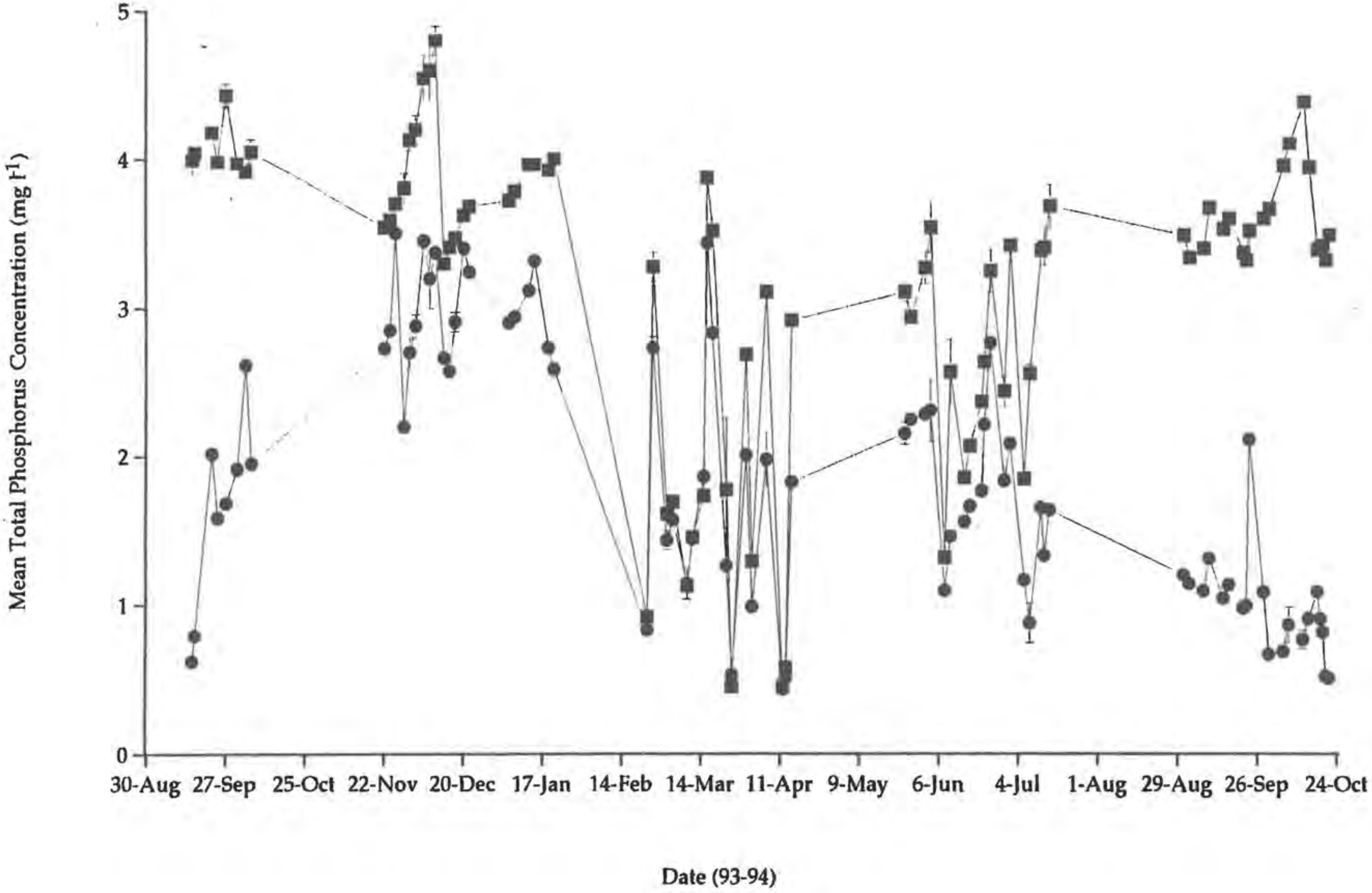
Nitrite- and Nitrate -nitrogen concentration of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



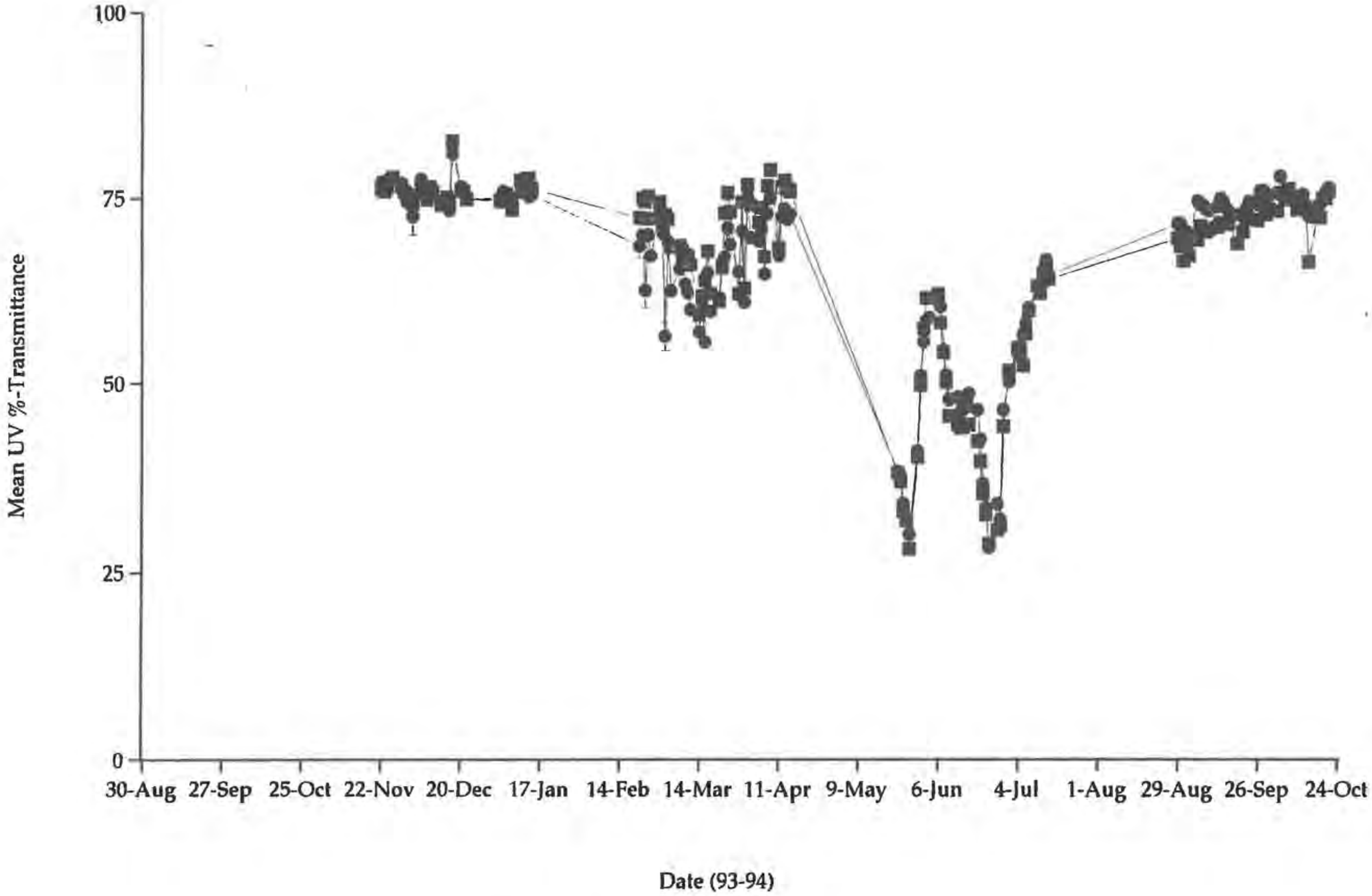
Total organic nitrogen concentration of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



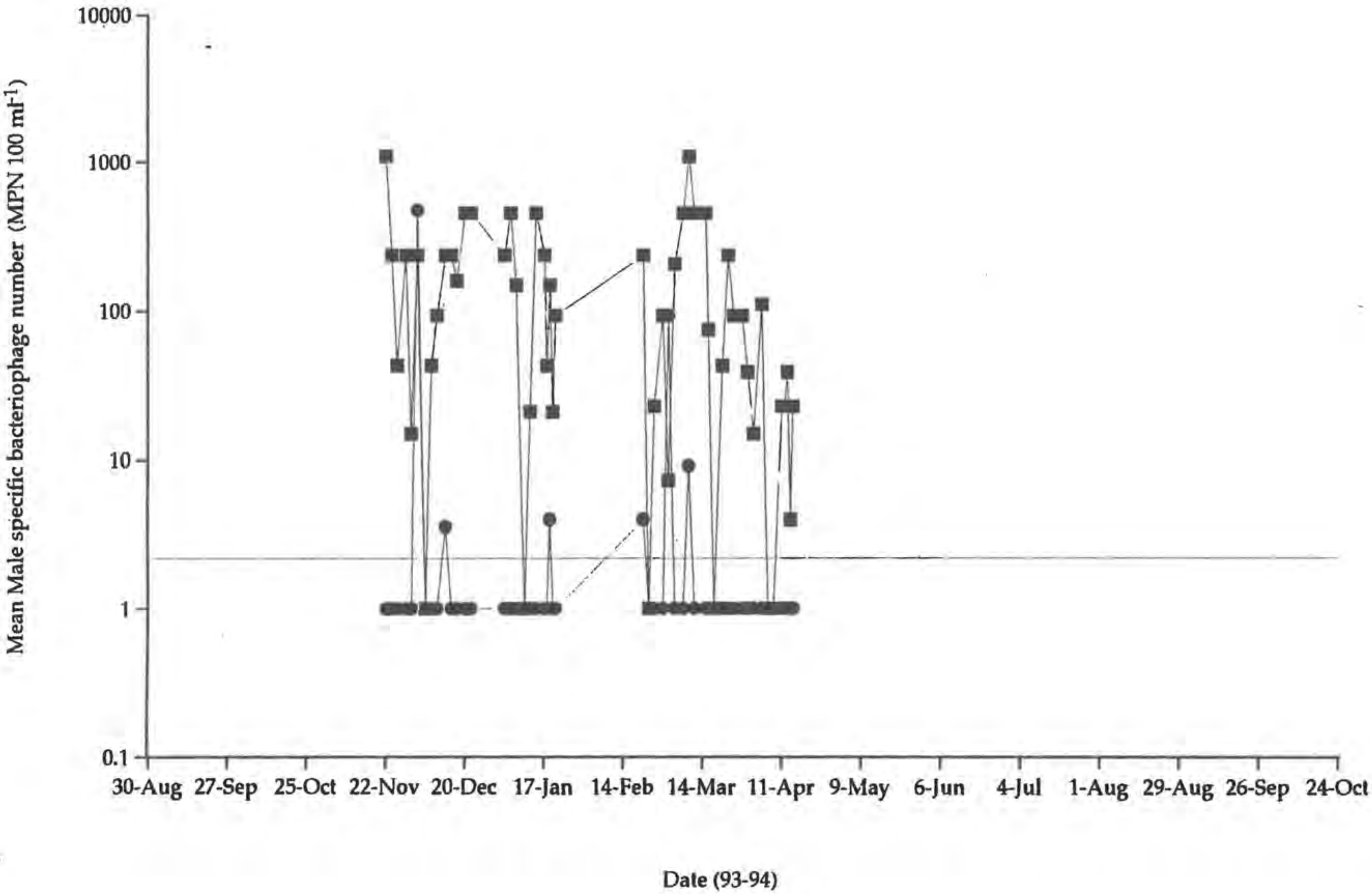
Total coliform numbers of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.



Total phosphorus concentration of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.

