FULL SCALE DEMONSTRATION OF FILAMENTOUS BULKING CONTROL AT A BIOLOGICAL NUTRIENT REMOVAL ACTIVATED SLUDGE PLANT

by

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Pilot plant set-up, operation and monitoring.

For this purpose, two parallel pilot plants at the Mitchell's Plain Wastewater Treatment Plant were made available by the Cape Metropolitan Council (CMC). The two pilot plants (Modules A and B) were redesigned as N & P removal UCT configuration systems, such that the two systems had the same design and operating parameters. The sludge age was 15 days and the anaerobic, anoxic and aerobic mass fractions 0.091, 0.350 and 0.559 respectively. The treatment capacity of the two modules was estimated to be 2.0 and 2.7 Mℓ/d for Modules A and B respectively but due to aeration capacity limitations of the old fine bubble ceramic dome aeration system, the flows were reduced to 1.4 and 2.1 Mℓ/d. The idiosyncrasies of this old aeration system and persistent problems with the sludge back flow into the pilot plants from the sludge treatment facilities resulted in the anoxic and aerobic reactors not functioning as such (leading to poor anoxic denitrification and significant aerobic simultaneous nitrification-denitrification) and poor sludge age control. These problems compromised achieving the two research objectives and ultimately forced cessation of the investigation after 589 days.

To test the AA filament bulking hypothesis at large scale, in the one system (Module B), the nitrate/nitrite concentration in the anoxic reactor would be controlled to be > 2 mgN/ℓ and hence in terms of the hypothesis should bulk, while in the other parallel system (Module A) it would be controlled to < 1 mgℓ and hence in terms of the hypothesis should not bulk. To control the nitrate/nitrite concentrations at the transition from anoxic to aerobic conditions, the 'a-recycles' (aerobic to anoxic) were varied to under and overload with nitrate the anoxic reactors of Modules A and B respectively.

In the 589 day investigation, the pilot plants were sampled routinely once weekly by the CMC and an additional 3 times weekly specifically for this project. From an examination of the influent, operational parameters and measured system performance, eight 'steady state' long term periods where these remained approximately constant were identified. An identical laboratory scale system (~1:200000) was operated for 163 days from day 470 to day 632 (43 days after the termination of the pilot plant investigation) to evaluate the magnitude of the aeration and sludge wastage problems on the results of the pilot plant.

Pilot plant performance

i) COD removal

Over the 589 day investigation the average (for the eight 'steady state' periods) percentage COD removal was 87 and 89 % for Modules A and B respectively. The COD mass balance of the two modules over the investigation could not be determined because steady state conditions were not achieved due to waste sludge ingress from the main treatment plant and therefore the oxygen utilisation rates (OUR) were not measured.

ii) Nitrification, denitrification and N removal

For the first two periods (332 days), the nitrification performance was reasonable, with effluent FSA concentrations at about 1 mgN/ℓ. For all the subsequent periods nitrification was partial only, indicated by the relatively high effluent TKN and FSA concentrations (5 - 30 mgN/ℓ). For most periods, the effluent nitrate concentrations were low (10 - 17 mgN/ℓ) in Module A and B and indicates that denitrification in the system was very good (~50 - 55 mgN/ℓ), except for Periods IV and V Module A where nitrification stopped (denitrification < 2 mgN/ℓ) due to aeration problems. The nitrate concentrations in the anoxic reactors of both modules were higher than expected (5 - 8 mgN/ℓ) which resulted in (i) nitrate feed back to the anaerobic reactor and (ii) not achieving low nitrate at the anoxic-aerobic transition in Module A. Reducing the 'a-recycle' ratios on Module A and B from 2:1 and 5:1 to 0:1 and 3:1 respectively did not solve this problem. Later in the investigation it became apparent that these high anoxic reactor nitrate concentrations were due to air leaks in the air distribution network and back mixing from the aerobic reactor, in particular in Module A.

To examine the nitrification and denitrification performance, nitrate and nitrite mass balances were calculated around each reactor and SST from the results. Net denitrification in the anoxic zones was very low, on average only 2 and 23 mgN/ℓ influent for Modules A and B respectively. Compared with the influent TKN of 95 to 98 mgN/ℓ, with such low denitrification it is impossible to achieve effluent nitrate concentrations between 10 and 17 mgN/ℓ unless significant simultaneous nitrification-denitrification was taking place in the anoxic and aerobic reactors. This was confirmed during Periods VII and VIII when the air supply to Module A was increased and resulted in a net nitrate production (nitrification) in the anoxic reactor. While such simultaneous N removal can have advantages, it comes at considerable risk to nitrification, indicated by the relatively incomplete nitrification. The overall average N removal was 77 % for Modules A and B. The average N balances calculated for Modules A and B were 57 % and 76 % respectively due to the simultaneous nitrification-denitrification in the anoxic and aerobic reactors (in the N balance calculations it is assumed that no denitrification takes place in the aerobic reactor and no nitrification in the anoxic reactor). Operation of the laboratory scale UCT system also confirmed simultaneous ND - this system yielded a good (99 %) N balance (verifying that no simultaneous ND took place in it) and its effluent nitrate concentration was 38 mgN/ℓ, double that of the pilot plants. Furthermore, the lab system VSS and TSS concentrations were ~40 % lower than those in the pilot plants indicating that sludge ingress was substantial.

iii) Biological P removal

With the exception of Module A Period III, the filtered (< 0.45 μm) effluent TP concentration > 2 mgP/ℓ, indicating that the P removal was not limited by the influent P concentration. This allowed the overall average system P removal capacity for Modules A and B to be measured, which based on unfiltered influent and filtered effluent TP was 10.0 and 9.3 mgP/ℓ influent respectively. The P removal attained was considerably reduced below that potentially achievable due to the high concentration of nitrate recycled to the anaerobic reactors; on average at 5.6 and 5.0 mgN/ℓ for Modules A and B respectively. This reduced the P removal by an estimated 3 mgP/ℓ. Nevertheless, consistently good biological P removal was obtained at 0.015 and 0.014 mgP/mg influent COD for Modules A and B respectively. In contrast to the N mass balance, the overall average P mass balance for Modules A and B were excellent, at 103 and 97 % respectively.

The average anaerobic P release was very similar in both modules at 26 and 29 mgP/ℓ influent for Modules A and B respectively. The average aerobic P uptake in Module B is significantly higher than in Module A at 45 compared with 19 mgP/ℓ influent respectively. In the anoxic reactors the two modules appeared to exhibit divergent behaviour. Throughout the investigation P uptake occurred in the anoxic reactor of Module A, while in Module B P release occurred in the anoxic reactor. For Module A, over the investigation 48 % of the P uptake occurred in the anoxic reactor. Initially it was thought this was anoxic P uptake in Module A. Hu *et al.* (2001) noted that anoxic P uptake tends to be stimulated by an overload of nitrate on the anoxic reactor and has been observed quite often in laboratory-scale and full-scale plants. When it takes place, the BEPR is only two thirds to three quarters of BEPR with predominantly (>90 %) aerobic P uptake (Ekama and Wentzel, 1997). So its occurrence in Module A is apparent and not real because (i) both modules were overloaded with nitrate, (ii) had similar average anoxic nitrate concentrations and (iii) aerobic P uptake took place in Module B and (iv) the BEPR was the same in both modules. Moreover, when the air supply to Module A was increased (at the expense of Module B), the anoxic reactor switched from poor denitrification (2 mgN/ℓ) to nitrification (5 mgN/ℓ) confirming that the reactor was more aerobic than anoxic. Although not apparent during the investigation, the occurrence of P uptake in the anoxic reactor therefore is best explained as aerobic P uptake as a result of excessive DO ingress into the Module A anoxic reactor. Thus for Module A the experimental evidence suggested P uptake by PAOs under aerobic conditions rather than under <u>anoxic</u> conditions. This was later confirmed after termination of the investigation - many air leaks were found in the air distribution network passing through the anoxic reactor.

To determine the unbiodegradable particulate COD fraction ($f_{S,up}$) of the sewage fed to the pilot plants, the appropriate $f_{S,up}$ value was selected so that the system VSS mass calculated with the BEPR model of Wentzel *et al.* (1990) was equal to the measured VSS mass using the measured influent readily biodegradable COD (RBCOD) concentration, the influent characteristics of the sewage (*i.e.* $f_{S,us}$ and total influent COD) and the known system parameters (anaerobic mass fraction and sludge age) as input taking due account of the nitrate recycled to the anaerobic reactor. An overall average $f_{S,up}$ value of 0.239 was estimated. The P content of the PAOs ($f_{XBG,P}$) was estimated as that value which set the calculated P removal equal to the measured P removal. An overall average $f_{XBG,P}$ value of 0.322 mgP/mgPAOAVSS was estimated for the pilot plants. A $f_{S,up}$ value of 0.239 for the settled wastewater is far too high and is the result of the sludge ingress from the main treatment plant. Accordingly a more realistic $f_{S,up}$ of 0.05 was selected for the settled wastewater (the lab-scale system yielded a $f_{S,up}$ of 0.03) and the calculations repeated. The $f_{S,up}$ of 0.05 yielded a PAO P content ($f_{XBG,P}$) of 0.39 mgP/mgPAOVSS which is very close to the Wentzel *et al.* (1990) model standard of 0.38 for 100 % aerobic P uptake BEPR, confirming that the BEPR in the pilot plants was normal aerobic P uptake BEPR, and as high as can be expected.

Sludge settleability and filamentous organisms

The filament most frequently dominant in both Module A and B was *M. parvicella* (41 and 44 % respectively). The next most frequently dominant filaments were type 0092 and type 1851. All of these filaments are classified as typical of the low F/M category (Jenkins *et al.*, 1984) later renamed Anoxic-Aerobic(AA) (Casey *et al.*, 1994) and are almost always observed in full scale NDBEPR systems whether bulking or not (Blackbeard *et al.*, 1986, 1988). In both modules the anoxic nitrite concentrations were very low throughout the investigation with an overall average of 0.17 and 0.25 mgN/ℓ for Modules A and B respectively. In both modules anoxic nitrate concentrations were high, with an overall average of 5.36 and 5.17 mgN/ℓ for Modules A and B respectively. The high nitrate concentrations in the anoxic reactors indicated that the proposed control of nitrate in the Module A anoxic reactor to low concentrations had not been achieved in practice, even though the 'a-recycle' was set to zero from Period III onwards. However, the proposed control of nitrate in the Module B anoxic reactor to high concentrations had been achieved in practise. Thus, while it was not possible to demonstrate the effect of complete anoxic denitrification on sludge settleability, the effect of incomplete anoxic denitrification could be demonstrated. However, because the intended anoxic and aerobic conditions were not achieved in the anoxic and aerobic reactors, and these reactors were a continuous quasi anoxic quasi aerobic reactor, it is difficult to apply the AA filament bulking hypothesis to the results. In terms of the hypothesis and the bulking control strategy, since both modules have high anoxic nitrate concentrations both should produce a bulking sludge due to AA filament proliferation. In contrast both modules produced very good settling sludges with low overall DSVIs of 97 and 102 mℓ/gTSS and at no time during the investigation did the 7 day moving average DSVI exceed 120 mℓ/gTSS in both modules. The quasi anoxic quasi aerobic conditions in the pilot plants would be similar to those in Carousel, Orbal and ditch type ND systems, which often produce poor settling sludges, yet the sludge in the pilot plants settled well. To compound the matter further, the laboratory scale system fed the same wastewater with 0:1 'a-recycle' like Module A but with defined anoxic and aerobic conditions and high anoxic to aerobic transition nitrate concentration (2.1 mgN/ℓ) produced a poor settling sludge (DSVI > 250 mℓ/gTSS), as expected from the AA filament bulking hypothesis.

Simulation of pilot plant performance

By giving the same influent flow and concentrations and system design parameters as input, the system performance was modeled with two NDBEPR simulation programmes, *UCTPHO* (Wentzel *et al.*, 1992) and *BIOWIN* (Envirosim & Associates, Canada, 2001 release), the first representing models based on 100 % COD balance and the latter representing models that have included the inexplicable COD loss. Because the modules could not be operated with well defined aerobic and anoxic conditions and without sporadic sludge ingress, the measured results cannot be used to comment on the model predictions. Therefore, the second objective, that of establishing whether or not the unexplained COD loss observed in laboratory scale NDBEPR systems also takes place in large scale systems, could not be validated.

Conclusions

Despite the significant expenditure by the CMC to modify and refurbished the pilot plants to UCT NDBEPR systems and major effort in operating, monitoring and analysis of the pilot plants, the persistent problems with the aged fine bubble aeration system, back-mixing of mixed liquor across the anoxic-aerobic reactor baffle and the back flow of sludge from the main treatment plant, prevented achieving the project objectives.

(1) COD mass balances could not be done so no additional information could be obtained

to date on the unexplained COD loss in NDBEPR systems.

(2) From the way the pilot plants actually operated, *i.e.* significant simultaneous ND in the quasi-anoxic quasi-aerobic conditions of the anoxic and aerobic reactors, in terms of the AA filament bulking hypothesis, AA filament bulking should have taken place in both modules, but didn't. Orbal, Carousel and other ditch type ND systems also have such simultaneous ND conditions and often have bulking sludge. Curiously, the parallel UCT system did produce an AA filament bulking sludge in conformity with the AA bulking hypothesis. In seeking an explanation for this divergent behaviour one possibility is the difference in aerobic DO concentration; Casey *et al.* (1994) have demonstrated that aerobic DO does influence DSVI. This is an area that requires further research. Clearly finding an absolute cure for AA filament bulking in NDBEPR systems remains elusive despite the considerable South African and international research attention it has received over the past 20 years.

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LIST OF ABBREVIATIONS AND SYMBOLS

SYMBOL	DESCRIPTION
AA	Anoxic-aerobic; group name for most of the low F/M filamentous organisms
ADWF	Average dry weather flow
ASM	Activated sludge model
BEPR	Biological excess phosphorus removal
BIOWIN	Activated sludge simulation programme by Envirosim & Associates, Canada, 2001 release
BNR	Biological nutrient removal
BNRAS	Biological nutrient removal activated sludge
°C	degree(s) Celsius
CMC	Cape Metropolitan Council administration of the City of Cape Town
COD	Chemical oxygen demand
d	day(s)
DO	Dissolved oxygen
DOHO	Denitrifying ordinary heterotrophic organism (OHO)
DPAO	Denitrifying polyphosphate accumulating organism (PAO)
DSVI	Diluted sludge volume index
ESS	Effluent suspended solids
et al.	and others
$f_{av,OHO}$	Active fraction of the sludge with respect to the OHOs
$f_{av,PAO}$	Active fraction of the sludge with respect to the PAOs
f_{cv}	COD to VSS ratio of the volatile sludge mass
$f_{S,up}$	Unbiodegradable particulate COD fraction in the influent

SYMBOL	DESCRIPTION
$f_{S,us}$	Unbiodegradable soluble COD fraction in the influent
f_{ts}	RBCOD fraction with respect to the total influent COD concentration
$f_{XBG,P}$	Fraction of PAO biological active mass that is phosphorus
F/M	Food to microorganism ratio
FSA	Free and saline ammonia
h(r)	Hour(s)
IWA	International Water Association
IAWQ	International Association on Water Quality
lab	Laboratory
MUCT	Modified University of Cape Town system for biological removal of nitrogen and phosphorus
N	Nitrogen; all nitrogen concentrations *i.e.* nitrate, nitrite or TKN are expressed as mgN/ℓ
NO	Nitric oxide
NO_3; NO_2	nitrate and nitrite respectively as N
NO_x	Nitrate + nitrite
NO,N_2O	nitric oxide and nitrous oxide respectively, the two gaseous denitrification intermediates between NO_2 and N_2
N_2	Di-nitrogen gas, the end product of denitrification
N & P	Nitrogen and phosphorus
OHO	Ordinary heterotrophic organism
OUR	Oxygen utilisation rate; mass oxygen utilised per unit reactor volume per unit time
P	phosphorus expressed as mgP/ℓ
PAO	Poly-phosphate accumulating organism

SYMBOL	**DESCRIPTION**
PDWF	Peak dry weather flow
PST	Primary settling tank
PWWF	Peak wet weather flow
RAS	Return activated sludge
RBCOD	Readily biodegradable COD component of the influent COD
R_s	Sludge age in days
SBCOD	Slowly biodegradable COD component of the influent COD
SRT	Solids retention time
SS	Suspended solids
SST	Secondary settling tank
S_{ti}	Total COD concentration in the influent expressed as mgCOD/ℓ
S_{bsi}	Biodegradable soluble COD concentration expressed as mgCOD/ℓ
TEFL	Total extended filament length
TFL	Total filament length
TKN	Total Kjeldahl nitrogen
TKN/COD	Ratio of the influent TKN and COD concentrations
Total P or TP	Total phosphorus
TSS	Total suspended solids
UCT	University of Cape Town. Also name of activated sludge system for biological removal of nitrogen and phosphorus
UCTPHO	Activated sludge simulation programme based on Wentzel *et al.* (1992) model
USCOD	unbiodegradable soluble chemical oxygen demand
VFA	Volatile (or short-chain) fatty acids

SYMBOL	DESCRIPTION
VSS	Volatile suspended solids
WAS	Waste activated sludge
WRC	Water Research Commission, a water research co-ordination and funding agency in South Africa
WWTP	Wastewater treatment plant
3-D	Three-dimensional
θ	Arrhenius coefficient for temperature dependency

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This thesis examines at pilot scale (~2 Mℓ/d) two important aspects of biological nutrient removal activated sludge (BNRAS) systems *viz.* :

(1) Control of low F/M filamentous bulking and
(2) Low COD balances (80 - 85 %) and undetermined COD loss in nitrification-denitrification (ND) biological excess phosphorus removal (BEPR) systems compared with ND systems.

1.2 BACKGROUND TO LOW F/M FILAMENT BULKING

The activated sludge process is an efficient means whereby the nutrients nitrogen (N) and phosphorus (P) can be reduced biologically to low concentrations in municipal wastewater effluents. However, a major disadvantage of the process is that in the sludge mass which develops, filamentous organisms can proliferate which results in poor settleability of the sludge in the secondary settling tank. From a survey of nutrient removal plants in South Africa (Blackbeard *et al.*, 1988) it was found that out of 45 BNRAS plants, 33 had bulking problems of considerable proportions which severely reduced the treatment capacity of these plants.

It has been shown by Ekama and Marais (1986) that an important factor limiting the treatment capacity of an activated sludge plant is the inefficient separation of solids from the liquid phase in the secondary settling tank caused by poor sludge settleability. For a mixed liquor with a suspended solids concentration of 3.5 g/ℓ and a Diluted Sludge Volume Index (DSVI) of 150 mℓ/g a maximum overflow rate of 1 m/h can be achieved without settling tank failure (*i.e.* solids carry over). If the DSVI is reduced from 150 mℓ/g to 100 mℓ/g the maximum overflow rate can be increased to 1.8 m/h, thereby increasing the treatment capacity by 2/3. However, if the DSVI deteriorates from 150 mℓ/g to 200 mℓ/g then a reduction in maximum overflow rate to 0.6 m/h can be expected, effectively reducing the treatment capacity by 1/3. These findings demonstrate the importance of developing and maintaining a good settling sludge. The large potential savings from increasing the treatment capacity of activated sludge plants through improvement in sludge settleability have motivated considerable research into the causes of bulking.

Bulking is caused by the excessive growth of filamentous organisms which leads to a deterioration in the separation of solids from the liquid phase. If a sludge contains very small quantities of filamentous organisms and is dominated by floc formers, then pin-point flocs result, which while providing a good settling sludge, tends to generate a poorly clarified effluent. Conversely, a sludge which is largely made up of filamentous organisms will settle poorly but generate a very well clarified effluent (if carry-over of solids is avoided). Clearly, the correct combination of these two extremes is desirable such that a good settling sludge is produced together with a well clarified effluent.

Lee *et al.* (1983) investigated the effect of the presence of different quantities of filamentous organisms - measured by Total Extended Filament Length (TEFL, km/g) - on the sludge settleability parameters Sludge Volume Index (SVI) and Diluted Sludge Volume Index (DSVI). They found that the DSVI was much better correlated to the TEFL than the SVI and when the DSVI increased above 150 mℓ/g, filamentous organisms began to dominate the settling characteristics of the sludge. From this finding, a sludge with a DSVI of greater than 150 mℓ/g is regarded as a bulking sludge. DSVI values between 80 and 100 mℓ/g are regarded as ideal because these have sufficient filaments to enable good flocculation and clarification but insufficient filaments to cause poor settleability.

The current methodology for analysis and control of filamentous bulking sludges is to use the filament categorization method of Jenkins *et al.* (1984) in which the presence of a specific filament type causing bulking is associated with a causative wastewater characteristic or a process operating condition (see Table 1.1). Eliminating the causative condition will result in cessation of proliferation of the specific filament type and hence amelioration of the bulking problem. This method of controlling filament bulking is termed "specific" and contrasts with "non-specific" control methods such as chlorination which impairs the growth of filamentous organisms to a greater extent than floc-formers because of their high surface area to volume ratio. The use of non-specific methods for the control of bulking does not address the causes of filament proliferation but merely treats the symptoms. Consequently, it was desirable to develop specific methods which control the causative filamentous organisms and to do this a more fundamental understanding of the interaction between floc-formers and filaments was necessary. Filament identification surveys of South African N & P removal activated sludge plants (Blackbeard *et al.*, 1988) indicated that the six most commonly dominant filamentous organisms were types 0092, 0675, 0041, *M. parvicella*, types 0914 and 1851. From Table 1.1 the first four of these belong to the Jenkins *et al.* (1984) low food to micro-organism ratio (F/M) group. Therefore in order to improve sludge settleability in low F/M or long sludge age BNRAS plants in South Africa, control strategies need to be investigated to minimize proliferation of filaments in the low F/M group.

Table 1.1 Categorisation of filaments according to certain causative conditions (Jenkins *et al.* 1984).

Suggested causative conditions	Indicative filament types
Low F/M ratio	*M. parvicella*, types 0041, 0675, 0092, 0581, 0961, 0803, 021N, *H. hydrossis*, *Norcardia* spp.
Low dissolved oxygen	Type 1701, *S. natans*, *H. hydrossis*
Presence of sulphide / septic sewage	*Thiothrix* spp., *Beggiatoa* spp., type 021N
Low pH	Fungi
Nutrient deficiencies	*S. natans*, *Thiothrix* spp., type 021N, and possibly *H. hydrossis*, types 0041, 0675

Chudoba *et al.* (1973) proposed a selection criterion to explain the occurrence and non-occurrence of filament bulking in low F/M systems, which was based on the differences in growth kinetics between floc-formers and filamentous organisms at different substrate concentrations. In the Monod formulation for specific growth rates it was found that filamentous organisms generally have lower values for both the half saturation coefficient (K_S) and the maximum specific growth rate (μ_H) making them more responsive to low bulk liquid substrate concentrations. Hence, in low F/M or long sludge age plants, filamentous organisms have a selective advantage and tend to dominate over the floc-forming organisms, thereby producing a poor settling sludge. Resulting from this, it was proposed that if a "selector" reactor was introduced to a system such that the substrate concentration in this reactor was maintained at a high level, then floc-formers would be selected for because of their higher maximum specific growth rate at high substrate concentrations. The mixed liquor would then tend to contain fewer filamentous organisms, producing a sludge with better settling characteristics. This idea stimulated considerable research into the use of selectors for low F/M filament bulking control, but by 1984 it became apparent that Chudoba's selection criterion does not completely account for the proliferation or suppression of this filamentous organism group with either aerobic or anoxic selectors. From the research it appeared that *S. natans* and *Thiothrix*, which are not low F/M filaments, and 021N, are possibly controlled by inducing a selector effect (Gabb *et al*., 1988), but there was still no conclusive evidence that the low F/M filaments are controlled by this method. Consequently a four year investigation (1985-1988) was initiated at UCT to consolidate and in some cases repeat experiments reported in the literature so as to provide conclusive evidence whether or not the low F/M filamentous organisms are controlled by selectors. A number of different experiments were carried out by Gabb *et al*. (1989a, 1991), in which the effect of anoxic, aerobic and anaerobic selectors on low F/M filament bulking was examined in fully aerobic, anoxic-aerobic and anaerobic-anoxic-aerobic systems. It was concluded that, although anoxic and aerobic selectors were (and still are) promoted as being a specific method for the control of low F/M filament bulking, they in fact did not do so (Ekama *et al*., 1996). This finding together with the observation that low F/M filament bulking seemed associated with alternating anoxic-aerobic conditions rather than the selector effect, terminated the selection criterion approach, both kinetic selection (anaerobic or anoxic selectors) and metabolic selection (anoxic or anaerobic selectors/reactors) and placed bulking research into low F/M filament bulking in N and N&P removal plants back into an exploratory stage.

A second wide-ranging follow-up research investigation began in 1989 to study the effect of various sewage characteristics and system operating parameters on low F/M filament bulking, in particular the low F/M filament response to:

(1) Readily biodegradable or slowly biodegradable COD from artificial substrate and real

sewage.

(2) Plant configurations (*i.e.* fully aerobic; fully anoxic; intermittent aeration; pre- and post-denitrification; MUCT and JHB).

(3) Sludge age [*i.e.* short (5 days) or long (22 days)].

(4) Proportion of anoxic/aerobic mass fraction.

(5) Frequency of alternation between aerobic and anoxic conditions.

(6) Dissolved oxygen in the aerobic zone.

(7) Nitrate and nitrite concentrations in the anoxic zone(s).

Some of the above parameters were investigated using artificial substrate by Gabb *et al.* (1989); Ketley *et al.* (1991); Hulsman *et al.* (1992); de Villiers *et al.*(1994); Casey *et al.* (1994). In many instances it was necessary (either for the purposes of confirmation or because the filaments found were not those generally found in full-scale plants), to study the effects of the above parameters with real sewage [Warburton *et al.* (1991); Ketley *et al.* (1991); Hulsman *et al.* (1992); de Villiers *et al.*(1994); Casey *et al.* (1994)] so that additional uncertainties with using artificial substrate did not unnecessarily complicate the objective of finding methods for ameliorating low F/M filament bulking in full scale plants.

From this research it was established that the following conditions have a significant influence on low F/M filament bulking (after Casey *et al.* 1994):

(1) Continuous anoxic or continuous aerobic conditions controlled low F/M filament proliferation to low DSVI values (< 100 mℓ/g).

(2) An aerobic mass fraction of between 30 and 40 % coincided with high DSVI values. In contrast, aerobic fractions greater or less than this are associated with progressively lower DSVIs until fully aerobic or fully anoxic conditions are present.

(3) Low F/M filament proliferation was observed in single reactor intermittent aeration systems irrespective of the biodegradability of the available substrate (*i.e.* RBCOD or SBCOD) for both artificial substrate and real sewage.

(4) Low dissolved oxygen concentration in the aerobic reactor had some influence on low F/M filament proliferation.

(5) The presence of nitrate and/or nitrite concentrations at the time the conditions in the various N and N&P removal systems become aerobic (having been anoxic) was

associated with low F/M filament bulking. In this respect, it appeared that nitrite had a greater influence than nitrate.

From research results Casey *et al.* (1992 a,b; 1994; 1999a,b,c) developed an explanation for the proliferation of low F/M filaments in N and N&P removal plants. Accepting that the filamentous organisms reduce nitrate only to nitrite and the floc-formers denitrify nitrate to dinitrogen gas, when denitrification is not complete in the anoxic reactor (observed by high nitrate and nitrite concentrations at the transition from anoxic to aerobic conditions), intracellular gaseous denitrification intermediates (NO, N_2O) in the floc-formers inhibit their oxygen uptake enzymes when conditions become aerobic. The filaments, which do not accumulate intracellularly those inhibitory denitrification intermediates, are not inhibited in their oxygen uptake ability and therefore have an advantage over the floc-formers. As a consequence Casey *et al.* (1994) renamed the low F/M filaments that tend to proliferate in N and N&P removal plants, anoxic-aerobic (AA) filaments.

From the above findings, Musvoto *et al.* (1992) studied the effect of very large anoxic mass fractions (>50 %) (to ensure low nitrate and nitrite concentrations - < 1 mgNO_x-N/ℓ, at the anoxic to aerobic transition) and concentrations of nitrate and nitrite entering the aerobic zone on low AA (F/M) filament bulking in nutrient removal activated sludge systems. They concluded that it is not the aerobic mass fraction *per se* which affects the proliferation of AA filaments, but rather the concentrations of nitrate and nitrite in the anoxic zone prior to the aerobic zone. Although not with 100 % repeatability, this phenomenon has been observed repeatedly in several subsequent laboratory investigations with NDBEPR (*i.e.* Pilson *et al.*, 1995; Sneyders *et al.*, 1998; and Mellin *et al.*, 1998) and ND (*i.e.* Ubisi *et al.*, 1997; Cronje *et al.*, 2000; and Beeharry *et al.*, 2001) systems. Hence it is desirable, for the purposes of design, to ensure that denitrification is complete (*i.e.* nitrate < 0.5 and nitrite < 0.2 mgN/ℓ respectively) in the anoxic reactor prior to the aerobic reactor.

These findings, while not always repeatable, provided support for the bulking hypothesis of Casey *et al.* (1992a, 1994) which attempts to explain the reason for the connection between high levels of nitrate (and nitrite) present in the anoxic reactor prior to the aerobic reactor, and high values of DSVI. The hypothesis and the experimental work leading to it, is reviewed in more detail in Chapter 2.

1.3 INEXPLICABLE COD LOSS FROM NDBEPR SYSTEMS

A second important phenomenon observed repeatedly in the laboratory-scale investigations on NDBEPR systems cited above as well as those on external nitrification (EN) biological nutrient removal (BNR) activated sludge (AS) systems (Moodley *et al.*, 1999; Sotemann *et al.*, 2000; and Hu *et al.*, 2001), is that in these systems low COD mass balances (80 to 90 %) were observed. In contrast, on ND systems (*i.e.* no anaerobic reactor) invariably the COD mass balances are much higher (90-95 %) and closer to the theoretically expected 100 %. This inexplicable loss of COD in NDBEPR systems has also been observed in other research laboratories *e.g.* Virginia Tech, Wable and Randall (1992). Because the COD mass balance is based on reconciling the COD mass exiting the system via effluent flow, sludge VSS wastage and carbonaceous oxygen demand, with the influent wastewater COD mass, the lower COD mass balance results in lower sludge production and carbonaceous oxygen demand. Indeed so often and repeated has this low COD mass balance been observed over the past decade that certain BNR models coded into commercially available computer simulation packages, include this COD loss (~15 %) and so calculate reduced sludge production and oxygen demand. The mechanism whereby this COD loss is included in the models is via the fermentation process which transforms the readily biodegradable (RB) COD to volatile fatty acids (VFA) in the anaerobic reactor - instead of an equal concentration of VFA being generated from the RBCOD, only a fraction (~50 %) of the RBCOD becomes VFA, the balance is COD that is lost. The fermentation process has been selected for this COD loss because it is one of the few biological processes confined to the anaerobic reactor. The COD loss cannot be due to a lower anoxic heterotrophic yield coefficient (0.54 mgCOD/mg COD instead of 0.66 mgCOD/mgCOD) because this (i) doesn't affect the COD balance and (ii) happens in both ND and NDBEPR systems. The question that arises from this COD loss phenomenon is - does this COD loss also happen at large or full scale so that it is scientifically defensible to include this COD loss and design full scale plants on this basis? Because the pilot plant is potentially a well controlled and monitored plant, it provides an opportunity to check the COD mass balance at a scale 200 000 x larger than laboratory scale.

1.4 RESEARCH OBJECTIVES

The hypothesis of Casey *et al.* (1992a, 1994) and the demonstration of Musvoto *et al.* (1992) indicate that AA filament bulking can be controlled by careful design and operation of the denitrification zones of N and N & P removal systems. However, as the above has been undertaken at laboratory scale, application of the proposed specific methods to control AA filamentous organism bulking needs to be demonstrated at full-scale.

The main objectives of this research were:

(1) *To demonstrate and evaluate at* ***full-scale*** *specific bulking control measures in biological N & P removal systems.*

(2) *To transfer research and development in bulking control undertaken at laboratory-scale to* ***full-scale****.*

(3) *To verify at* ***full-scale*** *the specific bulking control hypothesis developed from research over the past 6 years.*

(4) *To check the COD mass balance at* ***full-scale****.*

1.5 RESEARCH APPROACH

From the hypothesis for bulking by AA filaments, it is evident that if the nitrate and nitrite concentrations leaving the anoxic reactor/zone and entering the subsequent aerobic reactor/zone can be controlled to be < about 1 mgN/ℓ, then bulking by AA filaments should be minimised, and *visa versa*. ***The principal aim of this research project was to demonstrate this control methodology at full-scale.*** For this purpose, the two parallel Stage 1 modules at the Mitchells Plain Wastewater Treatment Plant (WWTP) were used. The two modules were refitted as N & P removal UCT configuration systems, such that the two systems have the same operating parameters. This would allow one system to be used as a control and the other as an experimental system, to compare behaviour. In the one system (Module B), the nitrate/nitrite concentration in the anoxic reactor was to be controlled to be > 2 mgN/ℓ and hence in terms of the hypothesis should bulk, while in the other parallel system (Module A) it was to be controlled to < 1 mgℓ and hence in terms of the hypothesis should not bulk. To control the nitrate/nitrite concentrations leaving the anoxic reactors, the 'a-recycle'[1] (aerobic to anoxic) would be varied to under or overload the anoxic reactors with nitrate as required. In this manner, by monitoring the sludge settleability in the two systems (via the DSVI), the efficacy of the control strategy formulated from the hypothesis could be demonstrated (this approach was shown to be not completely successful due to difficulties in plant operation). The two modules were to be monitored sufficiently intensively and regularly to be able to conduct Total N, Total P and COD mass balances, to see how the COD mass balance compares with laboratory-scale NDBEPR systems. Further, bulking in nutrient removal plants is inextricably linked to the nutrient removal performance (Casey *et al.*, 1992a, 1994). Hence, the data was to be analysed in detail to examine these and possible links to bulking.

During the course of the investigation it became apparent that poor N mass balances were being achieved. To investigate this further, a laboratory-scale system was set up with the same operating parameters as the full-scale systems, and operated in parallel on the same wastewater.

The successful design and operation of full-scale NDBEPR plants have been aided by the development of kinetic simulation models which predict system performance with regard to the biological removal of carbon, nitrogen and phosphorus. Hence, the effect of COD loss in NDBEPR systems would be examined by comparing the measured system performance of the experimental systems with the predicted results of two kinetic simulation programs, *UCTPHO* (no COD loss included) and *BIOWIN* (COD loss included).

[1]In this investigation, the 'a-recycle' refers to the inter-reactor mixed liquor recycle pumped from the end of the aerobic reactor to the beginning of the anoxic reactor.

CHAPTER 2

LITERATURE REVIEW

2.1 PREAMBLE

Casey *et al.* (1994; see also 1999a,b,c) conducted a comprehensive literature review on specific bulking control in order to consolidate and integrate the findings of other researchers with the bulking research program undertaken at the University of Cape Town. It is not the intention in this chapter to do a separate review, but rather to give a brief overview of filamentous organisms and their effect on sludge settleability and thereafter to review the research which ultimately led to the formation of a hypothesis (Casey *et al.*,1994; see also Casey *et al.*, 1999a,b,c) for the causes of filamentous organism proliferation (bulking) in nutrient removal plants. The review ends with a discussion on the objectives of the research presented in the remainder of the document.