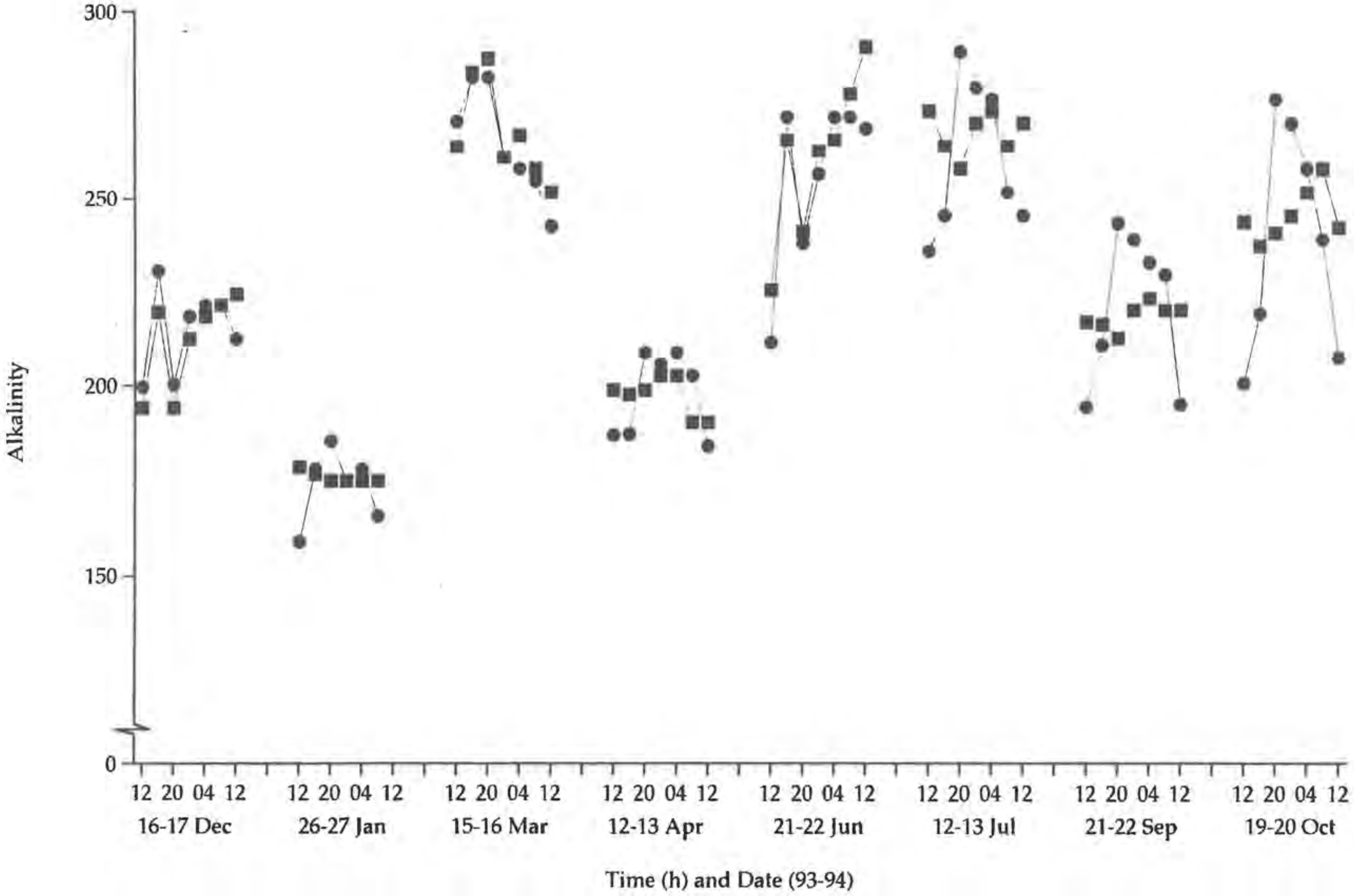


UV %-Transmittance of influent (■) and effluent (●) of the ATS/UV system. Values are means ± s.d. of two replicate samples.

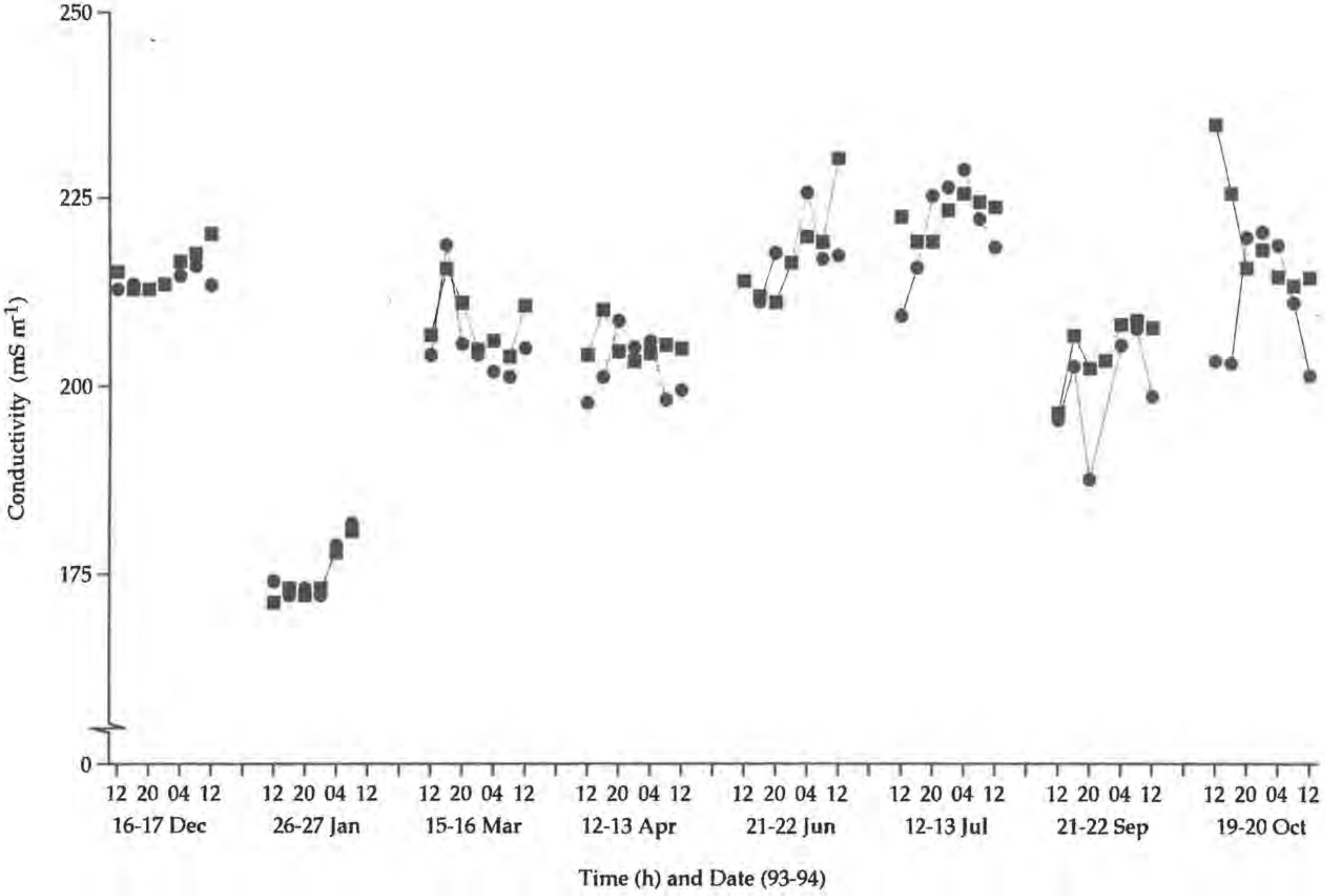


Male specific bacteriophage numbersof influent (■) and effluent (●) of the ATS/UV system.