2.2 FILAMENTOUS ORGANISMS

Filamentous organisms are a natural component of activated sludge biocenosis and their occurrence, in small quantities, is in fact beneficial. They frequently form a "back bone" to which flocs attach and this increases the overall floc density and in addition, filament lengths extending into the bulk liquid form web-like structures which tend to screen small particles thereby improving clarification. However, when the occurrence of filamentous microorganisms exceeds a certain level (*i.e.* a total extended filament length (TEFL) greater than 30 km/g, Lee *et al.*, 1983; a DSVI greater than 150 mℓ/g, Ekama and Marais 1986; a TEFL greater than 10^7 μm/mℓ or 10^4 m/g, Jenkins *et al.*, 1984) they begin to dominate the settling behaviour of the sludge causing excessive volumes of settled activated sludge in the secondary clarifier due to low compactibility and slow zone settling velocities. There are 29 different types of filamentous bacteria (Eikelboom and van Buijsen, 1981; Jenkins *et al.*, 1984), some of which are associated with foaming rather than with bulking (*e.g. Nocardia* spp. and *Microthrix parvicella*).

While different filaments tend to dominate in WWTPs in different countries [England (Foot, 1992); United States (Jenkins *et al.*, 1984); France (Pujol *et al.*, 1991); Germany (Ziegler *et al.*, 1990); South Africa (Blackbeard *et al.*, 1988)] it is apparent that 12 filaments are frequently found in many activated sludge plants (Wanner, 1993). Of these 12, 9 are included in the 14 filaments identified by Blackbeard *et al.* (1988), which occur in nutrient removal plants in South Africa. Ranked in descending order of occurrence (as opposed to dominance) the top 6 of the above mentioned 14 in South Africa are: type 0092, type 0914, *M. parvicella*, type 1851, type 0675 and type 0041.

Different filamentous organisms proliferate under different conditions and because of this, measures used to control their proliferation must apply to as many different filament types as possible for maximum effect. However, even this is not always sufficient since certain filaments with a similar abundance to others have a greater effect on sludge settleability. For instance the occurrence of *M. parvicella* is believed to influence settleability to a far greater extent than type 0092 (ranked as 3rd and 1st respectively in South Africa by Blackbeard *et al.*, 1988).

2.3 FACTORS AFFECTING THE GROWTH OF FILAMENTOUS ORGANISMS

There are two approaches to the control of filamentous organisms in activated sludge plants. The first is "non specific" control which is designed to address the symptoms of bulking by addition of inhibitory chemicals such as chlorine, ozone or hydrogen peroxide which selectively kill the filaments. While this approach is suitable in emergency situations it is undesirable as a primary control measure (due to cost, the formation of chloro-organics and the fact that it is only a temporary measure) and hence "specific" control, which attempts to address the cause of filament proliferation is preferable. To isolate specific bulking control strategies a wide range of research programs have been conducted to elucidate the factors which affect the growth of filamentous organisms. Since Chudoba *et al.* (1973) proposed an organism selection criterion as an explanation for the occurrence or non-occurrence of filamentous bulking, numerous studies have been conducted both at laboratory-scale and full-scale which have attempted to delineate strategies for the control of these "weeds of activated sludge" (Donaldson, 1932) or the "AIDS of activated sludge" (Rogalla, 1993).

The research reported in this investigation pertains specifically to Nitrogen (N) and Nitrogen and Phosphorus (N&P) removal plants and therefore the following review is devoted to the research applicable only to filamentous bulking in these types of activated sludge plants.

From a wide ranging investigation Ekama *et al.* (1996) concluded that neither kinetic selection (*i.e.* the stimulation of high substrate utilisation rates via the imposition of a soluble COD concentration gradient) nor metabolic selection (*i.e.* the introduction of an anoxic and/or an anaerobic reactor to the system) nor a combination of these could control the proliferation of low F/M filaments in long sludge age nutrient removal activated sludge plants. From this important conclusion it was evident that an additional factor or factors hitherto not considered was responsible for the proliferation of low F/M filamentous organisms in N and Nutrient removal plants. As a foundation for future research, five aspects were identified as possibly influencing filament proliferation. These were:

1) Biodegradability of influent (*i.e.* RBCOD or SBCOD).
2) Continuous aerobic and continuous anoxic conditions (*i.e.* no switching between anoxic and aerobic conditions).
3) Magnitude of aerobic (or anoxic) mass fraction.
4) Concentrations of NO_3^- or NO_2^- in the anoxic zone prior to aeration (or the aerobic zone).
5) The difference between intermittent aeration nitrification-denitrification (IAND) and 2-reactor nitrification-denitrification (2RND) systems.
    - 5.1 Frequency of alternation between anoxic and aerobic conditions, (*i.e.* magnitude of 'a-recycle').
    - 5.2 Utilization of RBCOD under aerobic, anoxic or aerobic/anoxic conditions.
    - 5.3 DO concentration in aerobic zone/period (*i.e.* constant or variable).
    - 5.4 Nitrate concentration in anoxic zone/period (*i.e.* constant or variable).

2.4 EXPLORATORY INVESTIGATION

In order to assess the influence of the above aspects on filament proliferation a series of experimental investigations were carried out using both defined artificial substrate and real municipal sewage as influent. For clarity the work conducted using these two different types of influent is discussed separately below (Part I relates to experiments with defined artificial substrate and Part II relates to experiments with real municipal sewage as influent) although some sections of the work were carried out concurrently. These investigations were carried out using one of the following system configurations:

1) single reactor, either continuously aerobic/anoxic or intermittently aerated nitrification-denitrification (IAND),
2) two reactor, either modified Ludzack-Ettinger (MLE) or Wuhrman, the former being a pre-denitrification system and the latter a post-denitrification system,
3) multi-reactor University of Cape Town (UCT) system or modified UCT (MUCT) systems, capable of N & P removal.

The single and two reactor systems in Parts I and II were operated at 15 days sludge age and the multireactor systems in Part II were operated at 20 days sludge age. All systems were operated at 20 °C.

2.4.1 Part I - Defined Artificial Substrate as Influent

2.4.1.1 Introduction

From initial investigations by Gabb (1988) it became apparent that the initial response to each new batch of real sewage of the laboratory systems being operated, differed with each new batch of real sewage obtained from Mitchell's Plain - a domestic sewage treatment plant in the greater Cape Town area. In an attempt to eliminate these inevitable variations Gabb (1988) motivated for the development of a defined artificial substrate as a substitute for municipal sewage as influent. However, to ensure that the defined substrate was a suitable substitute, it had to have: (1) a similar chemical composition to municipal sewage, (2) a similar kinetic response, and (3) a similar biological response, in that similar organisms types would develop that are similar to those with municipal sewage. A literature survey on sewage compositions was completed and the defined artificial substrate was tested and adjusted such that it complied with the above 3 provisos. While the defined artificial substrate appeared to be an adequate substitute in single reactor batch fed long sludge age systems, it was found that when fed to a MUCT system the response was very different to that exhibited by a similar system fed municipal sewage. It was concluded that the MUCT configuration was too complex, as a starting point, to elucidate the mechanisms inducing bulking and hence attention was focused initially on single reactor systems.

2.4.1.2 Biodegradability of influent (RBCOD or SBCOD)

In work by Casey *et al.* (1994; see also 1999a,b,c) and Lakay *et al.* (1999) the effect of including and removing RBCOD and SBCOD from the artificial substrate was investigated on Intermittent Aeration Nitrification-Denitrification (IAND) systems. It was found that the DSVI increased substantially (from ≈ 500 to ≈ 1000 mℓ/g) following a change from SBCOD only to RBCOD only substrate, and decreased substantially following a change from RBCOD only to SBCOD only substrate, with the dominant filaments being *H. hydrossis* or type 1851, or both. It is difficult to draw direct conclusions from these observations, but it is possible that filaments are either capable of adapting more rapidly to the change in substrate in the short term and that the trend would have reversed over the long term, or that the substrate concentration in the reactor was not sufficient to favour the growth of floc-formers over filaments using the Chudoba selection criteria. In addition, it was also noted by Casey *et al.* (1994; see also 1999a,b,c) that an increase in DSVI corresponded with an increase in combined effluent NO_3^- and NO_2^- concentrations (NO_{2+3}^-) and conversely a decrease in DSVI corresponded to a decrease in effluent NO_{2+3}^-. This suggested that high DSVIs (from greater numbers of filaments) are associated with a reduced denitrification ability of the system. Also using IAND systems, the selector effect was examined by the addition of either aerobic or anoxic selectors. From these investigations it was found that, provided selector reactors were sized such that over 90 % of the influent COD was removed in those reactors and RBCOD-rich substrate was fed to the systems, a dramatic reduction in DSVI was observed. Comparison with similar IAND systems (all without selectors) fed municipal sewage (Warburton *et al.*, 1991) indicated that the use of the artificial substrate tended to "amplify" the DSVIs obtained compared to identical systems fed real sewage.

2.4.1.3 Continuous aerobic and continuous anoxic conditions

Ketley *et al.* (1991) reported that continuous aerobic and continuous anoxic single reactor systems fed artificial substrate developed low DSVIs (≈ 100 mℓ/g). This contrasted sharply with the finding that, in intermittently aerated systems fed artificial substrate, high DSVIs developed (≈ 800 mℓ/g). In order to control the excessive growth of filaments in this system it was exposed to continuous aeration and the DSVI decreased dramatically. On reimposing conditions of intermittent aeration the DSVI increased dramatically. This finding pointed to the switching between aerobic and anoxic conditions as being associated with high DSVIs and confirmed the work of Gabb *et al.* (1989) with real wastewater.

2.4.1.4 Magnitude of aerobic (or anoxic) mass fraction

Work by Casey *et al.* (1994; see also 1999a,b,c) on IAND systems showed that, while low DSVIs were developed in systems which were either completely anoxic or completely aerobic, systems subjected to alternating aerobic an anoxic conditions developed high DSVIs. By adjusting the aerobic period relative to the anoxic period it was possible to determine the worst combination in terms of the highest DSVI and this was found to develop at 30 to 40 % aerobic mass fraction (see Figure 2.1).

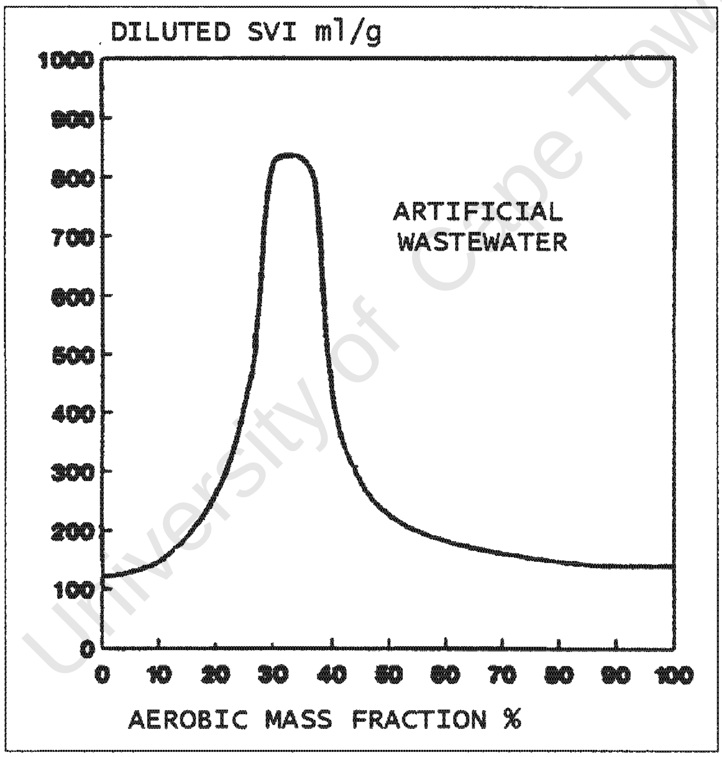

Figure 2.1 : Relationship between sludge settleability (DSVI in mℓ/g) and percentage aerobic mass fraction (%).

2.4.1.5 Concentrations of NO_3^- and NO_2^- in the anoxic zone prior to aeration (or the aerobic zone)

During an investigation into the relative roles of RBCOD and SBCOD in the proliferation of filamentous organisms by Casey *et al.* (1994; see also 1999a,b,c), it was noted that high DSVIs invariably occurred when high concentrations of NO_{2+3}^- were measured in the effluent. To further investigate this observation, an IAND system was operated with continuous NO_3^- addition to the reactor. The DSVI was initially high (>600 mℓ/g) with the effluent NO_{2+3}^- >25 mgN/ℓ. Once the NO_3^- addition was discontinued a dramatic reduction in DSVI was observed to 150 mℓ/g in 20 days due largely to a reduction in the growth of *H. hydrossis*. However, after a further 40 days the DSVI had again increased to over 400 mℓ/g through the proliferation of filament types 1851 and 1701. By removal of the ammonium (NH_4^+) fraction of the influent substrate it was possible to once again reduce the DSVI - this time to 200 mℓ/g after 44 days. The conclusion from these experiments was that there is a relationship between the NO_{2+3}^- in the effluent and the DSVI, although it was still not clear whether high concentrations of NO_{2+3}^- caused filament proliferation or whether filament proliferation caused high concentrations of effluent NO_{2+3}^-.

2.4.1.6 <u>Differences between IAND and 2RND systems</u>

Hulsman *et al.* (1992) operated 2RND systems with an aerobic mass fraction between 30 and 40 % of the total and found that, although the same filaments as were found in IAND systems (with similar mass fractions) occurred in these systems, *viz. H. hydrossis* and type 1851, they tended to develop significantly lower DSVIs (150-200 mℓ/g vs 400-600 mℓ/g). The reasons for this difference between two systems with apparently similar aerobic mass fractions were not specifically investigated with artificial substrate but were identified as relating to the following:

i) Frequency of alternation between anoxic and aerobic conditions is considerably greater in an IAND system (> 30/d), than in a 2RND system (< 5/d) as a consequence of the low mixed liquor a- (aerobic-anoxic) and sludge return s-recycles.

ii) RBCOD is utilized under both anoxic and aerobic conditions in an IAND system, whereas it is utilized exclusively under anoxic conditions in an MLE (pre-denitrification) system and exclusively under aerobic conditions in a Wuhrman system (post-denitrification) system.

iii) The DO concentration in an IAND system is similar throughout the mixed liquor at any given moment, but varies depending on whether it is in an aerobic period or an anoxic period or changing from anoxic/aerobic to aerobic/anoxic. In contrast a 2RND system has a constant high DO (≈>2 mgO/ℓ) in the aerobic reactor and a constant low DO (≈ 0 mgO/ℓ) in the anoxic zone and comparatively small masses of mixed liquor are changing from anoxic/aerobic to aerobic/anoxic at any given moment in time.

iv) The NO_2^- and NO_3^- concentrations in the aerobic period of an IAND system increase or decrease depending on whether conditions are aerobic or anoxic, whereas in a 2RND system, the NO_2^- and NO_3^- concentrations remain constant in the anoxic reactor given consistent concentrations of ammonium (NH_4^+) in the influent (*i.e.* steady state).

The four differences between IAND and 2RND systems identified above formed the basis for another series of experiments, this time on municipal sewage. Since the main objective of using defined artificial substrate had been fulfilled, *i.e.* to assess the impact of SBCOD-rich substrate on filament proliferation, and it was found that the filaments which developed using artificial substrate were not always similar to those found in full-scale plants, the use of defined artificial substrate was discontinued and all further experiments were conducted using real municipal sewage.

The importance of developing the same types of filamentous organisms in laboratory-scale investigations as are found in full scale plants, to establish credibility of the results from laboratory scale systems, prompted the re-examination of many of the aspects described above - but this time using municipal sewage. A summary of the results and discussion of these experiments follows in Part II below.

2.4.2 Part II - Municipal Sewage as Influent

2.4.2.1 Introduction

Using municipal sewage as influent, the five aspects identified previously as possibly influencing filament proliferation in N or nutrient removal plants motivated further research which is reviewed below. In addition the effect of sludge age on filament proliferation also received attention.

2.4.2.2 Biodegradability of influent (RBCOD or SBCOD)

Although Warburton *et al.* (1991) did not specifically study the effects of RBCOD-rich or SBCOD-rich substrates on filament proliferation it was apparent that with average proportions of RBCOD and SBCOD, the DSVIs obtained using municipal sewage tended to be lower than those obtained using defined artificial substrate.

2.4.2.3 Continuous aerobic and continuous anoxic conditions

In work by Casey *et al.* (1994; see also 1999a,b,c) it was found that whereas IAND systems tended to develop high DSVIs (250 mℓ/g), when these systems were subjected to continuous aeration the DSVIs decreased to below 100 mℓ/g from above 150 mℓ/g in approximately 17 days (*i.e.* just over a sludge age). These findings are in agreement with results obtained by Ketley *et al.* (1991) and by Gabb *et al.* (1989). It was further noted from the work of Casey *et al.* (1994; see also 1999a,b,c) that acceptable COD balances of between 95 and 100 % were generally obtained for systems subjected to continuous aeration. However, once these systems were subjected to intermittent aeration, COD balances deteriorated to as low as 73 %. At the time this work was carried out there was no satisfactory explanation for this, but from subsequent work a possible explanation has been put forward by Casey *et al.* (1994; see also 1999a,b,c) and is discussed later in this document in the section on the Casey bulking hypothesis.

Ketley *et al.* (1991) also investigated the effect of continuous anoxic conditions on filament proliferation and found that if continuous anoxic conditions were imposed on a system with a high DSVI (≈ 200 mℓ/g), this could be reduced (to ≈ 89 mℓ/g). This finding indicated once again that switching between anoxic and aerobic conditions promotes filamentous bulking under certain (and at this stage unexplained) conditions.

2.4.2.4 Magnitude of aerobic (or anoxic) mass fraction

In nitrification-denitrification systems, regardless of their configuration, the mass of nitrate generated is dependent on the influent Total Kjeldahl Nitrogen (TKN). The ammonium (NH_4^+), which contributes approximately 75 % of the nitrogen which makes up the TKN, is utilized as substrate by the autotrophs and because the growth rate of autotrophs is considerably slower than that of heterotrophs, the size of the aerobic reactor (or the aerobic sludge age) must be sufficient to ensure complete nitrification. In addition to these constraints, the size of the aerobic mass fraction has also been observed to influence the DSVI. Warburton *et al.* (1991) studied the effect of the aerobic sludge mass fraction in IAND systems on the proliferation of filaments. In this investigation, conducted at 10 days sludge age, it was found that a 30 % aerobic mass fraction produced much higher DSVIs than a 70 % aerobic mass fraction. A similar conclusion was arrived at by Casey *et al.* (1994; see also 1999a,b,c) who conducted experiments using an MUCT configuration. In this investigation, two systems were operated for 180 days, and it was found that with an aerobic mass fraction of 33 %, DSVIs of ≈ 200-250 mℓ/g were obtained and this decreased to 100-150 mℓ/g when the aerobic mass fraction was increased to 65 %. It was also noted that when the DSVI increased, as a result of a reduction in aerobic mass fraction, the effluent NO^-_{2+3} decreased which appeared, initially, to conflict with earlier findings. However, this observation was explained by the fact that a reduction in aerobic mass fraction was essentially an increase in anoxic mass fraction and *visa versa*. Since the larger the anoxic mass fraction the larger the system's denitrification potential, this meant that decreasing the aerobic mass fraction (and hence increasing the anoxic mass fraction) increased the system denitrification potential and consequently reduced the effluent NO_{2+3}^-. With regard to the N balances of these systems, it was observed that high or increasing DSVIs tended to produce low N balances, whilst low or decreasing DSVIs tended to produce higher and more acceptable N balances. Work by Musvoto *et al.* (1992) investigated the effect of a large anoxic mass fraction (>50 %) on the proliferation of low F/M filaments and concluded that it is not the anoxic mass fraction *per se* which affects the proliferation of low F/M filaments, but rather the extent to which denitrification is complete in the anoxic reactor preceding the aerobic reactor.

2.4.2.5 Concentrations of NO_3^- and NO_2^- in the anoxic zone prior to aeration (or the aerobic zone)

Casey *et al.* (1994; see also 1999a,b,c) investigated the influence of NO^-_{2+3} concentrations in the 2nd (*i.e.* pre-aerobic) anoxic reactor of MUCT systems and showed that increasing the TKN/COD ratio of the influent to 0.12 to 0.14 by addition of ammonium (NH_4^+), increased the NO^-_{2+3} concentration in the 2nd anoxic reactor and also increased the DSVI. Conversely, reducing the influent TKN/COD ratio from 0.08 to 0.10, by discontinuing ammonium addition, reduced the NO^-_{2+3} concentration in the 2nd anoxic reactor and also reduced the DSVI. It was further observed from these experiments that as the DSVI decreased the VSS increased, and as the DSVI increased the VSS decreased.

As noted in a previous investigation of Casey *et al.* (1994; see also 1999a,b,c) concerning N balances, it was apparent that low N balances were obtained when DSVIs were high or increasing, while high N balances were obtained when DSVIs were low or decreasing.

The investigation of Casey *et al.* (1994; see also 1999a,b,c) described above showed that high concentrations of NO_{2+3}^- in the anoxic reactor preceding the aerobic reactor were associated with high DSVIs. It was not clear, however, from these experiments whether the DSVI correlated more closely to the concentration of nitrate or nitrite.

2.4.2.6 Sludge age

From work done by Warburton *et al.* (1991) who examined the effect of sludge age on the proliferation of filaments in an IAND system, it appears that reducing the sludge age of a system from 20 days to 10 days has little effect on DSVI. Reducing the sludge age still further, from 10 to 7 and then to 5 days did reduce DSVI marginally, but short sludge ages (*i.e.* < 10 days) are detrimental to the maintenance of stable nitrification, particularly at cold temperatures (*i.e.* winter conditions) and thus cannot be realistically put forward as a control mechanism for filament proliferation in nutrient removal plants. Foot *et al.* (1994) came to the same conclusion from full scale plant operation.

2.4.2.7 The difference between intermittent aeration nitrification-denitrification (IAND) and 2-reactor nitrification-denitrification (2RND) systems

From work performed with artificial substrate (see Part I) certain differences between IAND and 2RND systems were identified as areas where further research was required in order to explain the different behaviour of these two types of system (with regard to filament proliferation) which had apparently similar operating conditions. The differences identified (*i.e.* the frequency of alternation between anoxic and aerobic conditions, the utilization of RBCOD under anoxic, aerobic or anoxic/aerobic; the DO concentration - constant or variable; the nitrate concentration - constant or variable) are discussed below and their relative impacts on filamentous bulking reviewed.

i) The frequency of alternation between anoxic and aerobic conditions

Ketley *et al.* (1991) conducted experiments on IAND systems with aerobic periods of 30 % relative to the total and with NO_3^- dosed throughout the anoxic period to ensure that conditions did not become anaerobic which might have provided suitable conditions for the biological removal of Phosphorus - a further undesirable complication. To assess the effect of the frequency of exposure of the sludge to anoxic and aerobic conditions the anoxic-aerobic cycle lengths were varied between 20 minutes and 3 days. It was found that proliferation of low F/M filaments took place irrespective of the frequency of anoxic-aerobic cycles.

In follow-up work conducted by Hulsman *et al.* (1992), two 2RND systems were operated, with aerobic mass fractions of 30-40 % of the total. The 'a-recycle' ratio (from the aerobic reactor to the anoxic reactor) in one system was relatively low (3:1) while the 'a-recycle' in the other was high (> 30:1). With an 'a-recycle' ratio of > 30:1 it was hoped that a frequency of alternation similar to that found in an IAND could be achieved. However, it was found that neither the system with a low 'a-recycle' nor that with a high 'a-recycle' promoted the growth of filamentous organisms. These findings indicated that the frequency of exposure of the sludge to anoxic-aerobic conditions could not be the difference between an IAND and a 2RND system which promotes bulking in the former but not in the latter.

ii) Utilization of RBCOD under anoxic, aerobic or anoxic-aerobic conditions

In order to approximate the feeding pattern of an IAND system, Casey *et al.* (1994; see also 1999a,b,c) conducted experiments using a 2RND system in which the influent was fed to the anoxic and aerobic reactors in proportion to their contributions to the total sludge mass of the system. This investigation was conducted over a period of 56 days during which time the DSVI remained constant at 150 mℓ/g. The conclusion from this work was that the feeding pattern, provided feeding to either the anoxic zone or the aerobic zone was continuous, did not appear to stimulate filament proliferation. In further work on this aspect by Casey *et al.* (1994; see also 1999a,b,c), sewage was separated into RBCOD and SBCOD using ultrafiltration and these separate sewage fractions were fed to different IAND systems to assess their influence on filament proliferation. In one system, the DSVI remained >200 mℓ/g irrespective of whether RBCOD or SBCOD was used as influent, but on closer examination the dominant filament present was found to be type 021N which is often associated with septic sewage. In the other IAND system, it was found that the DSVI increased to ≈400 mℓ/g from the proliferation of the low F/M filament *M. parvicella*, when SBCOD was used as influent, and decreased initially to <150 mℓ/g when RBCOD was used as influent. However, this decrease was short-lived and the proliferation of *H. hydrossis* and type 1701 caused the DSVI to increase again to ≈400 mℓ/g. These findings confirmed results obtained previously by Still *et al.* (1985) (see also Ekama *et al.*, 1986) which suggested that low F/M filaments do not require RBCOD to proliferate, even in nitrification-denitrification systems.

To assess the effect of utilization of RBCOD exclusively in a predenitrification anoxic reactor (*i.e.* anoxic reactor of an MLE system) and exclusively in an aerobic reactor (*i.e.* aerobic reactor of a post-denitrification system), an investigation was carried out by Casey *et al.* (1994; see also 1999a,b,c), in which RBCOD was fed to an IAND system only during the aerobic period, and then in a separate investigation, only during the anoxic period. It was found that when RBCOD was fed during the aerobic period the DSVI declined rapidly and when fed during the anoxic period, increased rapidly due to the presence of *H. hydrossis* and type 0041. From these experiments it was concluded that with RBCOD as substrate, low F/M filaments common to nutrient removal plants did not proliferate irrespective of whether it was fed during exclusively aerobic or anoxic conditions and also during anoxic-aerobic conditions (*i.e.* continuously fed to an IAND system).

iii) The effect of a variable or constant DO concentration

Another difference between IAND and 2RND systems is that in the former at any given time the DO concentration throughout the sludge mass is the same but this value depends on whether aeration is taking place in the reactor or not or whether the system is in a transition phase between aerobic and anoxic conditions. In a 2RND system, the DO concentration in the aerobic reactor is always high (*i.e.* >2.0 mgO/ℓ) whilst the DO concentration in the anoxic reactor is zero with the change taking place rapidly. In order to assess whether these differences are responsible for the greater low F/M filament proliferation observed in an IAND system, two sets of experiments were carried out by Casey *et al.* (1994; see also 1999a,b,c). In the first set, experiments were conducted on IAND systems to examine the effect of low DO (*i.e.* 0.2 < DO < 0.5 mgO/ℓ) conditions on filament proliferation, and the following observations were made:

1) In spite of the low DO (0.2 < DO < 0.5 mgO/ℓ) conditions, filaments did not proliferate if aeration was continuous.

2) For an IAND system with a high DSVI, amelioration of the bulking condition was achieved more rapidly by continuous aeration at a high DO (*i.e.* 0.2 < DO < 2.0 mgO/ℓ) than at a low DO (0.2 < DO < 0.5 mgO/ℓ).

3) For an IAND system operated with cycles set at 35 % aerobic and 65 % anoxic, the higher the peak DO during the aerobic period, the higher the DSVI.

4) The presence of an anoxic period adversely influences sludge settleability.

In the second set of experiments, 2RND systems were operated to examine the effect of a decreasing DO concentration. In an attempt to prevent the sudden reduction in DO normally experienced by sludge in the 'a-recycle' which passes from the aerobic reactor with a high DO concentration, to the anoxic reactor with a negligible DO, a small reactor was introduced to the 'a- recycle'. The DO in this reactor was controlled to be < 0.5 mgO/ℓ. Resulting from this modification, a small reduction in DSVI was noted from ≈ 155 mℓ/g to ≈ 120 mℓ/g in 41 days. This reduction, however, was not considered to be significant and thus the conclusion drawn from this experiment was that the comparatively slow decrease in DO, inherent in an IAND system, compared with the rapid decrease in DO from aerobic to anoxic conditions in a 2RND system is not responsible for the proliferation of filaments in the former system.

iv) Variable or constant NO_3^- concentration

The fourth difference between IAND and 2RND systems concerns the concentration of NO_3^-. For an IAND system at the beginning of an anoxic period, the nitrate concentration is initially high but decreases during the anoxic period to zero or to some positive value depending on whether denitrification is complete or incomplete respectively. At the beginning of the aerobic period, the concentration depends on the extent of denitrification in the preceding anoxic period, and then increases to some maximum value related to the nitrification rate and/or the initial mass of ammonium (NH_4^+) available for nitrification. The concentration of nitrate is thus in a constant state of flux in an IAND system. However, in a 2RND system operating under steady state conditions, the nitrate concentration in the aerobic reactor is constant at some high value related to the influent ammonia (NH_4^+). Also, the nitrate concentration in the anoxic zone is constant and is set by the extent of denitrification. If the nitrate concentration is negligible then denitrification is complete but if appreciable concentrations of nitrate are present, then denitrification is incomplete, *i.e.* residual concentrations remain when conditions become aerobic.

To examine this difference in the nitrate concentration between IAND and 2RND systems, a series of experiments were conducted by Casey *et al.* (1994; see also 1999a,b,c) in which the redox potential and nitrate/nitrite concentrations were measured. Initially, a 2RND system was operated to establish average redox potential values in the anoxic (≈ -81 mV) and in the aerobic (+48 mV) zones. Having established these, the system was changed to operate as an IAND system and after a period of time sufficient to allow a consistent DSVI to be attained, redox measurements were taken throughout an 8 hr intermittent aeration cycle together with measurements of the nitrate and nitrite concentrations. From this test, the redox potential was observed to drop from +40 mV at the end of the aerobic period to -180 mV at the end of the anoxic period. Further, it was observed that the high concentrations of nitrate present at the beginning of the anoxic period were reduced to negligible concentrations quite some time before the end of the anoxic period and hence conditions during this latter part of the anoxic period were effectively anaerobic.

To ensure that anoxic conditions prevailed throughout the anoxic period in subsequent tests, ammonium (NH_4^+) was added to the influent, and it was observed that in the 9 day period after the addition, the DSVI increased from ≈ 200 mℓ/g to ≈ 220 mℓ/g. The ammonium (NH_4^+) addition was then increased still further, to increase the TKN/COD ratio to 0.14 and another increase in DSVI was observed - this time to 240 mℓ/g. From measurements taken throughout subsequent 8 hr intermittent aeration cycles (as before) it was found that, although anoxic conditions could be maintained throughout the anoxic period by addition of ammonia to the influent, this took place at the expense of the sludge settleability which was observed to deteriorate (DSVI increased) as the influent ammonia concentration was increased.

This important observation found support from previous work by Casey *et al.* (1994; see also 1999a,b,c). Using defined artificial substrate, the effect of RBCOD and SBCOD on filament proliferation was examined and it was noted that an increase in DSVI was associated with an increase in the NO^-_{2+3} concentration in the reactor. In previous work by Casey et al. (1994; see also 1999a,b,c) using municipal sewage fed to MUCT systems, it was observed that a high concentration of NO_3^- in the anoxic reactor preceding the aerobic reactor was associated with a high DSVI and conversely a low or negligible NO_3^- concentration was associated with a low DSVI.

2.5 CONCLUSIONS FROM THE EXPLORATORY INVESTIGATION

From the above experiments on N and N&P removal systems receiving real wastewater throughout most of which filaments common to N and N&P removal plants at full scale were observed (*i.e.* type 0092, *M. parvicella*, *Thiothrix*, type 0041, *H. hydrossis* and type 1851) it was concluded that a major factor influencing the proliferation of filaments in these systems was intermittent aeration, causing the organisms to be alternately exposed to aerobic conditions and anoxic conditions, provided complete reduction of NO_3^- and denitrification of NO_2^- did not take place before conditions again became aerobic. From this, two conclusions emerged: (i) that the name low F/M filaments was no longer appropriate and because the conditions for their proliferation appear to be closely linked to anoxic-aerobic conditions, they were renamed Anoxic - Aerobic (AA) filaments; (ii) that the cause for AA filament proliferation lay in the requirement of the sludge mass to switch between aerobic and anoxic metabolic pathways, this switching in some way affording filamous organisms a competitive advantage over floc-formers or alternatively disadvantage to the floc-formers. Clearly, a more fundamental understanding of the respiratory processes of facultative organisms was required, and entailed a thorough examination of the biochemical mechanisms responsible for anoxic and aerobic respiration and growth. Accordingly, Casey *et al.* (1994; see also 1999a,b,c) embarked on a comprehensive literature review of the biochemical mechanisms relevant to the growth of facultative aerobic organisms, particularly with regard to the interaction between aerobic and anoxic respiration pathways.

From the work of Krul (1976) on a facultative organism, *Alcaligenis* sp. extracted from activated sludge, it was found that if the organism was subjected to anoxic and aerobic conditions, its utilization of oxygen was severely inhibited by the accumulation of the denitrification intermediate, nitric oxide (NO). Other research had indicated that the presence of intracellular NO_2^- is also inhibitory, although not to the same extent as NO (Carr and Ferguson, 1990). From the above, together with an in depth study of the biochemistry of facultative organisms and the findings of bulking research on nutrient removal systems, Casey *et al.* (1994; see also 1999a,b,c) put forward a hypothesis for the causes of low F/M (AA) filament bulking.

2.6 AA Filament Bulking Hypothesis

From a settleability point of view, two groups or organisms are important in activated sludge systems: floc-formers and filaments. These two groups of organisms compete for substrate in order to grow and maintain themselves and any competitive advantage for the filaments in a system will promote the proliferation of these organisms and cause poor sludge settleability. In continuously aerobic or continuously anoxic conditions, filaments do not proliferate. However, in nitrogen or nutrient removal systems the organisms in the activated sludge are subjected to alternating anoxic and aerobic conditions which can lead to a competitive advantage for the filaments allowing them to proliferate should denitrification be incomplete when aerobic conditions commence.

The circumstances under which this occurs stem from the hypothesized ability of floc-formers to reduce nitrate to dinitrogen gas (nitrate denitrifiers), while the filaments are only able to reduce nitrate to nitrite (nitrate reducers). Under anoxic conditions, floc-formers denitrify nitrate according to the following sequence (Payne, 1973):

For nitrate reduction :

$$\underset{\text{nitrate}}{NO_3^-} \rightarrow \underset{\text{nitrite}}{NO_2^-}$$

For nitrate denitrification :

$$\underset{\text{nitrate}}{NO_3^-} \rightarrow \underset{\text{nitrite}}{NO_2^-} \rightarrow \underset{\text{nitric oxide}}{NO(g)} \rightarrow \underset{\text{nitrous oxide}}{N_2O(g)} \rightarrow \underset{\text{dinitrogen}}{N_2(g)}$$

In instances when the supply of electrons from biodegradable substrate in the anoxic zone is sufficient to ensure the complete reduction of nitrate to nitrogen gas, the subsequent utilization of oxygen by floc-formers in the aerobic reactor is unaffected and the filaments are afforded no competitive advantage. However, when the supply of electrons is insufficient to ensure the complete reduction of nitrate to nitrogen gas, the denitrification intermediate, nitric oxide (NO) is accumulated intracellularly in floc-formers. The presence of NO within the floc-formers is responsible for inhibiting the enzymes specific to aerobic respiration (constitutive oxidase o) on entry into the aerobic zone. Under these circumstances the inhibition of aerobic respiration causes electrons to continue to be directed to nitrate and the enzymes responsible for denitrification, until the floc-former has generated sufficient alternative (non constitutive) enzyme (oxidase aa_3) to proceed with aerobic respiration. This aerobic reduction of nitrate is in turn inhibited by the presence of nitrite and the net result is that the utilization of substrate by floc-formers is adversely affected and they experience retarded growth rates.