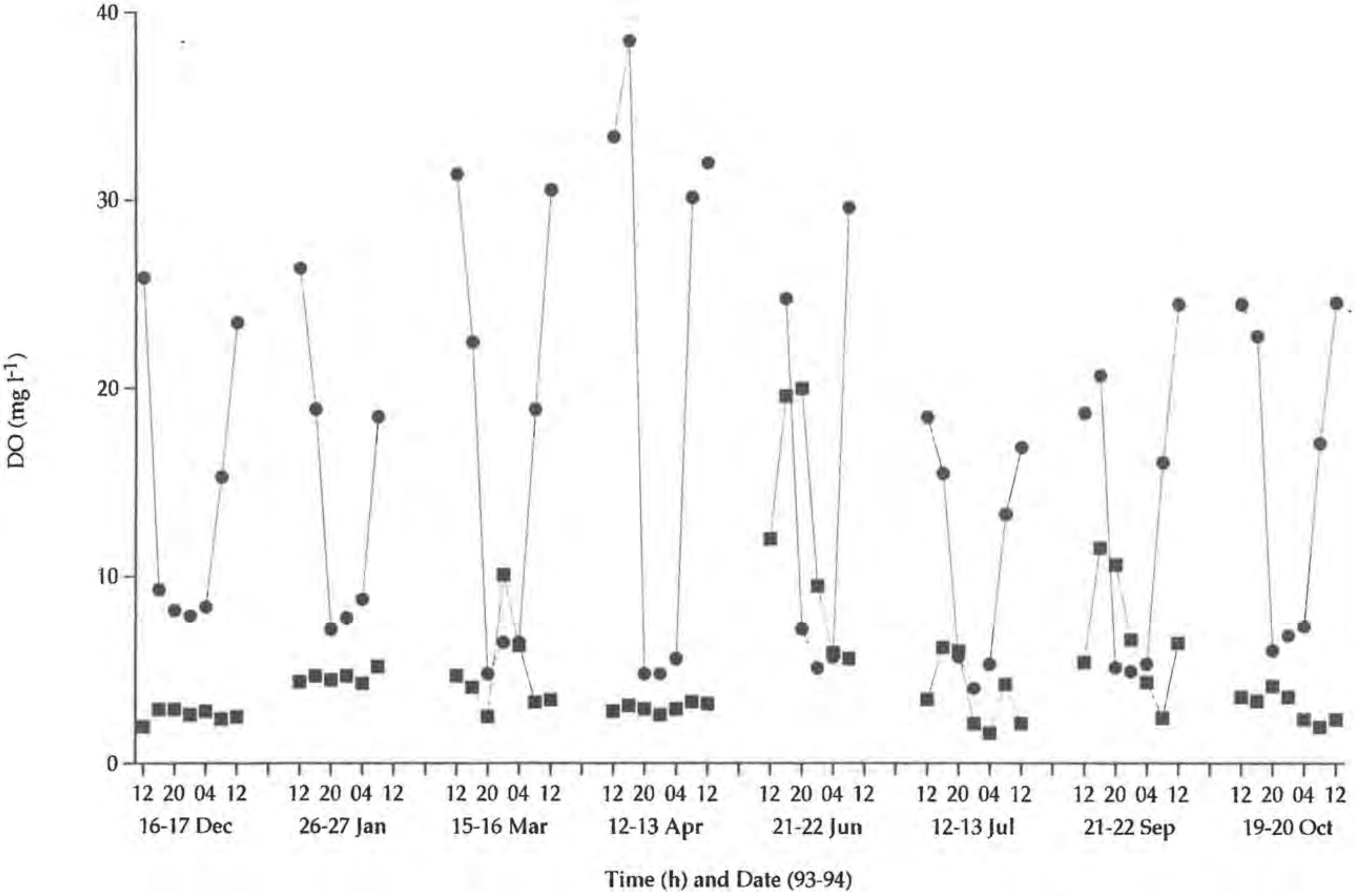
Appendix 4



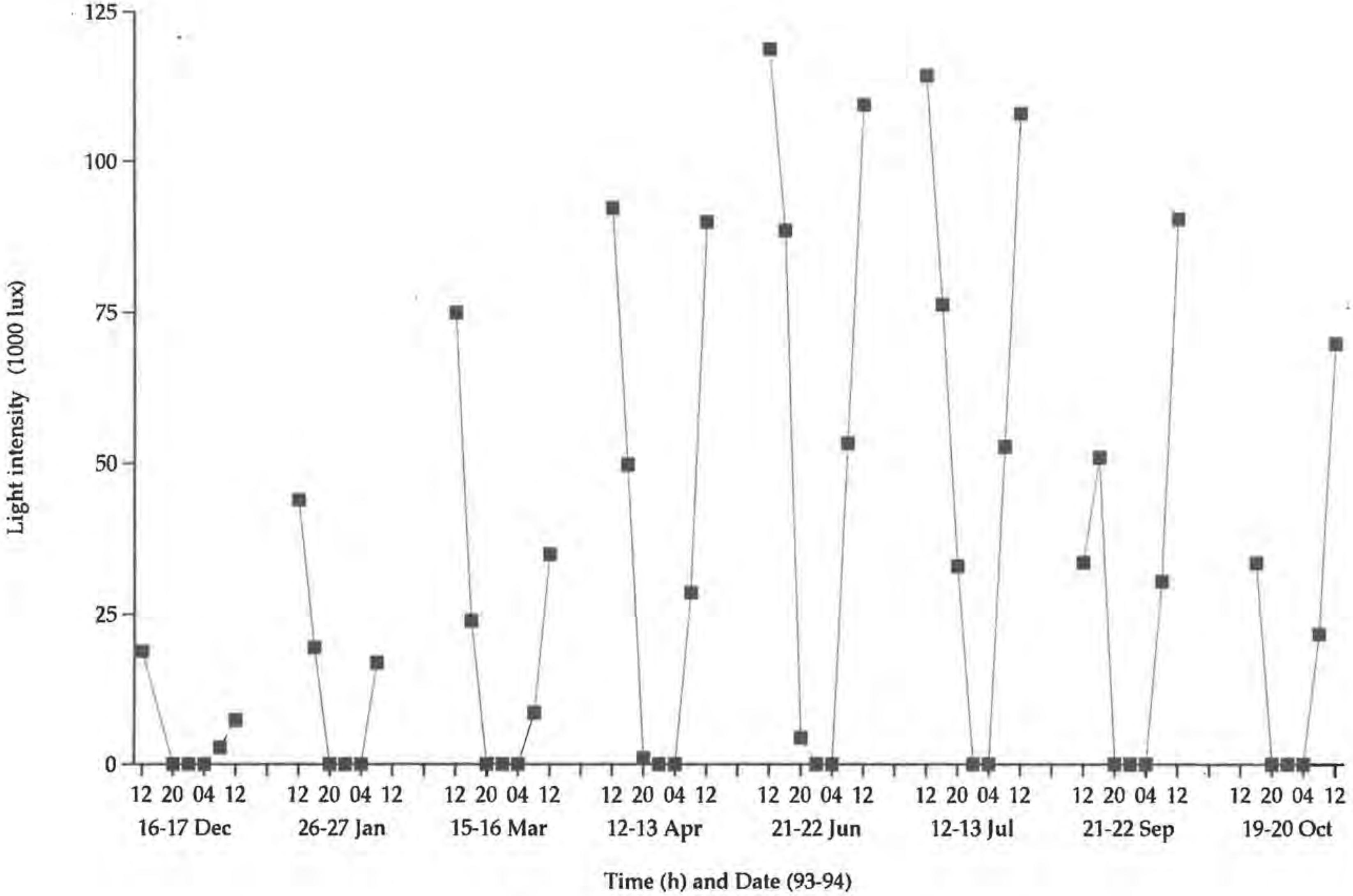
24 hour variation in Alkalinity of influent (■) and effluent (●) of the ATS/UV system.



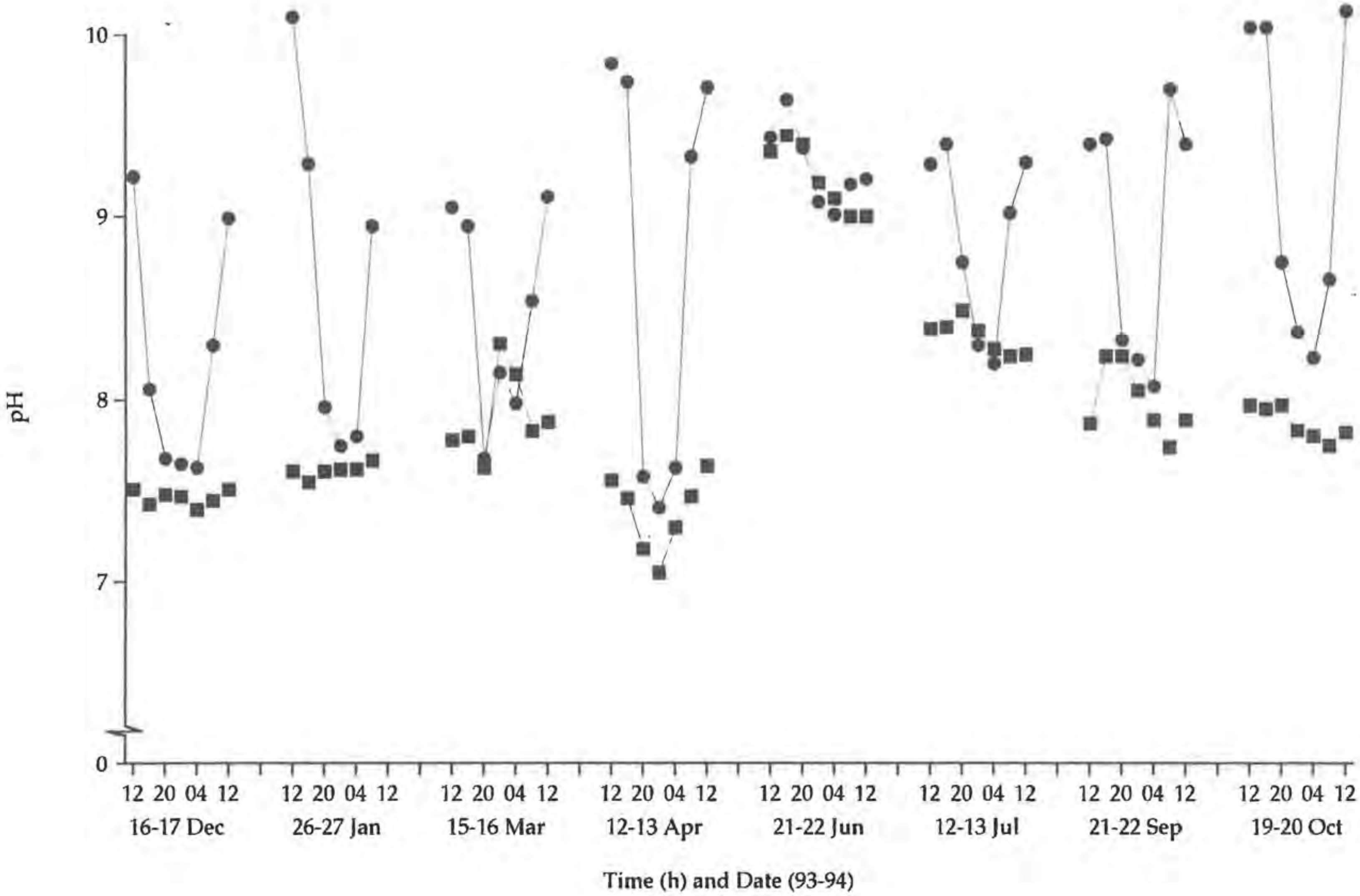
24 hour variation in Conductivity of influent (■) and effluent (●) of the ATS/UV system.



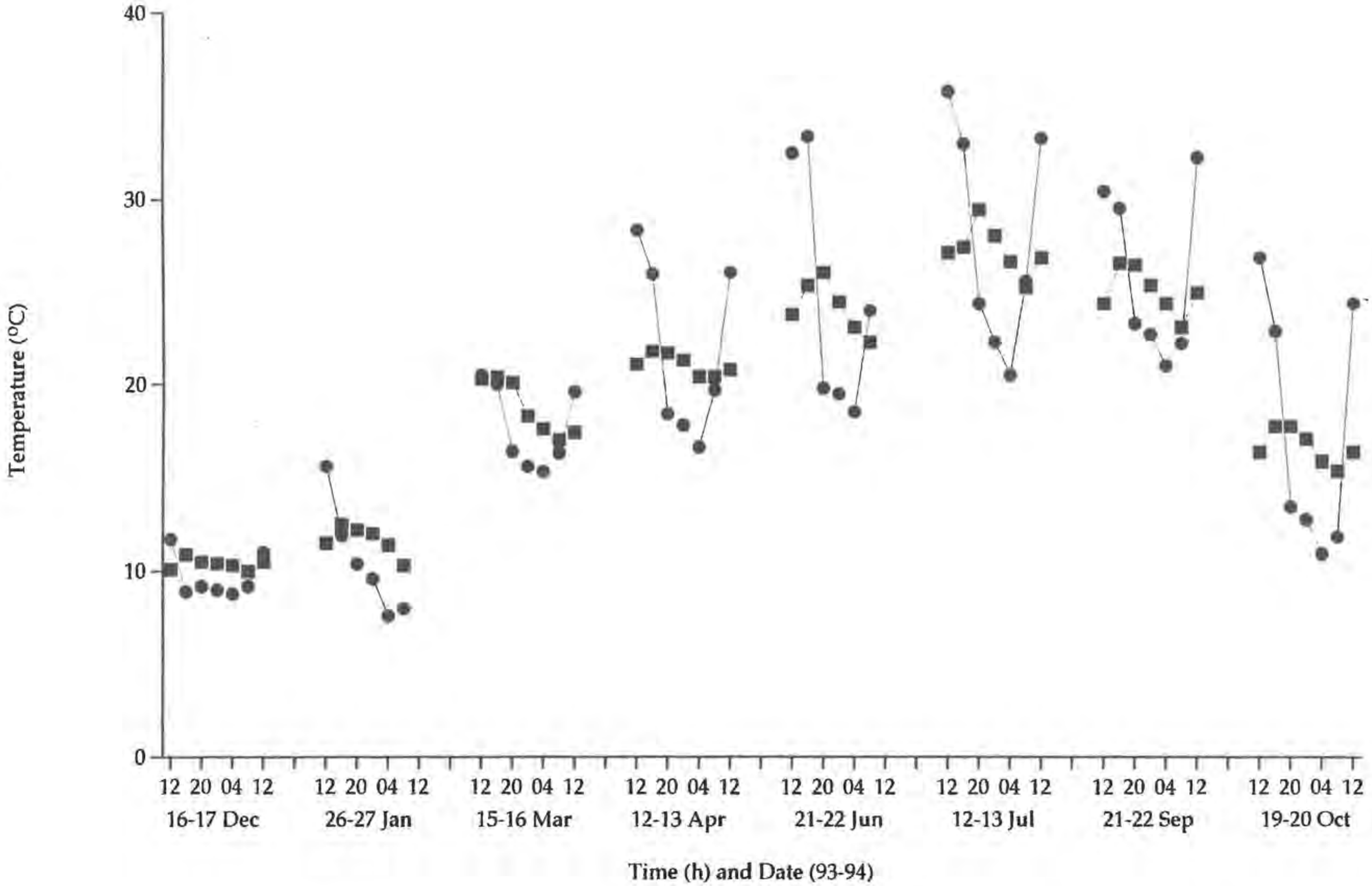
24 hour variation in Dissolved oxygen of influent (■) and effluent (●) of the ATS/UV system.



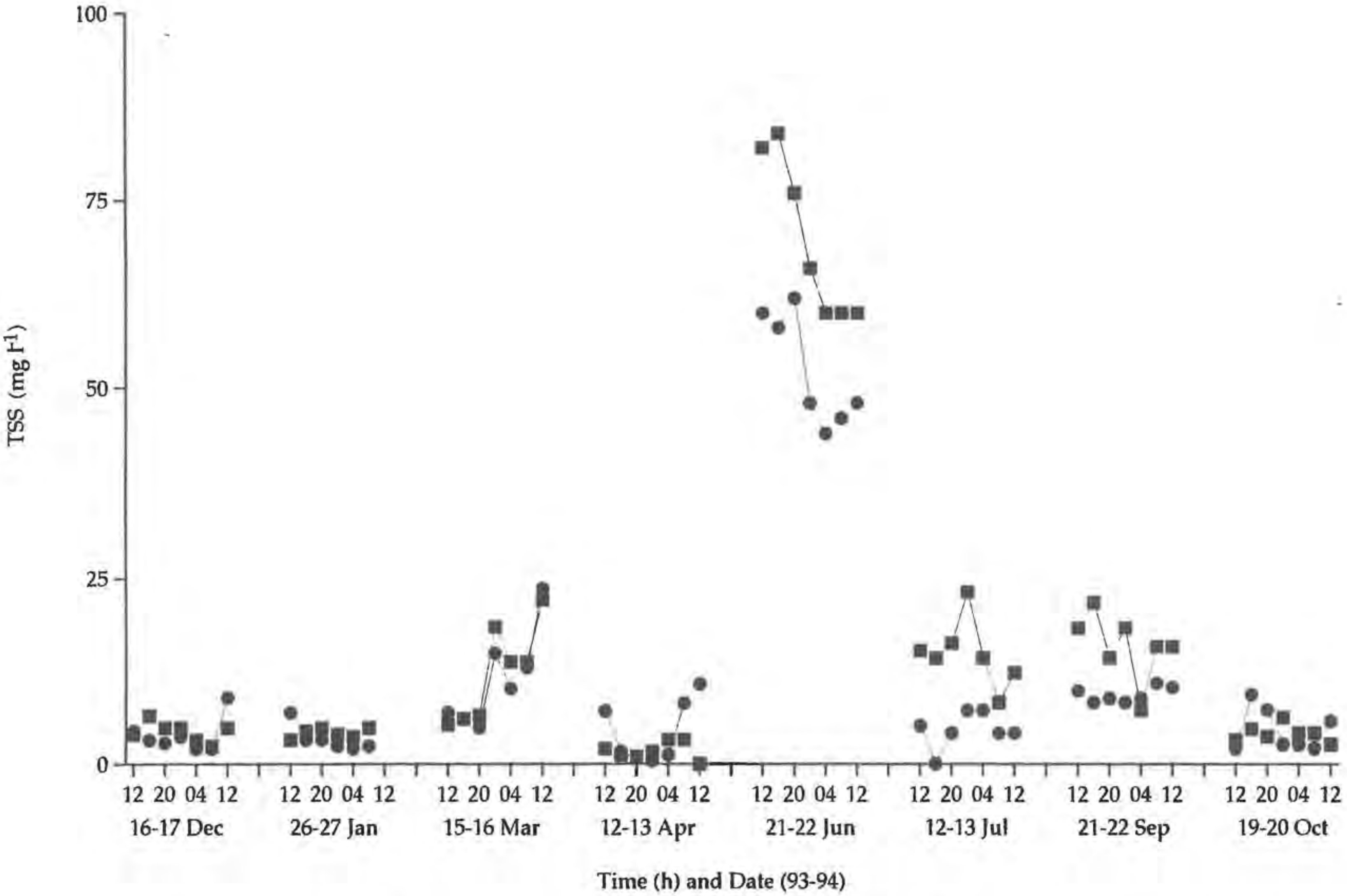
24 hour variation in Light intensity measured at time of sampling (11.00 am) .