Filamentous organisms, however, under anoxic conditions are hypothesized to effect nitrate reduction to nitrite only and are not capable of utilizing other denitrification intermediates as terminal electron acceptors, as follows:

$$NO_3^- \rightarrow NO_2^-$$

As a consequence of this, they are not able to accumulate NO and hence their subsequent utilization of oxygen in the aerobic zone is not inhibited.

In summary therefore, given alternating anoxic-aerobic conditions, if denitrification of nitrate and nitrite to nitrogen gas is incomplete in the anoxic reactor of a 2RND system or at the end of the anoxic period of an IAND system, it follows that the utilization of oxygen by floc-formers is inhibited while the utilization of oxygen by filaments is unaffected. This places floc-formers at a disadvantage and causes the proliferation of filaments causing a deterioration in sludge settleability. To validate the hypothesis it is necessary to show that (1) filaments denitrify only to NO_2^- and flocformers to dinitrogen gas and (2) the inhibition of oxygen utilisation is manifest in a bulking sludge. The first could not be conclusively tested by Casey *et al.* (1994; see also 1999a,b,c) since it requires specialised microbiological techniques and hence attention was focused on the second.

2.7 Experimental Evidence Supporting the Hypothesis

2.7.1 Demonstration of Inhibition

To determine whether or not inhibition of oxygen utilization takes place in activated sludge which is subjected to alternating anoxic-aerobic conditions, a series of batch tests were conducted on sludge drawn from the anoxic reactor of the 2RND system operated by de Villiers *et al.* (1994). To assess oxygen utilization the maximum specific OUR was measured (Ekama *et al.*,

1986) upon sewage addition with both anoxic and aerobic pretreatment conditions.

2.7.1.1 Anoxic denitrification

From Figure 2.2 below it is demonstrated that inhibition of OUR was induced in the sludge after a 2 hour anoxic period with NO_2^- present during both the anoxic and subsequent aerobic periods. The addition of ≈ 25.0 mgNO_2^--N/ℓ at the start of the aerobic period exhibited dramatic inhibition while less marked inhibition was noted on addition of ≈ 5.5 mgNO_2^--N/ℓ, and almost no inhibition was measured on addition of 0.1 mgNO_2^--N/ℓ.

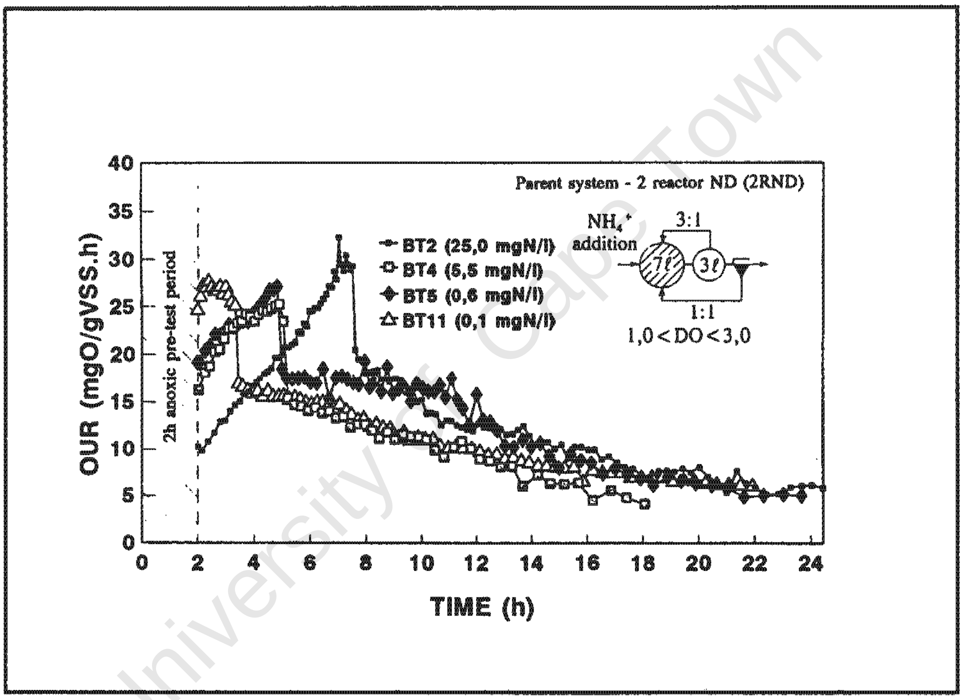

Figure 2.2 : Oxygen utilisation rate [OUR, in mgO/(g.VSS.h)] with time under aerobic batch conditions (nitrification inhibited) on sludge harvested from a 2 reactor ND system with a two hour anoxic period prior to the aerobic test and with varying nitrite concentrations at the start of the aerobic test, demonstrating the initial but gradually declining inhibitory effect of NO_2^- on maximum specific OUR (0.1, 5.5 and 25 mg NO_2^--N/ℓ).

Two conclusions were drawn from the observation (1) inhibition of OUR in the presence of NO_2^- is observed, and (2) the degree of inhibition is directly related to the concentration of NO_2^- at the beginning of the aerobic period. It could not be determined from these tests however, whether the inhibition results from the NO generated by NO_2^- denitrification under anoxic conditions or under aerobic conditions.

2.7.1.2 Aerobic denitrification

To determine whether activated sludge from the 2RND system exhibited aerobic denitrification, aerobic batch tests were conducted on specially prepared sludge samples. In the preparation of these samples virtually all the NO_3^- and NO_2^- were removed from the sludge by dilution with tap water, settling and decanting the supernatant three times. The sludge was then held anoxic in the presence of 120 mgCOD/ℓ sewage in order to denitrify any remaining NO that might be present within the organism.

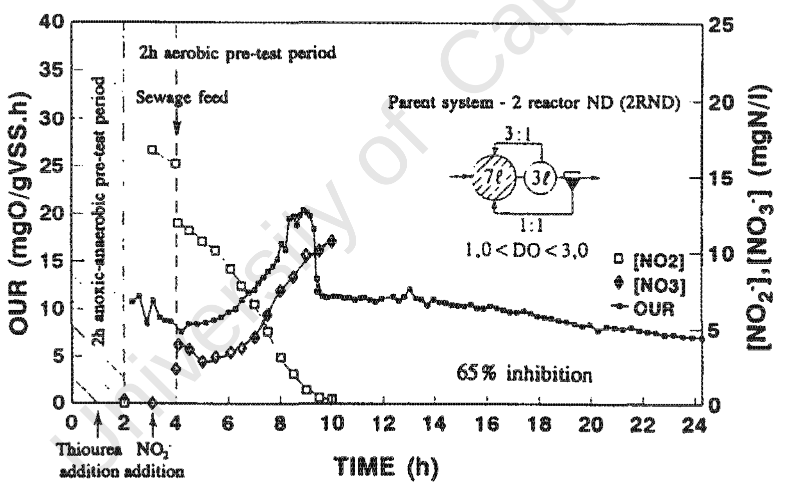

Figure 2.3 : Oxygen utilisation rate [OUR, in mgO/(g.VSS.h)] and nitrite and nitrate concentrations (NO_2^- and NO_3^-, in mgN/ℓ) with time under aerobic batch conditions (nitrification inhibited) on sludge harvested from a 2 reactor ND system with a two hour anoxic-anaerobic period during which NO_2^- was added (20mgN/ℓ), prior to the aerobic test.

After 2 hours, during which thiourea was added (10mg/ℓ) to inhibit NO_2^- formation by *Nitrosomonas*, aeration was commenced (2.0 < DO < 4.0 mgO/ℓ). After 1 hr aeration, 20 mgNO_2^-- N/ℓ of nitrate was dosed. After a further 1 hour aeration, 360 mgCOD/ℓ (final batch volume) sewage was added and the OUR, nitrate and nitrite concentrations measured with time. Figure 2.3 above shows that OUR inhibition is exhibited. In a similar test but with NO_3^- addition (20 mgN/ℓ) instead of NO_2^-, no inhibition was exhibited. These observations suggested that NO inhibition does take place with NO_2^-, (the NO apparently produced by aerobic denitrification of NO_2^-) but not with NO_3^-. In a control batch test, in which no NO_2^- or NO_3^- was added, no inhibition was exhibited, these results were reproducible with sludges from IAND and MUCT systems. In the batch tests presented so far, it appears that during the aerobic period after sewage addition the inhibition is relieved, reflected in a steadily increasing maximum specific OUR, in some cases levelling off at a constant value before the precipitous decrease in OUR when the RBCOD has been depleted. The relief of OUR inhibition possibly arises because the presence of significant quantities of RBCOD under aerobic conditions accelerates the $NO \rightarrow N_2O \rightarrow N_2$ part of the denitrification pathway so that the NO produced from NO_2^- denitrification does not accumulate.

2.7.1.3 Effect of RBCOD on OUR inhibition by NO

To check if OUR inhibition takes place in the presence of significant quantities of RBCOD, an aerobic batch test was conducted in which NO_2^- was added after the sewage addition but while RBCOD was still present, rather than before sewage addition when only SBCOD (principally generated from organism death and lysis) is present as in the previous batch experiments. In this test no inhibition was noted, and it was concluded that the presence of RBCOD (in sufficient quantity) prevented or relieved the inhibition. From this it seemed reasonable to accept the suggestion above that the RBCOD accelerates the $NO \rightarrow N_2$ steps of the pathway in such a way that NO no longer is accumulated, is reasonable.

2.7.1.4 Determination of the extent of NO_3^- reduction and denitrification under anoxic conditions by filaments and floc-formers

With the experiments above, it was demonstrated that OUR inhibition hypothesised to be by NO, takes place in the presence of NO_2^- in switching from anoxic to aerobic conditions. For the proposed explanation to be acceptable, it needed to be shown even superficially that floc-formers denitrify from NO_3^- to N_2 gas, and so are susceptible to OUR inhibition by accumulated NO, whereas the low F/M filaments reduce NO_3^- to NO_2^- only, and therefore do not accumulate NO and so are not susceptible to this inhibition. Clearly this is an experiment that needed to be taken up by microbiologists and biochemists (it has see Tandoi *et al.*, 1997), but for the purposes of testing the hypothesis, sludge samples from a fully anoxic (FX) system (low DSVI) and the 2RND system on which the batch tests above were done (high DSVI), both fed real sewage, were subjected to a nitrate reduction test, a test which allows the generation of NO_2^- and/or N_2 gas to be determined. The sample with the high DSVI (many AA filaments) showed an accumulation of NO^-_2 with no N_2 gas being detected in 8 out of 10 tests. The sample with the low DSVI (few AA filaments) accumulated N_2 gas, but no NO_2^- accumulated in 8 out of 10 tests. From this it is reasonable to accept that qualitatively, filaments tend to reduce NO_3^- to NO_2^- only, where floc-formers denitrify NO_3^- to N_2 gas. This observation lends credibility to the proposed hypothesis for low F/M filament proliferation. With a reasonable hypothesis for low F/M filament proliferation in N and N & P removal systems, attention was directed at devising strategies for the control of these filaments in the systems.

2.7.1.5 <u>The effect of incomplete denitrification on sludge settleability in MUCT systems</u>

Having found some credibility for the AA filament bulking hypothesis of Casey *et al.* (1994; see also 1999a,b,c) by demonstration of OUR inhibition and correspondingly substrate utilization in batch tests, Musvoto *et al.* (1992) set up two MUCT systems in order to demonstrate the effect of floc-formers inhibition on sludge settleability, in nutrient removal activated sludge plants running at steady state.

In these experiments the anoxic zones comprised 65 % of the system mass fraction (*i.e.* large to enable complete denitrification) with 15 % anaerobic and 20 % aerobic mass fractions. It was found that whilst no nitrate or nitrite was dosed to the 2nd anoxic reactor of these systems, and thus nitrate and nitrite concentrations entering the aerobic reactor were < 1. 0 $mgNO_3^-$-N/ℓ and < 0.2 $mgNO_2^-$-N/ℓ respectively, low DSVIs were observed. Conversely when nitrate was dosed to the second anoxic reactor of one system to provide an equivalent TKN/COD ratio of 0.16 mgN/mgCOD the DSVI increased from 80 mℓ/g to 176 mℓ/g (bulking) in 111 days. Also, when nitrite was dosed to the second anoxic reactor of the other system to provide an equivalent TKN/COD ratio of 0.18 mgN/mgCOD, the DSVI increased rapidly from 90 to 174 mℓ/g (bulking) in 55 days. These findings provided considerable support for the AA bulking hypothesis of Casey *et al.* (1994; see also 1999a,b,c).

2.7.1.6 <u>Observations from other laboratory and full scale systems</u>

The AA bulking hypothesis as an alternative to the selector approach for explaining the causes and control of low F/M (AA) filament bulking is a recent development and therefore still needs thorough evaluation and validation. However, a significant body of information providing indirect support for this alternative conceptualization of the low F/M filament bulking problem is emerging not only from laboratory scale systems reviewed above, but also from subsequent investigations conducted in the UCT laboratory such as those by Pilson *et al.* (1995), Sneyders *et al.* (1997) and Mellin *et al.* (1998). In this respect the conference proceedings of the 1st ASPD Specialist Group make interesting reading (for details see Ekama, 1994) *e.g.*:

1) From a survey of Danish plants, Andreasen and Sigvardsen (1993) concluded that the "first survey at nutrient removal plants show a higher percentage with *SVI*>150 ml/g and especially at some plants which include BEPR which seem to have constant high *SVI* with filaments *M. parvicella*, type 0041 and 0803". Also Kristensen *et al.* (1994) noted " a distinct variation over the year in sludge settling characteristics. Sludge settleability improved during summer and deteriorated during winter."

2) From a survey of Rome's plants, Rossetti *et al.* (1994) found that "systems operating with alternating aeration conditions (like Carousel type) with short anoxic-aerobic cycles show permanent high levels of low F/M filaments with the main filament being *M. parvicella*."

3) From a survey of German plants, Kunst and Reins (1994) state that "in the last years a lot of treatment plants with bio-P removal went into operation and people thought that anaerobic reactors in the treatment plants would be able to prevent sludge bulking - the experience in technical practice shows this didn't happen."

4) From practical experience in operating long sludge age plants in South England, Foot *et al.* (1994) concluded that (i) there is an inverse relationship between the total filament length (TFL) and the total oxidized nitrogen (TON) concentration in the effluent - the

higher the TON concentration, the lower the TFL and *visa versa*, and (ii) "the widespread occurrence of this species (*M. parvicella*) in WWTPs would tend to indicate that it is not so much the substrate (sewage characteristics) which are important as the configuration and operation of the plant."

5) From 10 years experience with bulking in Dutch full scale plants, Eikelboom (1993,1994) concludes that (i) "development of *M. parvicella* shows a distinct seasonal pattern with highest *DSVI*s in spring and lowest in autumn", (ii) "*M. parvicella* grows better in Carousel type systems than in other extended aeration plants and it is worse with settled sewage", (iii) "the usefulness of selectors for controlling *M. parvicella* decreases as the overall load on the plant increases", (iv) "after introduction of nutrient removal conditions, the *DSVI* increased in 60 % of these plants and *M. parvicella* was dominant in 87 % of them" so that (v) "the application of BNR methods will even increase the dominating position of this organism", and (vi) "the ultimate effect of selectors for control of *M. parvicella* is insufficient and unpredictable so far. In Holland over 80 selectors have been incorporated in full-scale plants. Comparing the results with 15 years ago, it seems that the percentage of plants with bulking has not significantly changed with application of selectors".

While most of these statements and conclusions indirectly but inconclusively support the research on low F/M (AA) filament bulking reviewed above, those of Foot *et al.* (1994) and Eikelboom (1994) are particularly pertinent; (i) the problem being worst in spring (also noted by Kunst and Reins, 1994), (ii) worse with settled wastewater, (iii) the inverse relationship between the TFL and effluent TON, and (iv) the efficacy of aerobic selectors decreasing if denitrification is permitted to take place in the main aeration reactor (due to either under aeration or increased plant load). All these factors influence the denitrification performance of the plant and increase the likelihood of significant nitrate and nitrite concentrations being present at the transition from anoxic to aerobic conditions. Interestingly, in later research prompted by the publication of this hypothesis, Tandoi *et al.* (1997) showed that a strain of *M. parvicella* isolated from an Italian WWTP and genetically similar to Australian strains, reduced nitrate to only nitrite, which provides some direct microbiological support for the AA filament bulking hypothesis.

2.8 Scope of this Research

From the research reviewed above, it has been established experimentally that the presence of nitrate and/or nitrite at the transition from anoxic to aerobic, results in the inhibition of floc-formers when they pass into the aerobic reactor. In this respect nitrite is more important than nitrate because generally, nitrite accumulates slowly while nitrate is denitrified and is denitrified only when nitrate has reached low values (< 1.0 mgN/ℓ) (Stern and Marais, 1974; Pilson *et al.*, 1995; Ekama and Wentzel, 1997). In terms of the hypothesis therefore, if leakage of nitrate and/or nitrite from the anoxic reactor to the aerobic reactor can be prevented, then inhibition of floc-formers should not occur and a non-bulking sludge should develop.