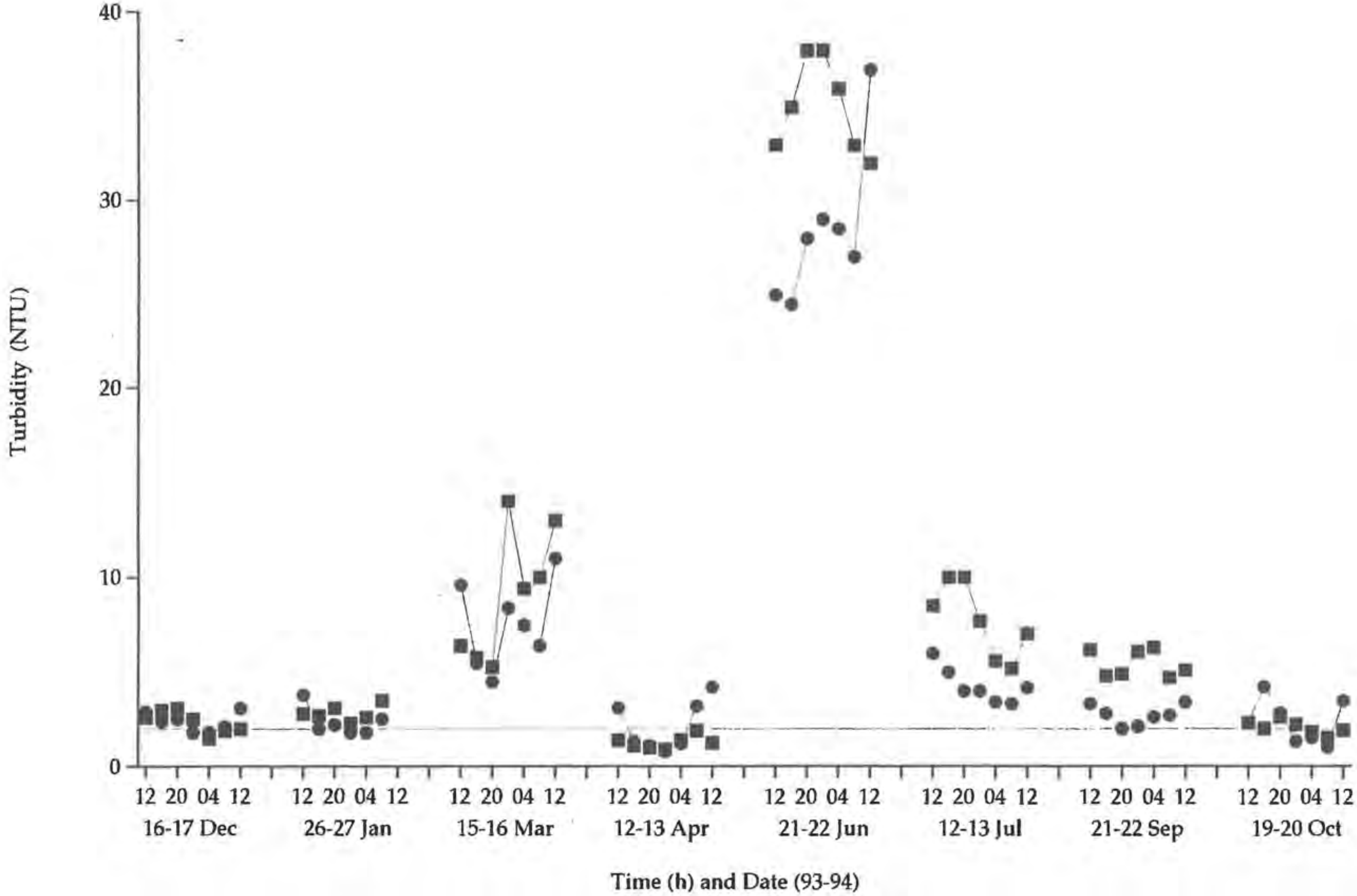
24 hour variation in pH of influent (■) and effluent (●) of the ATS/UV system.



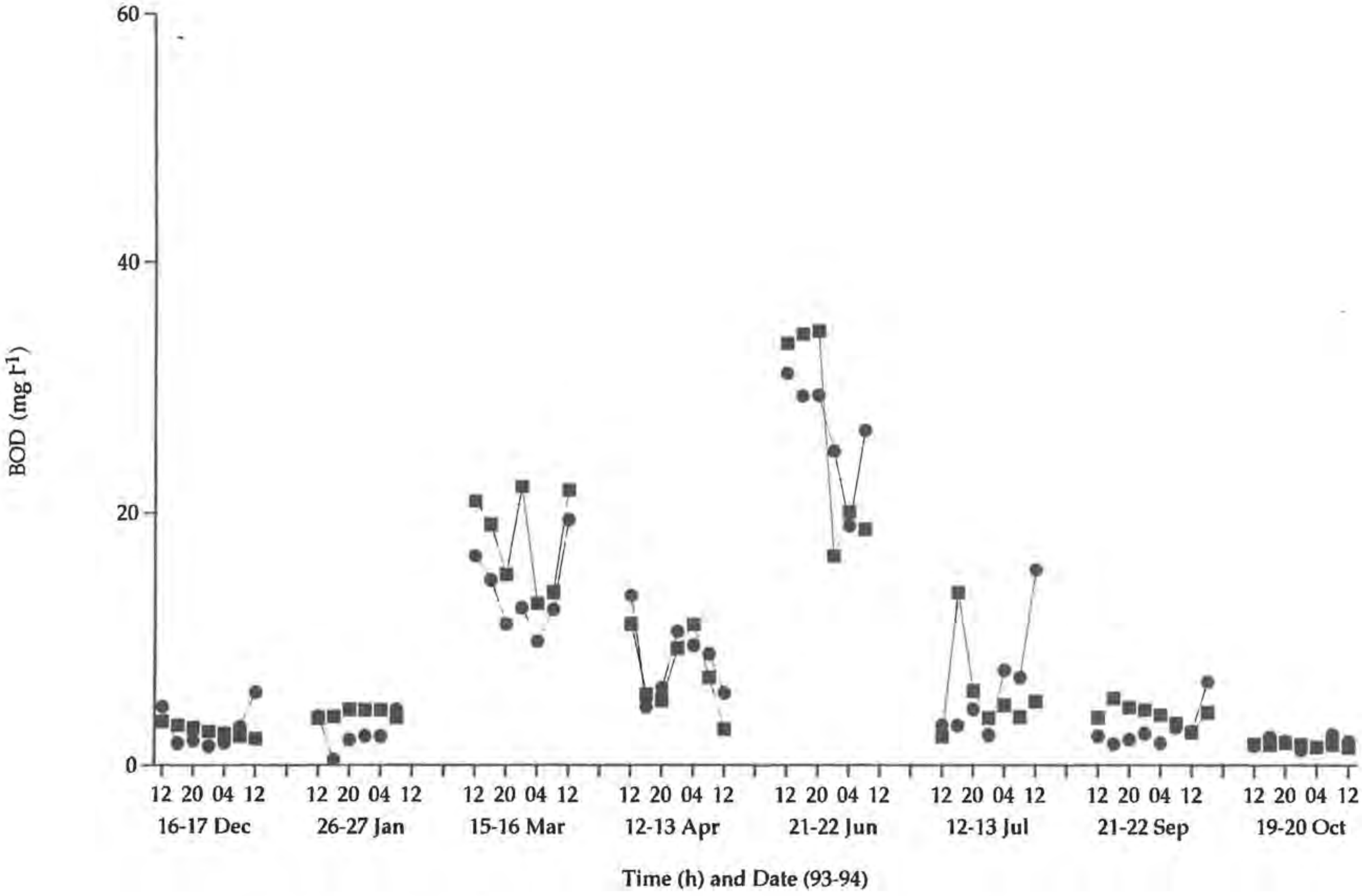
24 hour variation in Temperature of influent (■) and effluent (●) of the ATS/UV system.



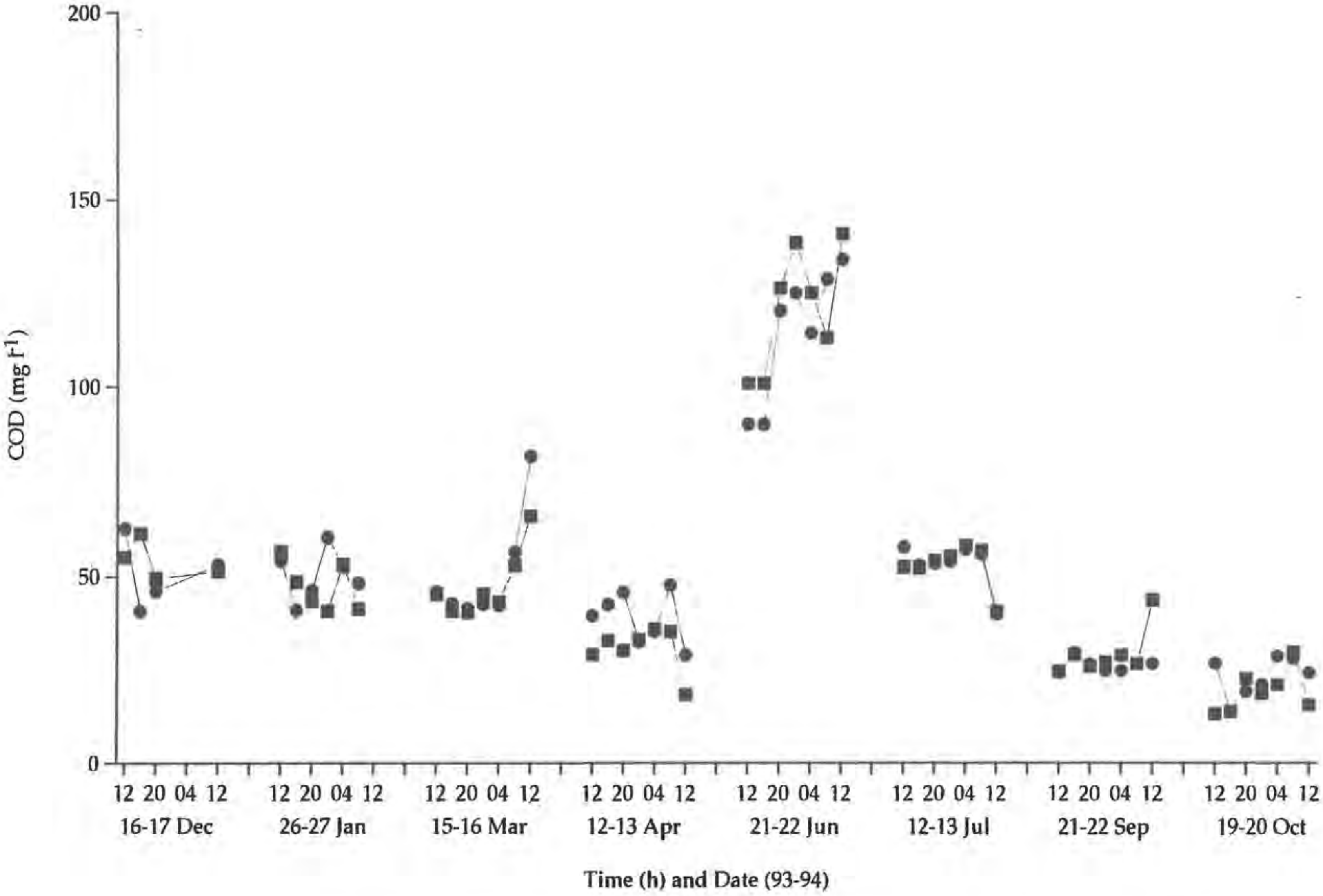
24 hour variation in Total suspended solids of influent (■) and effluent (●) of the ATS/UV system.



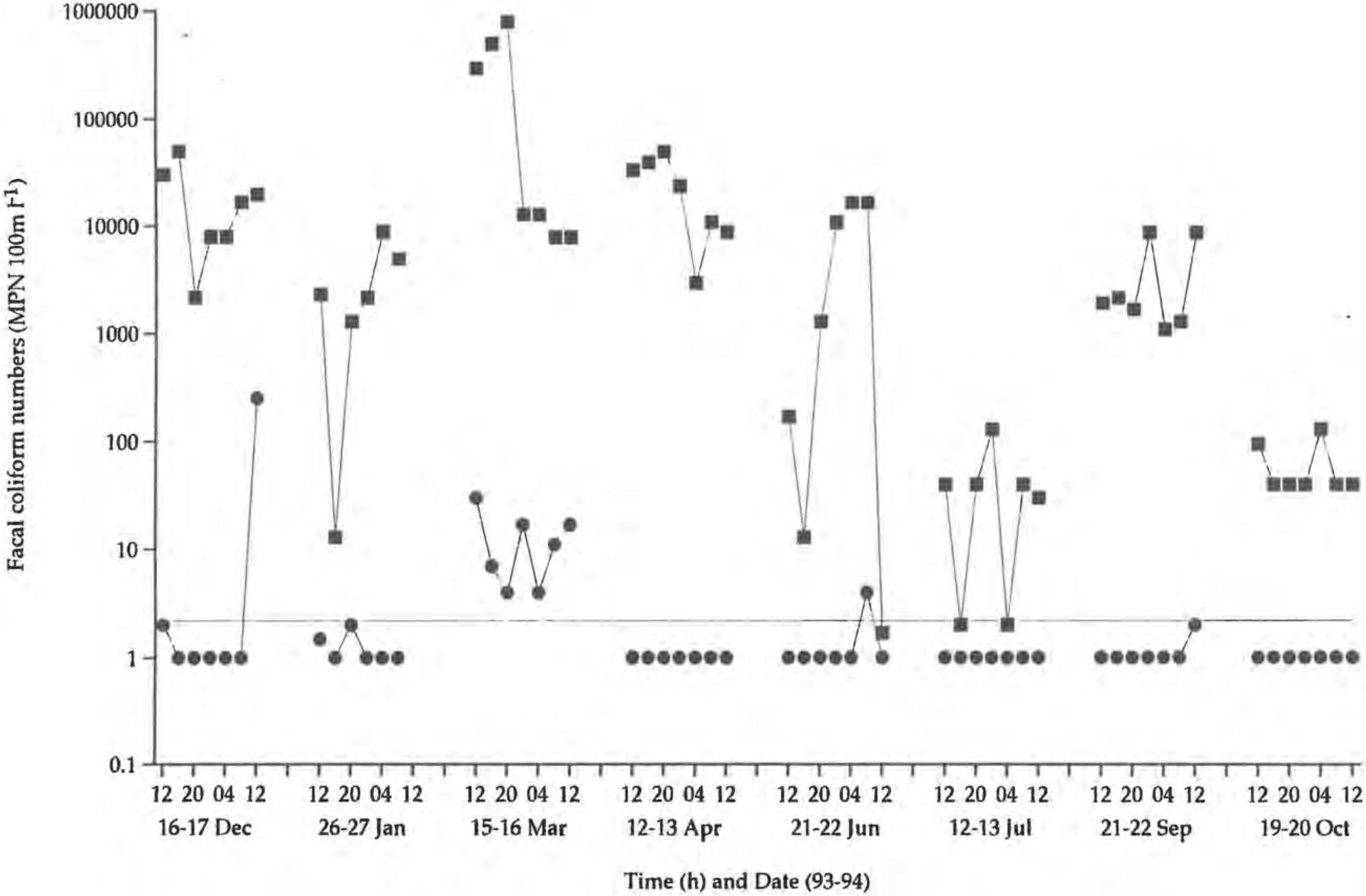
24 hour variation in Turbidity of influent (■) and effluent (●) of the ATS/UV system.



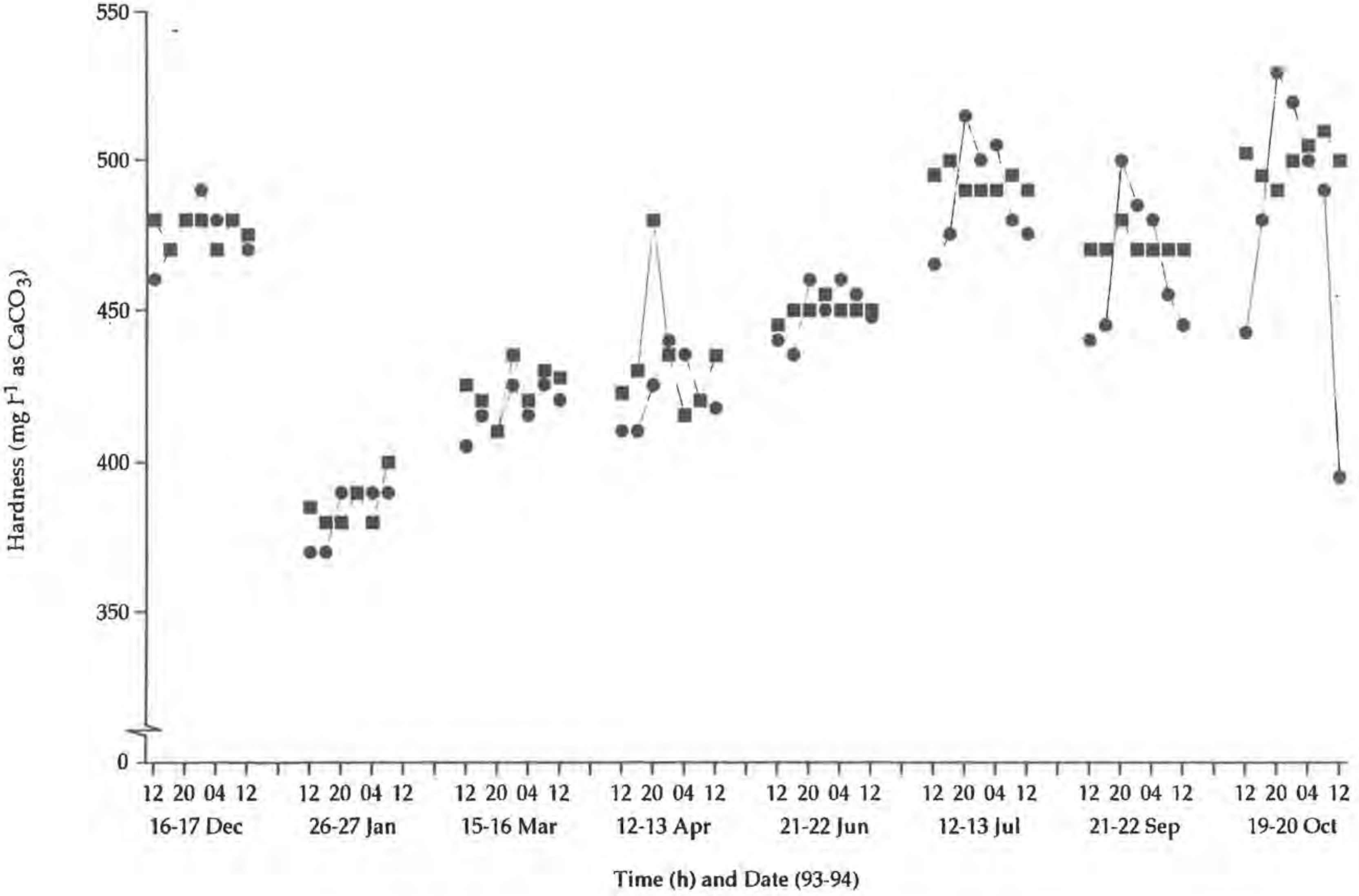
24 hour variation in biochemical oxygen demand of influent (■) and effluent (●) of the ATS/UV system.



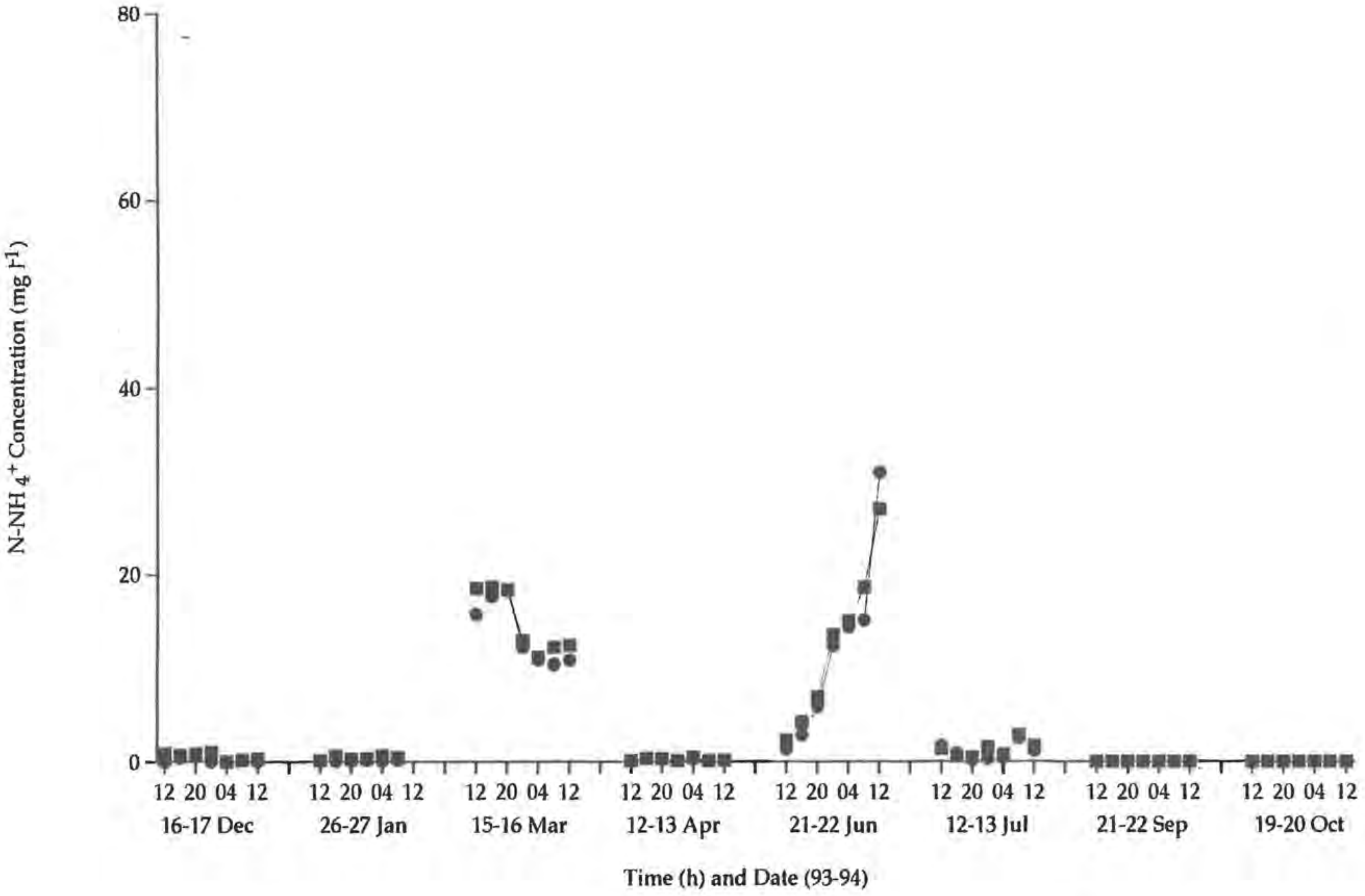
24 hour variation in chemical oxygen demand of influent (■) and effluent (●) of the ATS/UV system.