Accepting the validity of the hypothesis, this investigation seeks to check at large scale a low F/M (AA) filament bulking control strategy that follows from the hypothesis. By operating in parallel the two Mitchell's Plain Stage 1 full-scale plants with the same design and operating conditions, except for the mixed liquor 'a-recycle' from the aerobic to the anoxic reactor, the feasibility of controlling AA filaments in full scale NDBEPR plants will be tested. In one plant (Module A), the 'a-recycle' ratio will be set to a low value, so under-loading the anoxic reactor with nitrate leading to low nitrate/nitrite concentrations at the anoxic-aerobic transition. In the other plant (Module B) the 'a-recycle' will be set to a high value, so overloading the anoxic reactor with nitrate leading to a high nitrate/nitrite concentration at the anoxic-aerobic transition. In terms of the bulking hypothesis, a low DSVI is expected in the first module (A) and a high DSVI in the second module (B).

Additional to this objective, sufficient testing and monitoring will be undertaken on the two modules to determine the Total P, TKN and COD mass balances, thus to check whether or not the low COD mass balances (80-85 %) observed on laboratory scale NDBEPR systems also are observed on full scale NDBEPR systems.

CHAPTER 3

REDESIGN AND SIMULATION OF THE FULL-SCALE PLANTS

This chapter describes the layout of the Stage 1 full-scale plants and the redesign, simulation and modifications done to convert the original plants from nitrification-denitrification (ND) systems to nitrification-denitrification-biological excess phosphorus removal (NDBEPR) UCT systems taking cognizance of the research objectives.

3.1 LAYOUT OF THE STAGE 1 PLANTS AT THE MITCHELL'S PLAIN WWTP

At the Mitchell's Plain WWTP, the Stage 1 plants (Modules A and B) were built in 1975 by the Cape Town City Council to generate design data for the Stage 2 plant (Modules C to F) built a few years later. The two parallel full-scale-scale modules (A and B), appropriately modified, were to be used to demonstrate the full-scale application of AA filamentous organism bulking control. The position of the Stage 1 plants in relation to the rest of the Mitchell's Plain WWTP are shown in Figure 3.1(highlighted in box).

3.1.1 Description of the Influent Flow Path

The raw wastewater flows to the inlet works where it is lifted by two levels of Archimedean screw pumps. The inlet works typically removes solid material (such as rags, papers, plastics, glass etc.) by means of coarse and fine screens and grit by means of two Pista type grit removal tanks with air-lift pumps. Thereafter the wastewater flows through the disused fat flotation plant where flows in excess of the desired average flow of 27 Mℓ/d for the plant are diverted to the equalisation basins. The equalisation basins control the hydraulic load on the plant by storing the excess flows and pumping this stored wastewater when the influent flow drops below the desired average flow for the plant. The flows from the inlet works and the equalisation basins are further lifted at the intermediate pump station into an open channel where it is measured by means of a venturi measuring flume with an ultra-sonic flow recording facility. The measured flow is channelled to a flow splitter which splits the flow between the full-scale plants (Stage 1, Modules A and B) and the rest of the Mitchell's Plain WWTP (Stages 2 to 4, Modules C to H). Flow control at the overflow weirs of the splitter is achieved by means of crude and inefficient sluice plates which control the head over the weirs. The flow to the full-scale plants (Stage 1) gravitates from the flow splitter to a primary settling tank (PST) where particulate material and organics are settled out in the primary sedimentation phase. The overflow (settled wastewater) from the single PST is split between the biological reactors of Modules A and B. The flows to Modules A and B are measured by v-notch weir plates in their respective influent channels. Because the reactor volumes of the Modules A and B are not equal (see Figure 3.1), the flow to each module was set in proportion to it's volume. The inlet arrangement and flow scheme were not modified.

3.2 Description of the Stage 1 Plants before Modification

A schematic layout of the full-scale plants before modification is shown in Figure 3.2 with the details of the original infrastructure summarised in Table 3.1.

3.2.1 Primary Settling Tank

The single 22 m diameter Stage 1 PST served both Modules A and B. The primary settler had a sloped floor and primary sludge settled on the tank floor was scraped by mechanical scraper arms and collected for removal with the underflow.

3.2.2 Biological Reactors

The two full-scale plant reactors were not identical:

Module A: 1361 m^3 two reactor anoxic/aerobic Modified Ludzack Ettinger (MLE) N removal plant, see Figure 3.2 and Table 3.1.

Module B: 2043 m^3 four reactor anoxic/aerobic/anoxic/aerobic 4stage Bardenpho N removal plant, see Figure 3.2 and Table 3.1.

In both modules aeration was achieved via fine bubble aeration through ceramic diffuser domes served by three Roots type blowers. During the investigation this aeration system gave considerable problems due to progressive blocking of the aged ceramic domes and eventually failed irreparably resulting in termination of the project.

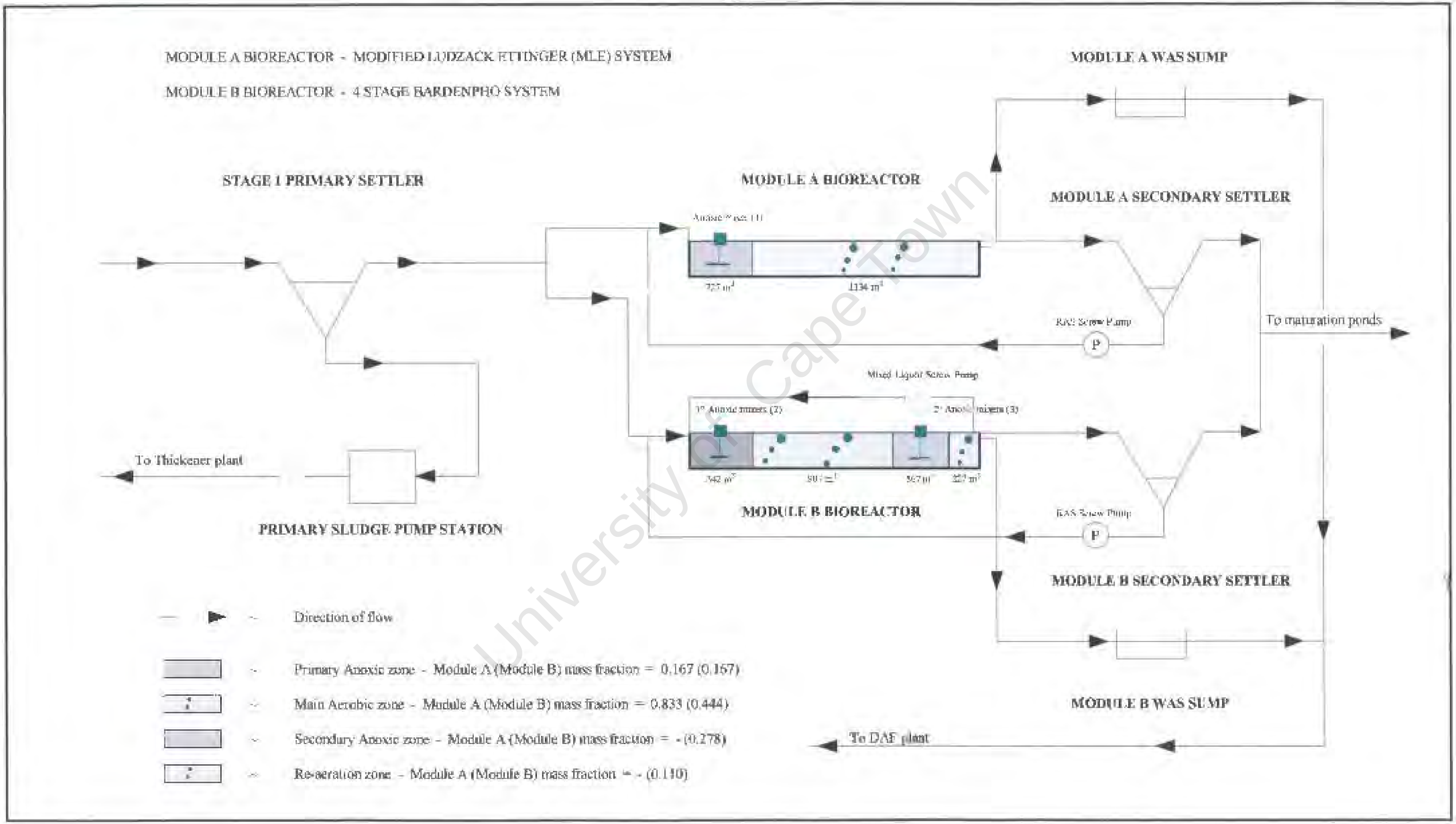

Figure 3.2 : Existing Mitchell's Plain Stage 1 plants, before modifications.

Figure 3.1 : Stage 1 plants in relation to the rest of the Mitchell's Plain WWTP.

In all the unaerated zones, sludge was mixed by bridge mounted mixers to prevent settlement. Module A had no mixed liquor 'a-recycle' whereas Module B had an Archimedean screw pump to pump mixed liquor from the ends of the aerobic zones to the head of the primary anoxic zone.

At the end of the aeration zone of each module, waste activated sludge (WAS) was drawn off hydraulically to maintain a sludge age. This WAS flow was discharged to the downstream dissolved air flotation (DAF) and linear screen sludge handling unit operations of the main plant. This sludge wastage facility caused considerable difficulties in the investigation and will be discussed further in this chapter.

3.2.3 Secondary Settling Tanks

Each module had it's own flat-bottomed secondary settling tank (SST). Activated sludge settled to the tank floor was collected and returned (by suction lift) with the underflow ('s-recycle'[2]) to the sump of the return activated sludge (RAS) pumpstation from where it was pumped separately by Archimedean screws to the head of the appropriate module. Thus, the mixed liquor in the two modules was totally separated which meant that the two modules could be operated independently.

3.3 Influent Wastewater Characteristics

As the influent wastewater characteristics govern to a large extent both the selection of the process and the removals of nitrogen and phosphorus attainable in the process the characteristics of the wastewater are of prime importance for the design of the new configurations.

Two data sources were used to characterise the influent wastewater to the full-scale plants:

- Weekly records of the Scientific Services Department of the Cape Metropolitan Council (CMC), and
- Two 24 hour composite sample analyses by Laballo and Sibuyi (1992).

[2]In this investigation, the 's-recycle' refers to the activated sludge return from the SST to the beginning of the anaerobic or anoxic reactors.

From these two sources of data, projections of future wastewater concentrations and fractions were made and used as input to the *UCTPHO* (Wentzel *et al.*, 1992) NDBEPR simulation programme.

Table 3.1 : Summary of the original Stage 1 plant infrastructure, before modification

Primary Settling Tank	**Stage 1**	
Diameter (m)	22	
Area (m^2)	380	
Circumference (m)	69.12	
Side Wall Depth (m)	3	
Floor Slope (°)	15	
Biological Reactors	**Module A**	**Module B**
Total Process Volume (m^3)	1361	2043
Side Wall Depth (m)	4	4
Width (m)	7	7
Primary Anoxic Mass Fraction	0.167	0.167
Main Aerobic Mass Fraction	0.833	0.444
Secondary Anoxic Mass Fraction	None	0.278
Re-aeration Mass Fraction	None	0.110
Max. 's-recycle' (Mℓ/d)	6.2	6.2
Max. Mixed Liquor 'a- recycle' (Mℓ/d)	None	11
Primary Anoxic Zone Stirrers	One 5.5kW, 30rpm	Two 5.5kW, 30rpm
Secondary Anoxic Zone Stirrers	None	Three 4.0kW, 20rpm
Max. aeration - Aerobic Zone (gO/m^3/h)		6277
Max. aeration - Re-aeration Zone (gO/m^3/h)		None62
Secondary Settling Tank	**Module A**	**Module B**
Diameter (m)	25	25
Area (m^2)	491	491
Circumference (m)	78.54	78.54
Side Wall Depth (m)	3	3
Floor Slope (°)	0	0

3.3.1 Estimated Influent Diurnal Concentrations

The estimated COD, TKN and Total Phosphate diurnal variations in concentration for the settled wastewater entering Modules A and B are given in Table 3.2. The data in Table 3.2 is based on 24hr observations of the diurnal variation in influent concentration by Laballo and Sibuyi (1992). By means of extrapolation of annual trends determined from the CMC weekly records and applying these to the diurnal variation, the expected concentrations at the estimated time for commissioning of the UCT configured full-scale plants in mid. 1997, were determined.

Daily flow weighted mean values of 861 mgCOD/ℓ, 96 mgN/ℓ, 79 mgN/ℓ and 19.2 mgP/ℓ for the settled sewage were used as steady state inputs to the *UCTPHO* simulation programme for the influent COD, TKN, FSA and Total P concentrations respectively. An average influent TKN/COD ratio of 0.11 was estimated for the settled wastewater entering Modules A and B from these values.

Table 3.2 : Estimated diurnal influent COD, TKN and Total P concentrations.

Time of Day	COD (mgCOD/ℓ)	TKN (mgN/ℓ)	Total P (mgP/ℓ)
14 : 00	898.45	98.49	20.81
16 : 00	1014.73	96.7	20.50
18 : 00	1098.08	54.32	18.60
20 : 00	1098.06	106.84	17.66
22 : 00	1014.89	97.89	19.86
24 : 00	1014.89	87.74	15.13
02 : 00	831.89	90.73	20.01
04 : 00	449.22	60.29	18.37
06 : 00	382.66	50.14	21.98
08 : 00	798.61	121.17	17.58
10 : 00	798.61	148.03	20.87
12 : 00	831.89	139.67	19.04
Average	**861**	**96**	**19.2**

3.3.2 Estimated Influent COD, TKN and Total P Fractions

As input to the current mathematical models for activated sludge systems, it is necessary to quantitatively characterise the influent C, N & P components. Laballo and Sibuyi (1992) determined various fractions for the influent COD, TKN and Total P from sewage samples taken at the Mitchell's Plain WWTP. Table 3.3 below gives a summary of the fractions which were applied to the estimated average influent concentrations for settled wastewater given in Table 3.2. Detailed characterisation for the redesign calculations is given in Appendix A.

Table 3.3 : Estimated fractions and predicted influent concentrations.

COD fraction	**Settled wastewater fraction**	**Settled COD concentration**	**Estimated concentration (mgCOD/l)**
f_{usi}	0.095	S_{usi}	81.62
f_{upi}	0.040	S_{upi}	34.44
f_{bsi}	0.321	S_{bsi}	238.94
f_{zpi}	0.588	S_{bpi}	506.00
TKN fraction	**Settled wastewater fraction**	**Settled TKN concentration**	**Estimated concentration (mgN/l)**
f_{nai}	0.823	N_{ai}	79.00
f_{Nousi}	0.037	N_{ousi}	3.55
f_{Noupi}	0.024	N_{oupi}	2.33
f_{Nobsi}	0.058	N_{obsi}	5.56
f_{Nobpi}	0.058	N_{obpi}	5.56
Total P fraction	**Settled wastewater fraction**	**Settled Soluble P concentration**	**Estimated concentration (mgP/l)**
f_{Psi}	0.775	P_{si}	14.89

3.4 STAGE 1 PLANT TREATMENT CAPACITY AND SYSTEM OPERATIONAL PARAMETERS

The UCT NDBEPR configuration was considered to be the most appropriate for this research as this configuration allows biological P removal to be relatively independent of the effluent nitrate concentration at high influent TKN/COD ratios (>0.10). Hence, it was proposed to modify the two full-scale plants to the UCT N & P removal configuration, with the same anaerobic, anoxic and aerobic mass fractions.

3.4.1 Treatment Capacity Estimation

From the existing plants, the process volume of the bioreactor and the area of the SST were fixed as well as the influent wastewater concentrations. This left the influent flow rate and reactor mixed liquor concentration to be determined. Normally in design the worst combination of flows are used *i.e.* the peak wet weather flow (PWWF) is used in SST theory and the average dry weather flow (ADWF) in the bioreactor theory. However, the PWWF/ADWF ratio is considered unity as the flow, appropriately split between the Stage 1 plants and the rest of the WWTP, entering the full-scale plants is balanced and equalised by virtue of flow balancing in the equalisation basins and the long retention time in the large Stage 1 PST.

In order to estimate the treatment capacity of the existing Modules A and B, the aerobic steady state design equations were combined with the SST theory and design in the following manner:

For the bioreactor : (3.1)

$$V_p . X_t = \{Q_i . R_s . S_{ti}\} / f_i . \{ [(1 - f_{upi} - f_{usi}) . Y_h . (1 + f . b_{ht} . R_s)] / (1 + b_{ht} . R_s) + f_{upi} / f_{cv} \}$$

which relates the mass of TSS in the reactor to the influent COD load, and

For the SST :

$$Q_i / A = 0.80 . V_0 . e^{-n . X_t} . (24 / 1000) \quad (3.2)$$

which relates the overflow rate to the reactor TSS concentration and the selected sludge settleability (V_0 and n).

where : X_t = Total Suspended Solids (TSS) concentration of the mixed liquor in kg/m³

Q_i = Influent flow in Mℓ/d

A = Area of the SST in m²

V_p = Process volume in m³

V_0, n = Theoretical flux constants

Solving these equations simultaneously, the total suspended solids (X_t) and influent flow rate (Q_i) were determined based on the following assumptions :

- PWWF = ADWF = 1
- R_s = 15 days satisfying the requirement of the minimum sludge age for nitrification
- Minimum temperature = 13 °C
- A typical bulking sludge DSVI of 250 mℓ/g is selected (V_0 = 2.903 m/h, n = 0.615 m^3/kg)

This gave an influent flow rate of 2.04 and 2.72 Mℓ/d for Modules A and B respectively, and reactor TSS concentration of 4.224 and 3.775 kgTSS/m^3 respectively. Because NDBEPR systems produce about 10 % more TSS mass and 10 % less oxygen demand per kg COD load compared with ND systems (for which the above capacity analysis is valid), the effluent flows will be reduced to 1.75 and 2.50 Mℓ/d. Subsequent simulations (see Section 3.5 below) indicated that the capacity of the full-scale plants was limited by the air supply of the aeration system, rather than the SSTs. Accordingly the influent flow was reduced further to 1.4 and 2.1 Mℓ/d for Modules A and B respectively. Table 3.4 gives a summary of the estimated flows and design anaerobic, anoxic and aerobic mass and volume fractions. These fractions are good for NDBEPR but were selected not so much for the optimum UCT configuration but more to suit existing baffle walls in the modules and minimal reshuffling of aeration pipework and domes.