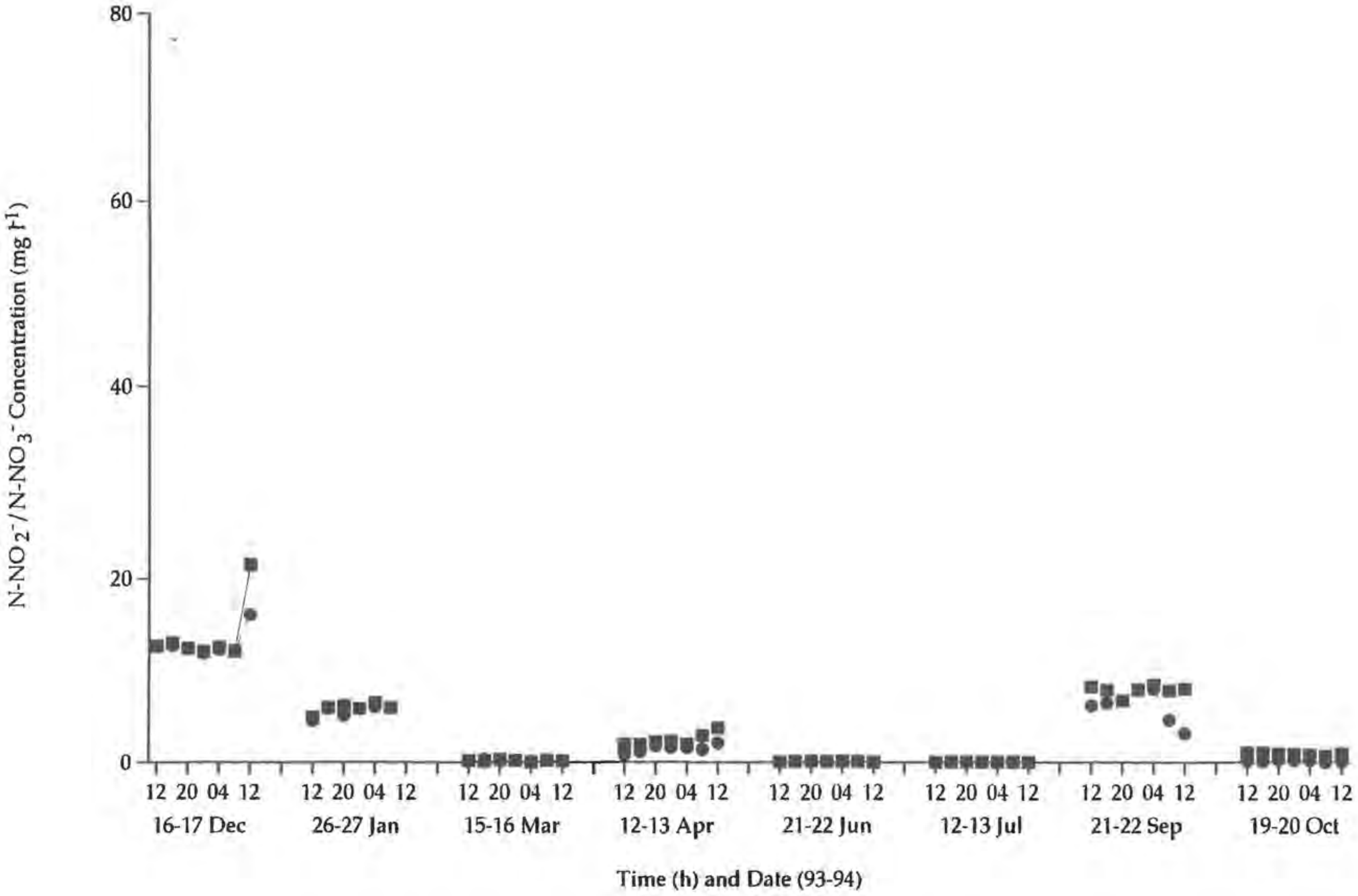
24 hour variation in faecal coliform numbers of influent (■) and effluent (●) of the UV system.



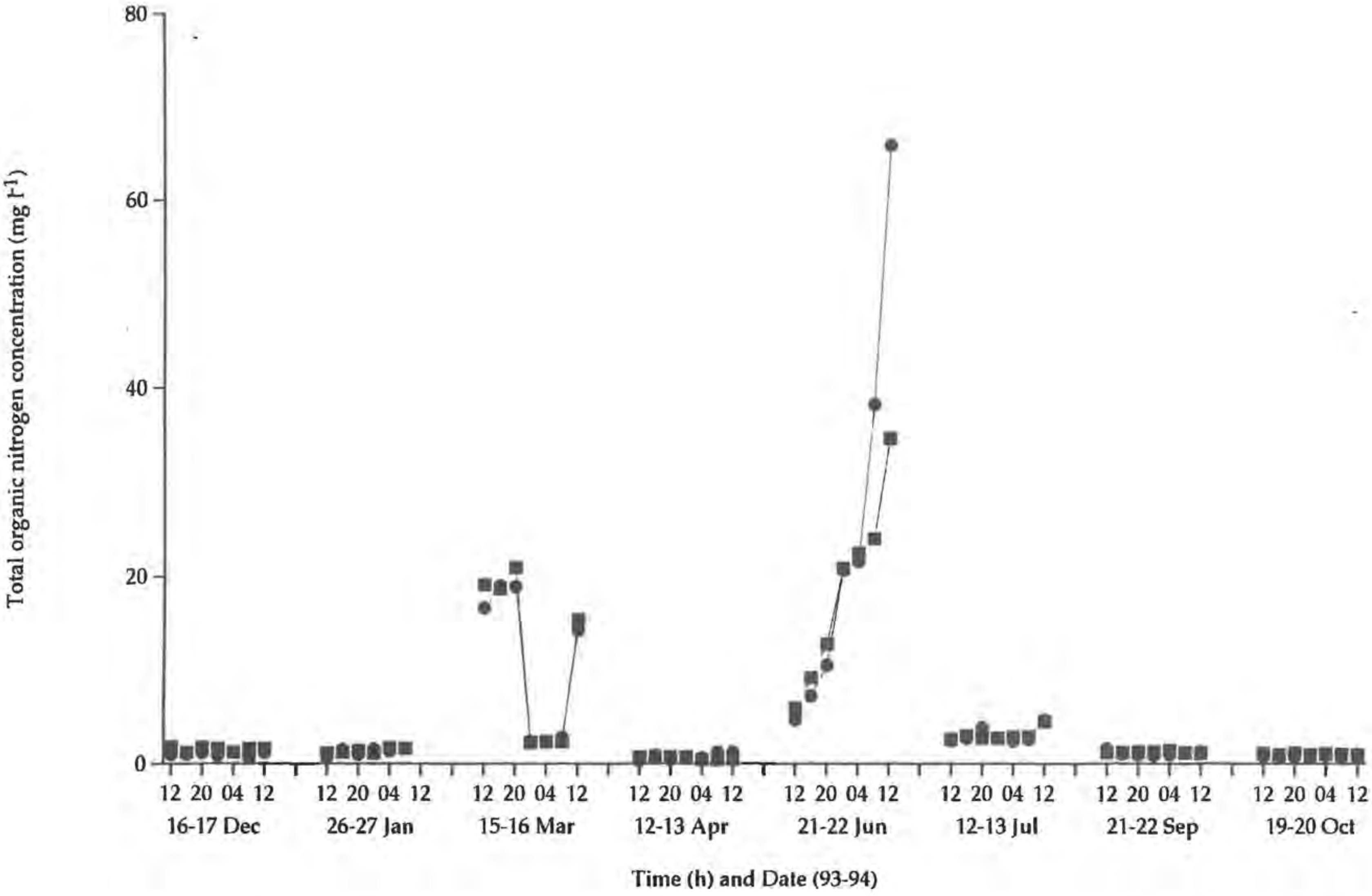
24 hour variation in hardness of influent (■) and effluent (●) of the ATS/UV system.



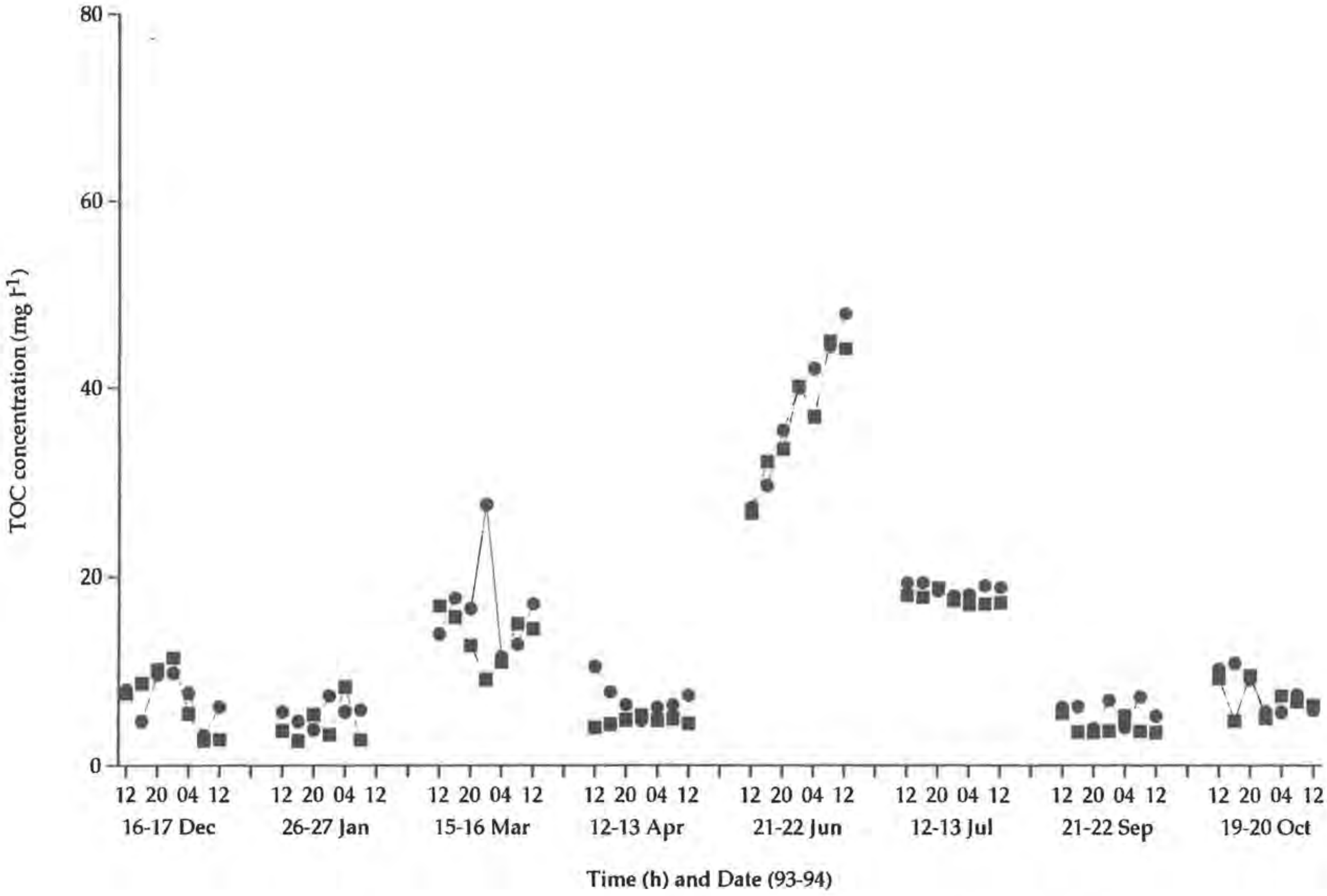
24 hour variation in ammonium-nitrogen concentration of influent (■) and effluent (●) of the ATS/UV system.



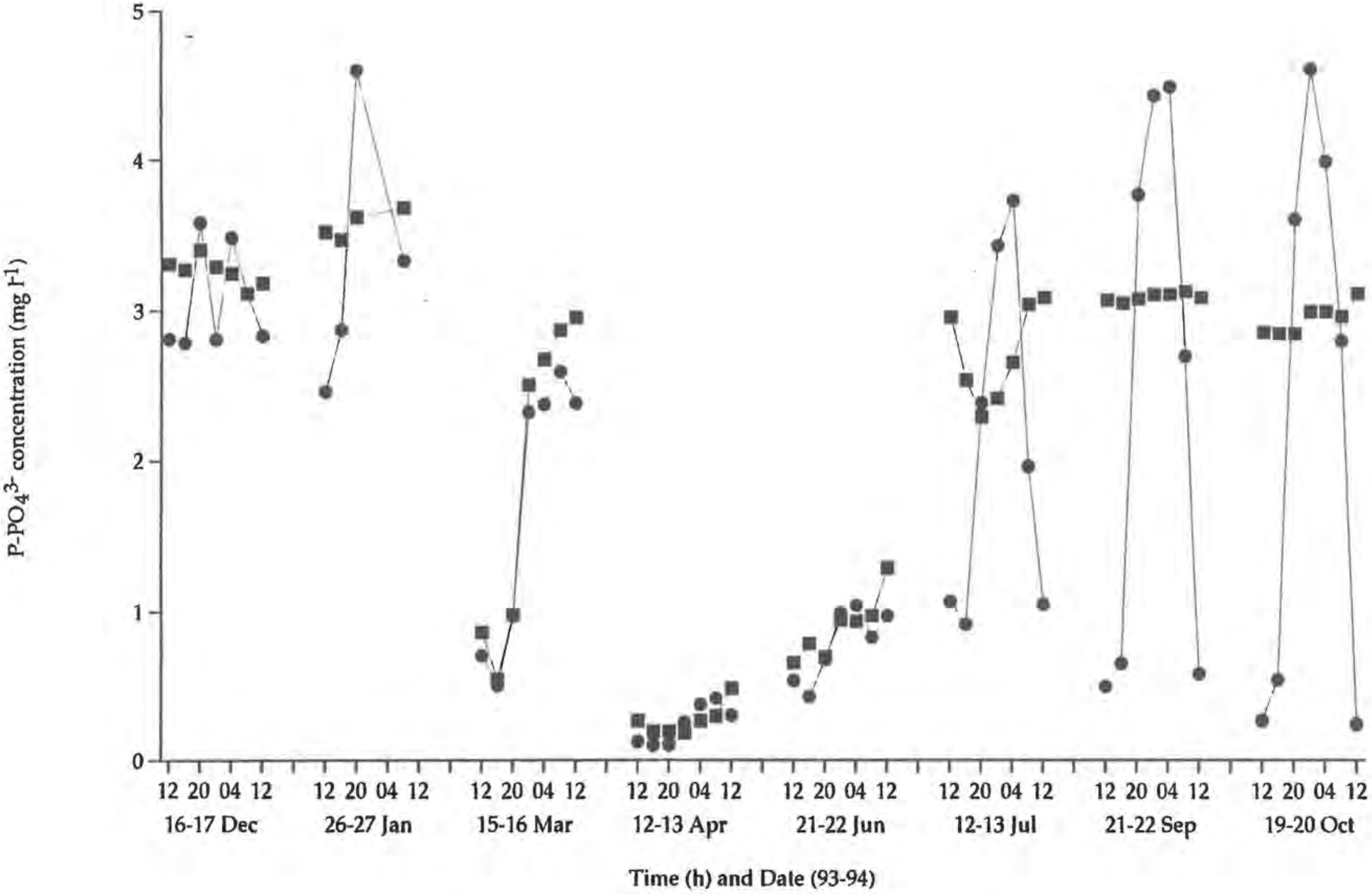
24 hour variation in nitrite- and nitrate-nitrogen concentration of influent (■) and effluent (●) of the ATS/UV system.



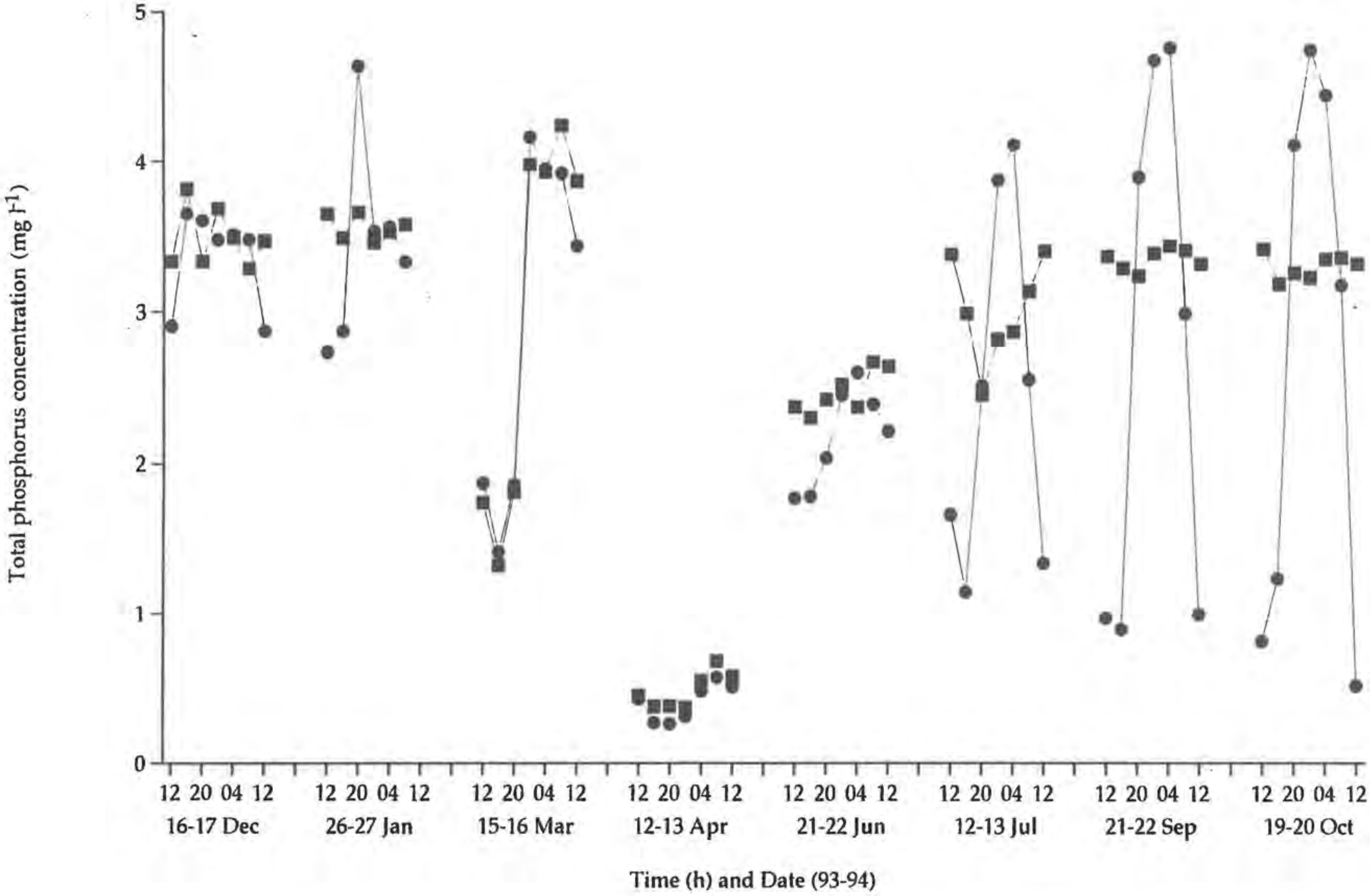
24 hour variation in total organic nitrogen concentration of influent (■) and effluent (●) of the ATS/UV system.



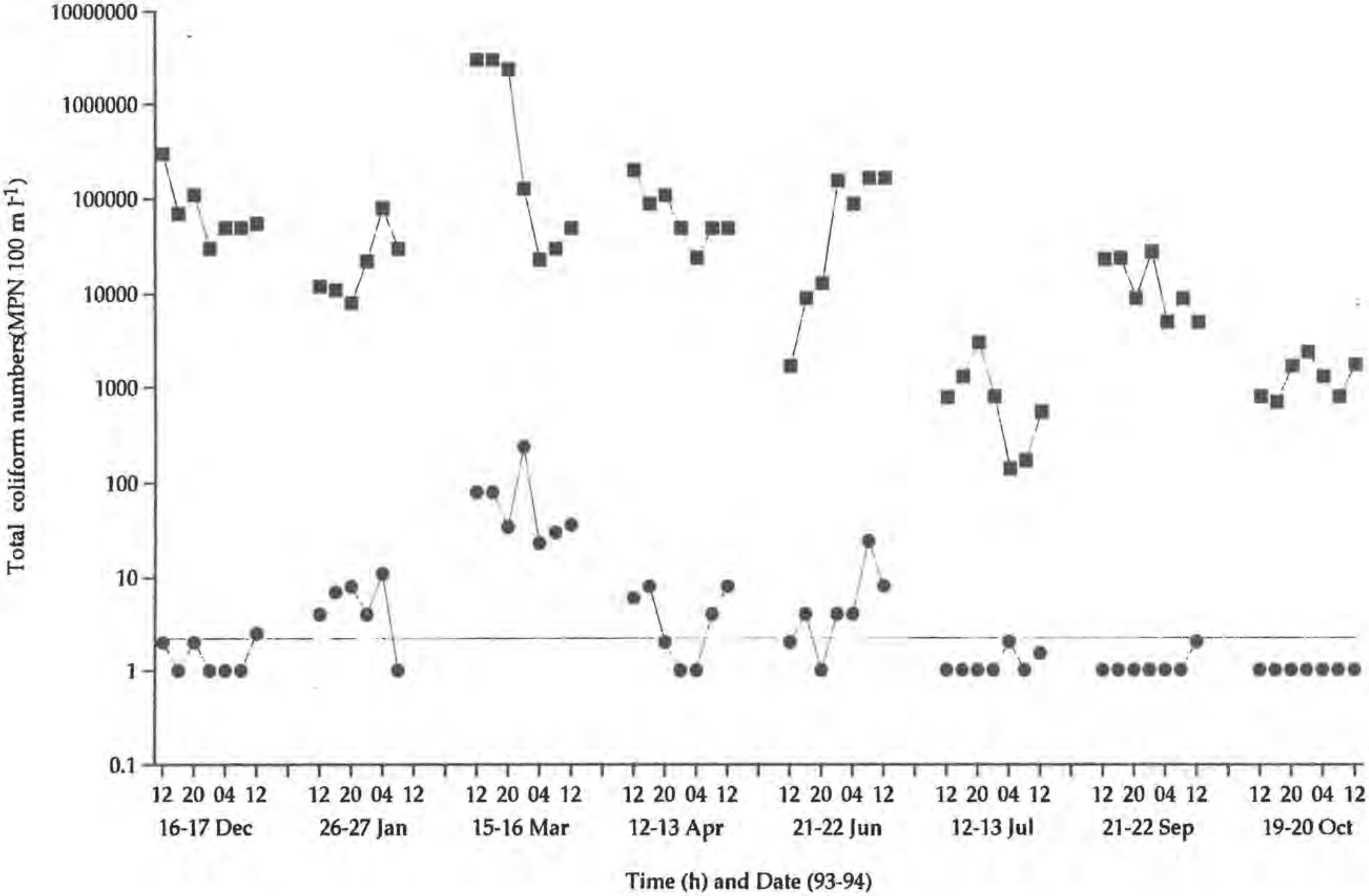
24 hour variation in total organic carbon of influent (■) and effluent (●) of the ATS/UV system.