3.4.2 System Operational Parameters : Sludge Age and Mass Fractions

With a sludge age of 15 days, the full-scale plant needed to be divided into anaerobic, anoxic and aerobic zones. In this division the primary consideration is that the system must be able to nitrify at the lowest expected temperature. The link between aerated mass fraction, sludge age, nitrifier maximum specific growth rate and temperature is given by (WRC, 1984):

$$R_S = \frac{S_f}{(1 - f_{xt})\mu_{nmT} - b_{nT}} \qquad (3.3)$$

where:

R_S = sludge age (d) = 15 d here

S_f = safety factor for nitrification = 1.2 here

$(1-f_{xm})$	=	aerated sludge mass fraction
f_{xm}	=	unaerated sludge mass fraction
μ_{nmT}	=	nitrifier maximum specific growth rate at temperature T = $\mu_{nm20}\theta^{(T-20)}$
μ_{nm20}	=	nitrifier maximum specific growth rate at temperature 20 °C
θ	=	Arrhenius temperature correction factor = 1.123
b_{nT}	=	nitrifier specific death rate at temperature T = $b_{n20}\theta^{(T-20)}$
b_{n20}	=	nitrifier specific death rate at temperature 20 °C = 0.04/d
θ	=	Arrhenius temperature correction factor = 1.029

Aerobic zone

Because the nitrifier maximum specific growth rate was not known for the plants, the minimum value, at the minimum expected temperature of 13 °C and the aerated sludge mass fraction of 0.56, was calculated to be 0.45/d (at 20 °C). Because this is a relatively low value, nitrification will take place all year round.

Anaerobic zone

For module A the existing anoxic reactor compartment (volume = 227 m^3) was considered for the anaerobic zone as a mixer and a baffle wall were already in place thereby saving on costs. For Module B the first two existing anoxic reactor compartments (volume = 171 m^3 each) were considered for the anaerobic zone again as the mixers and baffle wall were already in place. In both Modules A and B this yielded an anaerobic mass fraction of 0.091 which is somewhat low, but acceptable for good BEPR.

Anoxic zone

The aerated sludge mass fraction of 0.56 gave an unaerated mass fraction (anaerobic mass fraction + anoxic mass fraction) of (1-0.56) = 0.44. With the anaerobic mass fraction set at 0.091, the balance of the unaerated mass fraction was accepted to be anoxic which gave an anoxic mass fraction of approximately 0.35. The estimated flows, reactor TSS concentrations and proposed mass and volume fractions are summarised in Table 3.4 below.

3.4.3 Recycle Flows and Proposed Layout

The UCT configuration incorporates three recycle flows:

- 'a-recycle', from aerobic to anoxic reactor
- 's-recycle', from SST to anoxic reactor
- 'r-recycle', from anoxic to anaerobic reactor

Table 3.4 : Estimated flows and proposed fractions of the full-scale plants.

Parameter	Units	Module A	Module B
Estimated Reactor TSS (X_t)	$kgTSS/m^3$	4.224	3.755
Estimated Influent Flow (Q_i)	Mℓ/d	2.037	2.718
Sludge Age (R_s)	d	15	15
Anaerobic Mass Fraction	-	0.091	0.091
Anoxic Mass Fraction	-	0.350	0.346
Aerobic Mass Fraction	-	0.559	0.563
Anaerobic Volume Fraction	-	0.167	0.167
Anoxic Volume Fraction	-	0.321	0.317
Aerobic Volume Fraction	-	0.512	0.516
Waste Flow Rate (WAS)	m^3/d	91	136
SST Overflow Rate	m/h	0.173	0.231
DSVI	mℓ/g	250	250

In the proposed layouts, the 's-recycles' and 'r-recycles'[3] were each set at 1:1 with respect to the influent flow. To assess the bulking control strategy, one module (B) was to be operated such that the nitrate concentration leaving the anoxic reactor and entering the subsequent aerobic reactor would be > 2 mgN/ℓ, whereas for the other module (A) it would be < 1 mgN/ℓ. By monitoring the sludge settleability in the two modules and comparing these, the efficacy of the proposed bulking control strategy would be evaluated. It was proposed to control the nitrate concentrations in the anoxic reactor through the 'a-recycle' ratio: Module B would have a high 'a-recycle' ratio to overload the anoxic reactor with nitrate, and Module A would have a low 'a-recycle' to underload the anoxic reactor with nitrate. Accordingly, the Module A 'a-recycle' ratio was set at 2:1 with respect to influent flow and Module B at 5:1. Simulations with *UCTPHO* (Wentzel *et al.*, 1992, see below) indicated that these 'a-recycle' ratios would achieve the desired effect at the higher temperatures, but may require to be decreased at the lower temperatures. In practice, the 'a-recycle' ratios were adjusted depending on the measured anoxic nitrate concentrations, see Section 4.1. A process flow diagram showing the proposed operational layout is given in Figure 3.3 below.

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[3] In this investigation, the 'r-recycle' refers to the inter-reactor mixed liquor recycle pumped from the end of the anoxic reactor to the beginning of the anaerobic reactor.

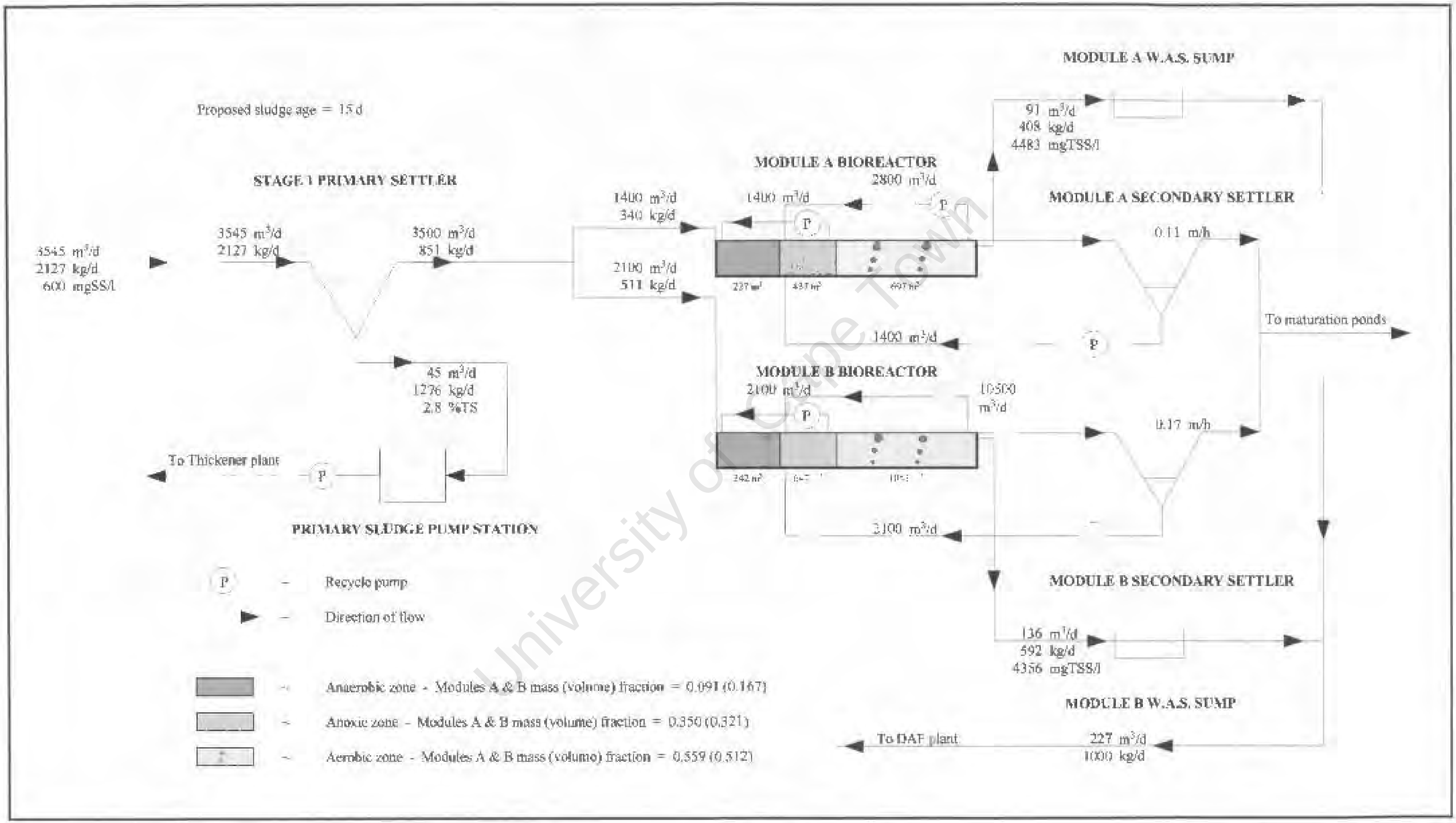


Figure 3.3 : Proposed Mitchell's Plain Stage 1 plant operation.

3.5 SIMULATIONS OF THE PROPOSED UCT SYSTEMS

Swanepoel (1996) did steady state and dynamic simulations of the proposed UCT configurations using the *UCTPHO* (Wentzel *et al.*, 1992) computer programme. His results showed that at a sludge age of 23 days maximum nitrogen removal could be attained provided that sufficient 'a-recycle' pumping capacity was available. However, from a research point of view, a shorter sludge age is desirable, so that (i) the influent could be higher and reactor TSS concentration lower and (ii) steady state can be achieved more rapidly following a system modification. Accordingly, the sludge age of 15 days was accepted for the full-scale plants.

In rearranging the diffused air pipework in Modules A and B, it was found that the aeration capacity would limit the influent flows to Modules A and B at about 1.7 Mℓ/d and 2.1 Mℓ/d respectively at the influent COD and TKN concentration of 861 mgCOD/ℓ and 96 mgN/ℓ (see Section 3.3.1 above). Further, it was proposed to operate the two modules as identically as possible. Thus, the load to the two modules should be proportional to their reactor volumes, so that the reactor mixed liquor concentrations are equal. To facilitate this, the influent flow to Module B was set at 2.1 Mℓ/d. The influent flow to Module A was calculated from that for Module B as being in proportion to the reactor volumes, to give 1.4 Mℓ/d. These influent flow rates were implemented from March 1999 to February 2000 (see Section 4.1).

Accepting the layout for the full-scale plants above, the expected response of the systems could be simulated with the *UCTPHO* (Wentzel *et al.*, 1992) computer programme. Results are summarised in Table 3.5 below, for the higher expected temperature of 20 °C, and the lower expected temperature of 13 °C.

From the simulations the following can be noted:

- Nitrification is achieved at all temperatures, as required, indicated by the low effluent ammonia concentrations.
- At 20 °C, Module A anoxic nitrate concentration = 0.4 mgN/ℓ, while Module B = 2.7 mgN/ℓ - the desired difference in nitrate concentration is achieved.
- At 13 °C, Module A anoxic nitrate concentration = 4.0 mgN/ℓ, while Module B = 8.6 mgN/ℓ - while the concentration for Module B is acceptable, the concentration for

Module A is too high; the 'a-recycle' ratio for Module A may require to be reduced at the lower temperatures.

- The predicted biological P removal is reasonable (effluent P = about 1 mgP/ℓ), but is reduced in Module A at the lower temperatures due to the recycling of nitrate from the anoxic to anaerobic reactors.
- The predicted VSS concentrations in Modules A and B are near identical (3062 and 3029 mgVSS/ℓ respectively at 20 °C); this indicates that the required equivalence for the two Modules has been achieved with the selected loading rates.
- The average and peak OURs for the two modules are virtually identical at about 55 and 65 mgO/ℓ/h respectively. Again the behaviour in the two systems is the same, as required.

Table 3.5 : Predicted performance of the UCT NDBEPR full-scale plants.

Parameter	Units	Module A		Module B	
		13 °C	20 °C	13 °C	20 °C
Reactor VSS (X_v)	kgVSS/m³	3.209	3.062	3.151	3.029
Estimated Influent flow (Q_i)	Mℓ/d	1.4	1.4	2.1	2.1
Sludge Age (R_s)	d	15	15	15	15
Anaerobic Volume Fraction	-	0.167	0.167	0.167	0.167
Anoxic Volume Fraction	-	0.321	0.321	0.317	0.317
Aerobic Volume Fraction	-	0.512	0.512	0.516	0.516
'a-recycle' Ratio*	-	2.0	2.0	5.0	5.0
'r-recycle' Ratio*	-	1.0	1.0	1.0	1.0
's-recycle' Ratio*	-	1.0	1.0	1.0	1.0
Total Oxygen Demand (OUR)	gO/m³/h	54.7	55.8	54.5	54.3
Peak Total Oxygen Demand	gO/m³/h	-	64.7	-	65.1
Effluent Ammonia	mgN/ℓ	3.7	0.9	3.5	0.7
Anoxic Nitrate	mgN/ℓ	4.0	0.4	8.6	2.7
Effluent Nitrate	mgN/ℓ	20.9	18.2	18.3	12.9
Effluent Phosphate (soluble)	mgP/ℓ	1.1	0.9	2.1	1.1
Effluent COD (soluble)	mgCOD/ℓ	87.2	89.1	86.3	88.6

* All recycle ratios are with respect to the influent.

3.6 MODIFICATIONS TO THE EXISTING PLANTS TO CONVERT TO UCT SYSTEMS

For the period July 1997 to February 1999 the following physical modifications, additions and alterations were made to the plants to upgrade them from ND to UCT NDBEPR systems.

- Construction of recycle channels. This was achieved by using existing channels and diverting the recycle flows to the appropriate UCT configured reactors.
- The required recycles were achieved by the installation of three submersible pumps (one 7.5 kW pump for the Module A 'a-recycle' and one 3.0 kW pump each for Modules A and B 'r-recycles') together with uPVC pipework, controls and power supply.
- Variable speed control of the new submersible recycle pumps was achieved by the installation of frequency inverters.
- Installation of two new Roots type blowers with an air flow capacity of 40 m^3/min each.
- Rearrangement of the diffused air aeration pipework in Reactors A and B. The new arrangements would provide sufficient air to the aerobic zones of the new UCT configurations for maximum influent flows of 1.73 Mℓ/d for Module A and 2.1 Mℓ/d for Module B at the estimated influent COD and TKN concentrations for the settled sewage.
- Installation of two new structural steel bridges (one in each module) together with mixers in the new anoxic compartments of Reactors A and B.
- Installation of baffle walls in both reactors to separate the new anoxic and aerobic zones.
- Installation of a gate valve in the WAS pipeline. This gate had two functions viz. (i) to prevent back-flow of waste sludge from the rest of the treatment plant and (ii) to allow a sludge flow from the rest of the works for sludge seeding during start-up.
- Installation of a fine-tune sluice gate control at the main splitter box to control the flow to the primary settling tank (PST) ahead of the full-scale plants.
- Installation of two fine-tune sluice gate controls at the PST splitter box to achieve the correct flow split to Modules A and B.
- Installation of influent and effluent channel screens. The former acted as a back up to the screens at the main inlet works and the latter prevented possible blockage of the pipes leading to the secondary settling tanks by floating objects in the bioreactors.
- Installation of ultrasonic flow transducers in the influent channels of Modules A and B and dataloggers to record any variations in the influent flows.

- Installation of flow measuring plates (v-notches and rectangular weir plates) to measure all inter-reactor mixed liquor and RAS recycles.
- Installation of two dissolved oxygen probes with a recording facility.
- Installation of scum traps to aid in containing the scum.
- Installation of new waste flow meters and measuring plates.
- Installation of new guardrails on the full-scale plants.
- Installation of new scum scraper arms on all the settling tanks.
- Repairs to broken diffuser pipework and the installation of new condensation lines at various points along the diffuser pipework.
- Repairs to the primary and secondary settling tanks.

3.7 PROCESS CONTROL AND SYSTEM CALIBRATION

In the operation of the full-scale plants, control of the influent flows and the various recycles is essential, to achieve the required conditions in the two modules. Also, adequate aeration is required to ensure nitrification. Control of these parameters is described below.

3.7.1 Influent flow control and measurement

The raw sewage to the Stage 1 PST was controlled at the main flow splitter of the Mitchell's Plain WWTP. Each overflow weir at the splitter was fitted with an adjustable sluice gate to achieve flow control to the full-scale plants and the rest of the Mitchell's Plain WWTP. The overflow (settled sewage) from the Stage 1 PST was controlled by means of adjustable sluice gates installed in the distribution box at the end of the PST which allowed appropriate flow distribution between Modules A and B. The influent to each module was measured by means of ultrasonic flow transducers located at measuring points upstream of v-notch plates in their respective inlet channels ahead of the anaerobic reactor. Flows to Modules A and B were recorded for monthly downloading by means of electronic loggers and totalisers located in the electrical switchroom at the Stage 1 blower house.