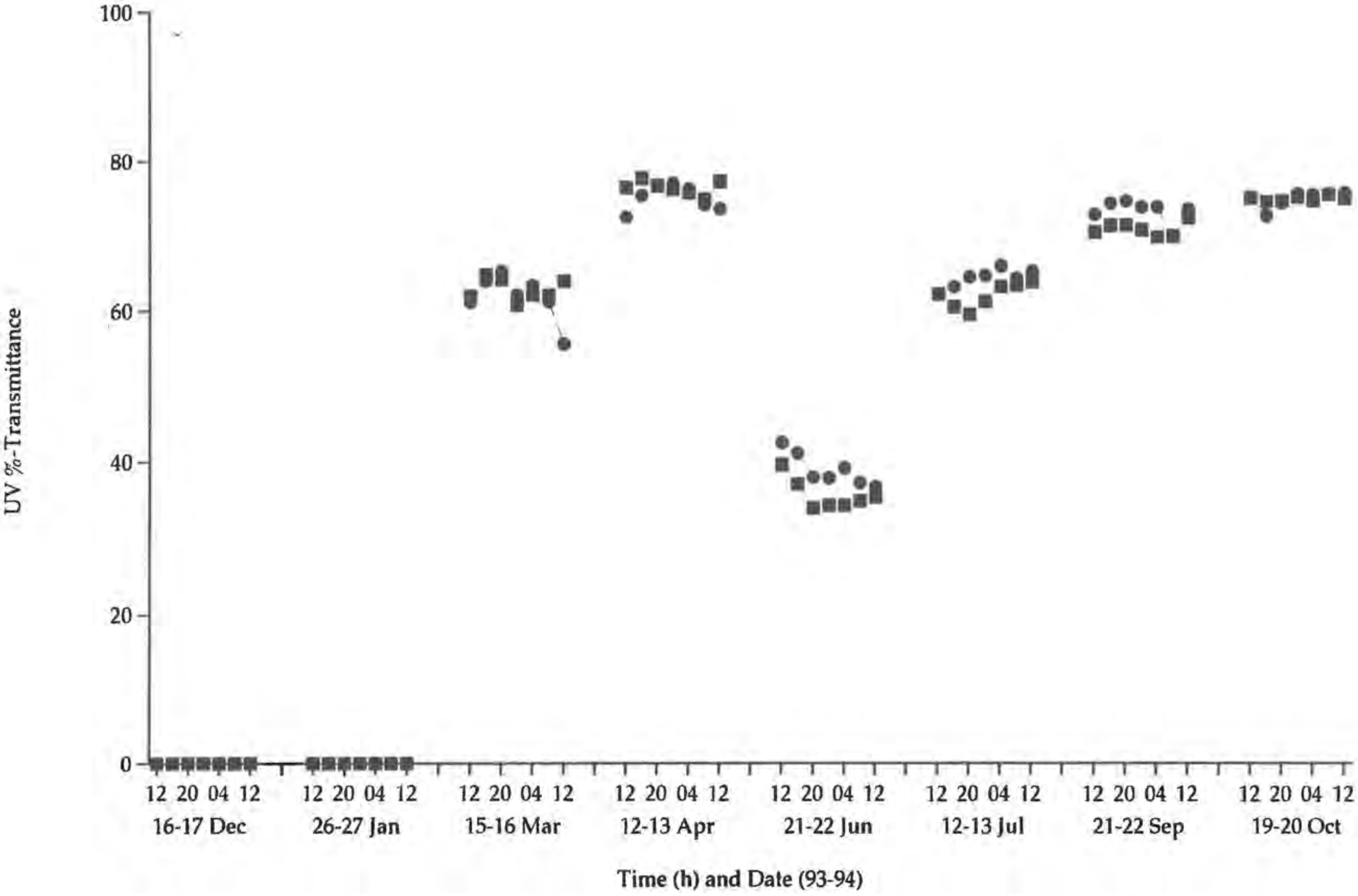
24 hour variation in soluble reactive phosphorus concentration of influent (■) and effluent (●) of the ATS/UV system.



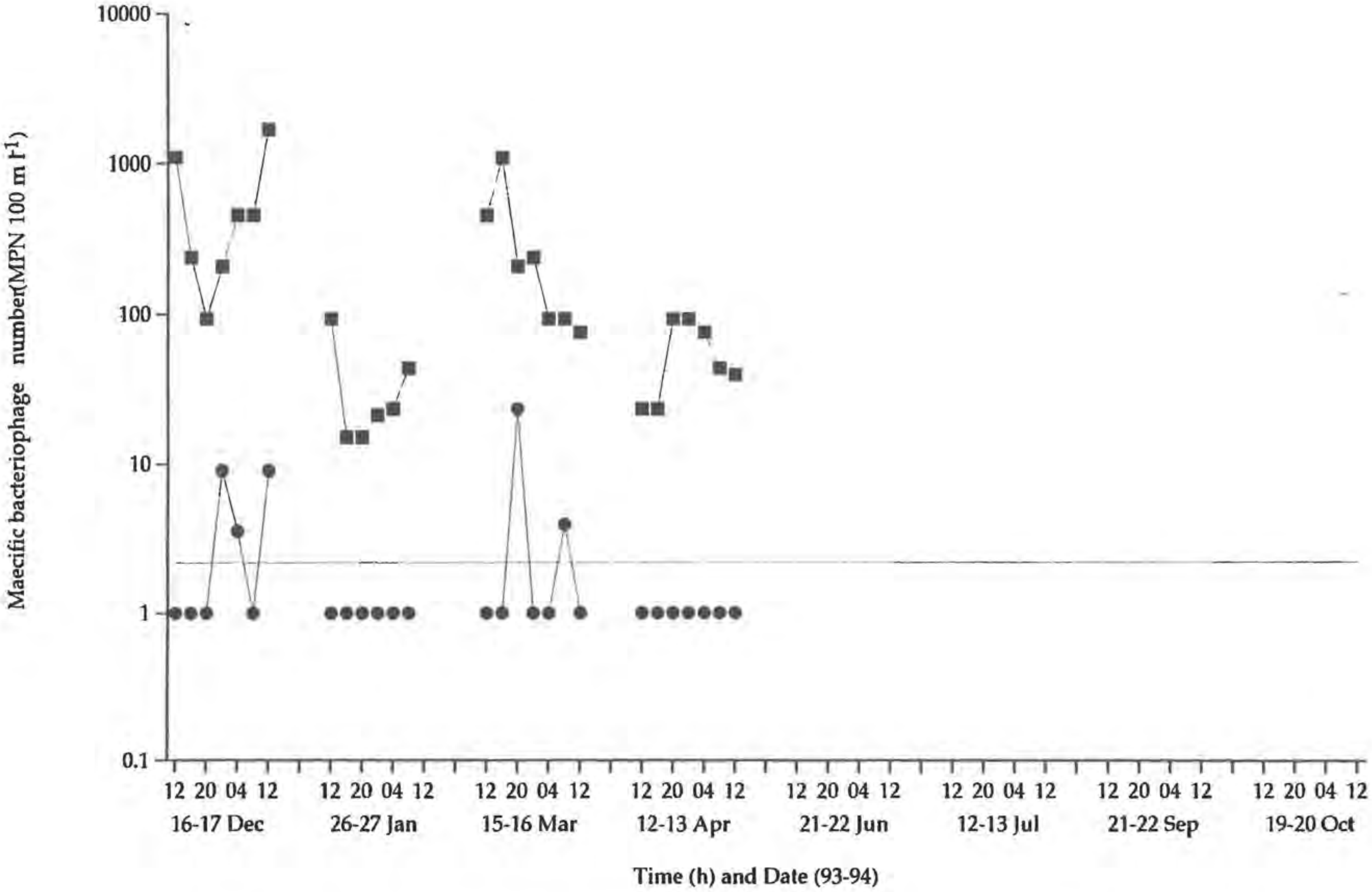
24 hour variation in total phosphorus concentration of influent (■) and effluent (●) of the ATS/UV system.



24 hour variation in total coliform numbers of influent (■) and effluent (●) of the UV system.



24 hour variation in UV %-transmittance of influent (■) and effluent (●) of the ATS/UV system.



24 hour variation in male specific bacteriophage numbers of influent (■) and effluent (●) of the UV system.

Nitrogen Data

Table	HLV m/d	Flow m^3/d	Influent mg/l	g/d
3.3	1.35	668.25	7.36	4918
3.4	1.35	668.25	6.46	4317
3.09	0.44	217.8	3.55	773
3.10	0.44	217.8	3.39	738
3.11	0.43	212.85	14.17	3016
3.12	0.44	217.8	12.66	2757
3.13	0.44	217.8	15.08	3284
3.14	0.22	108.9	14.74	1605
3.14	0.44	217.8	14.74	3210
3.15	0.22	108.9	26.04	2836
3.16	0.22	108.9	29.12	3171
3.17	0.22	40.5	28.77	1165
3.18	0.11	54.45	30.68	1671

West Effluent Removed

mg/l	efficiency	g/d	g/d rem	kg/wk rem	kg/yr rem	$/kg rem *
5.92	19.57%	3956	962	6.74	350.27	$7.57
5.67	12.23%	3789	528	3.70	192.16	$13.80
2.38	32.96%	518	255	1.78	92.76	$28.59
2.33	31.27%	507	231	1.62	84.04	$31.56
6.79	52.08%	1445	1571	11.00	571.78	$4.64
8.29	34.52%	1806	952	6.66	346.45	$7.65
8.21	45.56%	1788	1496	10.47	544.65	$4.87
7.4	49.80%	806	799	5.60	290.95	$9.11
7.4	49.80%	1612	1599	11.19	581.91	$4.56
18.85	27.61%	2053	783	5.48	285.01	$9.30
25.07	13.91%	2730	441	3.09	160.54	$16.52
26.12	9.21%	1058	107	0.75	39.07	$67.88
22.89	25.39%	1246	424	2.97	154.40	$17.18

East Effluent Removed

mg/l	efficiency	g/d	g/d rem	kg/wk rem	kg/yr rem	$/kg rem *
6.01	18.34%	4016	902	6.31	328.38	$8.08
5.69	11.92%	3802	515	3.60	187.30	$14.16
2.54	28.45%	553	220	1.54	80.07	$33.12
2.17	35.99%	473	266	1.86	96.72	$27.42
6.57	53.63%	1398	1618	11.32	588.83	$4.50
7.15	43.52%	1557	1200	8.40	436.83	$6.07
5.79	61.60%	1261	2023	14.16	736.50	$3.60
8.62	41.52%	939	666	4.67	242.59	$10.93
8.62	41.52%	1877	1333	9.33	485.19	$5.47
19.59	24.77%	2133	702	4.92	255.68	$10.37
24.55	15.69%	2673	498	3.48	181.15	$14.64
24.74	14.01%	1002	163	1.14	59.41	$44.64
22.5	26.66%	1225	445	3.12	162.13	$16.36

* Based on $0.475 per square foot over 7.5 years
O & M not included

Phosphorus Data

Table	HLV m/d	Flow m^3/d	Influent mg/l	g/d
3.3	1.35	668.25	1.66	1109
3.4	1.35	668.25	1.46	976
3.09	0.44	217.8	1.52	331
3.1	0.44	217.8	1.61	351
3.11	0.43	212.85	3.4	724
3.12	0.44	217.8	3.48	758
3.13	0.44	217.8	3.45	751
3.14	0.22	108.9	3.5	381
3.14	0.44	217.8	3.5	762
3.15	0.22	108.9	4.29	467
3.16	0.22	108.9	4.49	489
3.17	0.22	40.5	4.7	190
3.18	0.11	54.45	3.72	203

West Effluent Removed

mg/l	efficiency	g/d	g/d rem	kg/wk rem	kg/yr rem	$/kg rem *
1.32	20.48%	882	227	1.59	82.70	$32.07
1.15	21.23%	768	207	1.45	75.41	$35.17
0.32	78.95%	70	261	1.83	95.14	$27.88
1.07	33.54%	233	118	0.82	42.81	$61.95
1.32	61.18%	281	443	3.10	161.15	$16.46
2.48	28.74%	540	218	1.52	79.28	$33.45
2.35	31.88%	512	240	1.68	87.21	$30.41
0.92	73.71%	100	281	1.97	102.27	$25.93
0.92	73.71%	200	562	3.93	204.54	$12.97
3.02	29.60%	329	138	0.97	50.34	$52.68
4.13	8.02%	450	39	0.27	14.27	$185.84
5.77	-22.77%	234	-43	-0.30	-15.77	($168.13)
2.74	26.34%	149	53	0.37	19.42	$136.54

East Effluent Removed

mg/l	efficiecy	g/d	g/d rem	kg/wk rem	kg/yr rem	$/kg rem *
1.32	20.48%	882	227	1.59	82.70	$32.11
1.17	19.86%	782	194	1.36	70.54	$37.78
0.49	67.76%	107	224	1.57	81.66	$32.48
1.09	32.30%	237	113	0.79	41.23	$63.90
1.16	65.88%	247	477	3.34	173.55	$14.26
2.46	29.31%	536	222	1.56	80.86	$34.00
1.5	56.52%	327	425	2.97	154.59	$17.18
1.69	51.71%	184	197	1.38	71.75	$18.55
1.69	51.71%	368	394	2.76	143.50	$18.55
2.66	38.00%	290	178	1.24	64.61	$41.14
3.74	16.70%	407	82	0.57	29.73	$95.88
4.02	14.47%	163	28	0.19	10.02	$261.54
2.57	30.91%	140	63	0.44	22.79	$117.55

* Based on $0.475 per square foot over 7.5 years
O & M not included