3.7.2 Dissolved oxygen control and measurement

Control of the dissolved oxygen (DO) concentration was achieved by means of valves on the main air manifolds and a pressure-relief valve outside the blower house. These valves could be adjusted to increase or decrease the aeration in the aerobic reactors of Modules A and B. The DO concentrations in the aeration basins were recorded by DO meters located in the middle length of the aeration basin on the side wall. The DO concentrations were continually recorded on paper reams kept for record purposes. The DO probes were supposed to be regularly checked and calibrated by CMC maintenance staff with portable YSI DO meters but this did not happen.

3.7.3 Mixed liquor recycle control and measurement

In both Modules A and B variable speed control of the mixed liquor 'r-recycle' and 'a-recycle' of Module A was achieved by frequency inversion. The potentiometer of the frequency inverter allowed for the selection of any frequency in the range of 20 to 60 H_z thereby giving flexibility in the choice of flows. The Module B 'a-recycle' was controlled by a penstock at the end of the aerobic zone. By manually adjusting the penstock the flow to the Archimedean screw pump could be adjusted thereby achieving control of the recycle. Both Modules A and B 's-recycle' (RAS) flows did not have flow control and their flows were determined by the rate of sludge withdrawal from the SSTs. Each RAS Archimedean screw pump was independent and discharged the sludge return into separate channels. All the recycle flows were measured by rectangular or v-notch weir plates where the height above the weir was recorded and used in the calculation of the flow.

3.7.4 Waste flow control and measurement

Sludge age in the modules was maintained by hydraulic control, *i.e.* wasting the required sludge directly from the aeration basin, at a rate per day of 1/15 of the effective system volume. The waste activated sludge (WAS) flow from each reactor was taken directly from the end of the aerobic reactor via a valve and discharged into a sump where the flows were measured across rectangular weir plates, before discharge to the WAS pipeline.

3.8 COMMISSIONING AND OPERATIONAL ADJUSTMENTS TO THE FULL-SCALE PLANTS

The full-scale plants were commissioned on the 15 March 1999 with influent flows to Modules A and B initially set at 1.4 Mℓ/d and 2.1 Mℓ/d respectively which is in proportion to their respective total system volumes and satisfied the limitation imposed by the diffused air system. During the commissioning stage (March 1999 to October 1999) various problems were encountered which delayed the start of the system performance monitoring by a year. The main problem was the fragile/poor condition of the diffused air system mainly due to its already extended life span. Numerous holes appeared along the PVC pipework at each start-up causing poor air distribution in the aerobic reactors of both modules. Both modules had to be completely drained before remedial work (fibreglassing) could proceed and the rapid rate of infiltration of underground water into the drained tanks made repair work difficult. Despite these difficulties both modules received adequate air supply at their selected influent flows after the repairs and external surface cleaning had been done.

Another related problem experienced during commissioning was the considerable electrical problems with both new blowers. At the desired influent flows with the pressure-relief valve shut, both blower circuits drew high current and consequently tripped on thermal overload as the power absorbed at the blower shaft exceeded the rated power of the motor. This led to insufficient aeration in the two reactors ultimately causing Module A to be decommissioned. In order to remedy the problem with the new blowers, the motor pulley size was reduced which in turn reduced the torque and power absorbed by the blower. This resulted in a lower current drawn, together with a decrease in air flow. The initial air flow capacity of the blowers was 40 m^3/min each, but this was reduced to just over 37 m^3/min. This slightly lower air flow would have little effect on the two full-scale plants because the treatment loads were set lower than the oxygen supply limit of the system. However, the aeration system continued to give problems in the investigation mainly due to a progressive declining oxygen supply due to blocking of the ceramic domes. This resulted in reduced oxygen supply to the aerobic reactors stimulating simultaneous nitrification-denitrification in them.

Another problem was the excessive accumulation of scum in both the unaerated and aerated zones. On investigation it was discovered that the scum formed in the aeration zone and reached the unaerated zones mainly with the surface back-flow across the submerged aerobic-anoxic transition baffles and also via the 'a-recycle'. During this period the whole Mitchell's Plain WWTP experienced problems with scum. It was generally accepted that the high fat content of the influent wastewater to the Mitchell's Plain WWTP was the cause of the high level of scum on the surface of all the bioreactors. In order to prevent the accumulation of scum with its aesthetic and odour nuisances, it was decided to explore ways in which to encourage forward flow of the surface liquid to prevent back-flow from one zone to another. In this regard the appropriate baffle wall submergence and underflow drainage area based on the total flow passing the baffle was calculated and the anoxic-aerobic baffles were modified accordingly. In hindsight, while this effectively dealt with the foaming problem, the reduction in 'a-recycle' flows in both modules (see Chapter 4) caused an increased back mixing of mixed liquor from the aerobic to the anoxic reactors, which adversely affected their denitrification efficiency.

Remedial measures taken for other minor problems encountered after start-up included :

- Repairs to the Rotork pressure-relief valve on the main air manifold at the blower house.
- Overhauling of Module B mixers.
- Repairs to all Module B penstocks to achieve adjustable control.
- Electrical repairs to the Module B mixed liquor screw pump and Module A mixed liquor submersible pumps.

CHAPTER 4

EXPERIMENTAL INVESTIGATION

For the period October 1999 to June 2001, sustained operation of the UCT configured full-sca e plants was achieved with no significant system downtime experienced. This chapter describes the operational changes and experimental results of the investigation which lasted 589 days. At the end of the chapter a brief description of the experimental results of a parallel laboratory-scale UCT system is presented.

4.1 System Operating Conditions and Changes during Experimental Periods

In the operation of the full-scale plants, from an examination of the influent, operational parameters and measured system performance, eight periods were identified where these remained approximately constant during the 589 day investigation, see Table 4.1.

Table 4.1 : 'Steady state' long term periods of the investigation.

Long Term Period No.	Period	Day No.		No. of days	No. of sampling days
		From	To		
I	30/10/99 - 11/06/00	1	224	224	30
II	12/06/00 - 27/09/00	225	332	108	57
III	28/09/00 - 21/11/00	333	387	55	29
IV	22/11/00 - 14/12/00	388	410	23	12
V	15/12/00 - 26/01/01	411	453	43	15
VI	27/01/01 - 07/03/01	454	493	40	23
VII	08/03/01 - 04/05/01	494	551	58	26
VIII	05/05/01 - 11/06/01	552	589	38	20

The operating parameters for Modules A and B for these long term periods are listed in Table

4.2. During the investigation a number of incidents and changes to the operating parameters were made and are recorded in Table 4.3.

Table 4.2 : Full-scale plant operating parameters.

System Parameter	Mod.	Long Term Period No.							
		I	II	III	IV	V	VI	VII	VIII
Sludge age (d)[4]	A	14.2	13.3	11.5	14.5	14.2	14.1	14.2	14.1
	B	14.1	13.1	11.5	14.4	14.2	14.1	14.1	14.1
Influent (Mℓ/d)	A	1.49	1.47	1.52	1.13	1.63	1.91	1.70	1.90
	B	2.24	2.24	2.14	1.57	2.12	2.28	2.20	2.23
'a-recycle' (Mℓ/d)	A	3.20	1.80	0.00	0.00	0.00	0.00	0.00	0.00
	B	9.60	8.76	5.90	7.73	6.51	6.45	5.54	4.61
'a-recycle' ratio*	A	2.3	1.2	0.0	0.0	0.0	0.0	0.0	0.0
	B	4.6	3.9	2.8	4.9	3.1	2.8	2.5	2.1
's-recycle' (Mℓ/d)	A	5.20	4.75	1.77	3.20	5.20	3.44	2.24	2.18
	B	5.20	4.73	1.93	2.05	5.05	4.02	2.52	2.75
's-recycle' ratio*	A	3.7	3.2	1.2	2.8	3.2	1.8	1.3	1.1
	B	2.5	2.1	0.9	1.3	2.4	1.8	1.1	1.2
'r-recycle' (Mℓ/d)	A	1.40	1.58	1.50	1.41	1.45	1.41	1.51	1.61
	B	2.40	2.40	2.41	2.40	2.40	2.15	2.16	2.16
'r-recycle' ratio*	A	1.0	1.1	1.0	1.2	0.9	0.7	0.9	0.8
	B	1.1	1.1	1.1	1.5	1.1	0.9	1.0	1.0
Waste flow (m^3/d)	A	87.58	87.58	87.58	87.58	87.58	87.58	87.58	87.58
	B	132.67	132.67	132.67	132.67	132.67	132.67	132.67	132.67
Aerobic DO[+] (mgO/ℓ)	A	2.00	2.00	1.80	0.15	0.35	1.70	1.95	1.90
	B	2.10	2.00	2.10	2.00	0.90	2.05	0.50	1.70
Temperature of sludge (°C)		17 - 25	17 - 25	17 - 25	17 - 25	17 - 25	17 - 25	17 - 25	17- 25
Influent TKN / COD ratio		0.11-0.19	0.10-0.24	0.13-0.19	0.10-0.18	0.13-0.17	0.14-0.20	0.14-0.19	0.14-0.19

* All recycle ratios with respect to the influent. Average aerobic DO concentration for the 'steady state' period.

[4]From Section 3.5, the proposed design sludge age was 15 days. However in the UCT NDBEPR configuration the sludge age needs adjustment as the sludge concentration in the anaerobic reactor is about half that of the anoxic and aerobic reactors due to a dilution effect of the influent entering the anaerobic reactor. Therefore the effective anaerobic volume is a factor R/(1 R) multiplied by the actual volume, where R is the 'r-recycle' ratio.

Table 4.3 : Record of incidents and system operational changes to the full-scale plants.

Description of incidents or changes	Day No.		Action Taken
	From	To	
Blower's non-return valve faulty causing poor aeration.	120	121	Air switched off. Non-return valve repaired.
Influent re-split to Modules A & B.	122	589	Flows set at 1.6 & 2.4 Mℓ/d.
Module B SST rotating bridge stuck causing solids up-flow.	140	141	Obstruction removed.
Excessive scum build-up in aerobic zone of Reactor A.	193	201	Scum gate opened to allow scum to leave via waste flow.
Local power failure.	212	213	Electricity supply reinstated.
Blower 1 no longer in operation.	262	262	Standby blower switched on.
Reactor A anaerobic mixer down.	264	276	Motor repaired.
NO_3 load on Module A anoxic reactor too high.	306	589	Module A 'a-recycle' set to 0, 's-recycle' reduced.
Very low flow into Stage 1 PST.	328	331	Blockage at splitter cleared.
Module A RAS screw pump down.	369	370	Motor repaired.
Module B mixed liquor 'a-recycle' screw pump down.	370	375	Motor replaced. 'S-recycle' increased to compensate.
Low MLSS in Module A - no 's- recycle' Flow and air stopped on days 386 & 387.	383	397	Blockage in SST A pipework cleared. Flow and air reinstated.
Blockage in Module B 's- recycle'.	432	435	Blockage removed.
Flow to Module A stopped ?	450	451	Flow reinstated.
Increased aeration to Module A.	458	589	Control valves gradually adjusted.
Air leakage at Module A air manifold downpipe.	497	589	Situation monitored.
Solids carryover at Module B SST.	513	516	Samples treated.
Blower No. 2 tripping on thermal over-load causing poor aeration.	532	549	Blower restarted and reset each time to prevent tripping.
Module B mixed liquor 'a-recycle' screw pump down.	540	563	Screw pump's lower bearing replaced.
Modules A and B diffused air system failure.	588	589	Modules A & B decommissioned.

From Tables 4.2 and 4.3:

- A sludge age of approximately 14 days was achieved in both modules. However, difficulties were experienced in maintaining a constant sludge age (see below).
- From the design data for the influent (Section 3.3), the design influent flow for Module A was 1.4 Mℓ/d and for Module B 2.1 Mℓ/d. During Period I, it was found that the influent COD concentration was much lower than the expected 861 mgCOD/ℓ (see Table 3.2), at about 600 mgCOD/ℓ. Thus, from day 122, Period I the influent flow rates were increased to 1.6 and 2.4 Mℓ/d for Modules A and B respectively. The recorded influent flow rates are reasonably close to these values. Difficulty was experienced in attaining the exact flow rates as construction work at the inlet works and the equalisation basins caused unusual fluctuations in the influent flow.
- In the design, the 'a-recycle' ratios for Modules A and B were set at 2:1 and 5:1 respectively, but it was noted that these probably would have to be decreased at the lower temperatures. In operation, these recycle ratios were closely achieved for Period I (2.3 and 4.6:1 for Modules A and B respectively). However, from plant performance monitoring it was noted that the nitrate concentrations in the anoxic reactors of both modules were excessively high, which caused significant nitrate to be recycled to the anaerobic reactor, adversely influencing biological P removal. These high anoxic nitrate concentrations were due in part to the high 's-recycle' ratios (see below), and the high TKN/COD ratio of the settled wastewater. Accordingly, the 'a-recycle' ratios for both modules were reduced, as recorded in Table 4.2.
- In the design, the 's-recycle' ratio was set at 1:1. In operation of the modules, due to the suction lift draw-off from the SSTs, it was found not possible to control the 's-recycles' to the proposed 1:1 as this was too low to maintain suction lift. The 's-recycle' flow rates were measured in both modules, as recorded in Table 4.2. These flow rates were accepted for operation.
- For Periods I to III, the aerobic DO concentration was adequate at about 2 mgO/ℓ. These three periods which represent the longest experimental periods of the investigation (up to day 387 of 589) with the most stable plant operation (spanning about 27 sludge ages) gave good effluent quality results. However, from period IV difficulty in maintaining adequate aerobic DO was experienced in both modules due to the deteriorating condition of the diffused air system (see below).

During the first half of the investigation, difficulty in maintaining the desired sludge age was experienced due to considerable difficulties with activated sludge wastage from the full-scale plants. The underlying cause was the sludge handling facilities (DAF, linear screen *etc.*) downstream which had inadequate capacity to deal effectively with sludge wastage from the full-scale plants and the rest of the treatment plant. As the full-scale plants shared a common waste activated sludge pipeline with the rest of the treatment plant, waste sludge back flows into the full-scale plant were often experienced. The back flow of sludge into the full-scale plants from the main plant was substantial and resulted in reactor sludge concentrations at times in excess of 60 % of those that would normally accumulate in the reactor from the influent wastewater (see Section 5.5.1.1 for details). The seriousness and significance of this problem and its potential to compromise the objectives of the investigation were communicated to the Cape Metropolitan Council (CMC). The construction of an independent sludge wastage pipeline and pump was requested. However, the CMC did not have funds to install such a system and instead put a plant operator's sludge wastage protocol in place which if adhered to would have limited sludge ingress into the full-scale plants. The results however, indicate that this protocol did not successfully eliminate the problem, because if it did, the full-scale plants would not have accumulated so much more sludge than can reasonably be expected. To alleviate this problem a gate valve was installed in the existing sludge wastage pipeline but this also proved to be ineffective as the gate needed to be opened when wasting from the full-scale plants. Often when this gate was opened the problem was encountered due to simultaneous wastage from the full-scale plants and the rest of the plant. Finally, a new waste schedule for the entire treatment plant was set up which allowed wasting from the full-scale plants without simultaneous wasting from the rest of the plant. This strategy had a fair amount of success, but sporadic large fluctuations in reactor solids concentrations were still noted in the full-scale plants. This persistent problem throughout the investigation compromised the second objective of the investigation *i.e.*, checking COD balances for possible anaerobic reactor COD losses. The COD balance requires the oxygen utilisation rate (OUR) to be measured on both modules. Measurement of OUR is very labour intensive - it has to be measured hourly at 3 different places in the aerobic reactor over 24-30 hour period in both modules while all the other parameters were also measured. It was planned to do this only when reasonable surety of "steady state" conditions in the full-scale plants was achieved, which due to the sporadic ingress of sludge did not happen. Nevertheless, 2 x 24 hour tests were done on the full-scale plants by Modipa and Diale (2000) for their BSc theses. The COD and N balances obtained in these two tests were 150 & 44 % and 83 & 74 % respectively, too deviant to be useful for the second project objective and simulation.

In operation the most serious problem experienced was with the diffused air system. The ceramic diffuser domes became increasingly blocked as the investigation continued. To attempt to maintain aeration to ensure complete nitrification and avoid simultaneous denitrification in the aerobic reactor, the pressure relief valves on the blowers were shut. This increased the back pressure in the system to the extent that the blowers often tripped on thermal overload, despite adjustment to the blower pulleys made earlier in the investigation (see Section 3.8.2). On day 588 the back pressure in the diffused air system became so excessive that the end caps on the PVC piping blew out causing structural damage to the plants, and the investigation had to be terminated.

4.2 Data Acquisition and Sample Analysis

System performance monitoring commenced on 31 October 1999. Initially the plant was monitored once a week on Sundays by the Scientific Services Department of the CMC. The sampling on Sundays was done independently of this project for the CMC's own weekly laboratory records. Table 4.4 shows the samples taken and typical analyses which will be termed "CMC" data.

From June 2000 more extensive sampling and analysis was carried out on the plants every second day, excluding Sundays. These analyses will be termed "site" data. Table 4.5 shows the sampling and analysis schedule. The influent and effluent samples were 24 hour composites, and the reactor samples were grab samples. The results from the 2 x 24 hour tests showed that the daily variation in reactor concentrations were small due to constant flow and long retention time ~ 8 hr (see Section 5.6) so that the grab samples can be accepted as a composite equivalent. All grab samples from the various locations in the reactors were filtered immediately on-site and further prepared if necessary (*e.g.* flocculation and filtration) before being stored in a refrigerator for analysis the following day. Chemical and physical analyses of these samples were done at the Mitchells Plain WWTP laboratory and the Scientific Services laboratory. Table 4.6 below shows typical results for the "site" data. Filament identifications were done once monthly.

Graphs and tables of the bi-daily "site" data and weekly "CMC" data are given in Appendix B and C respectively. Table 4.7 below shows the analytical methods applied to the measured

Table 4.4 : Typical sample sheet for "CMC" sampling and analysis. Sampling done weekly, every Sunday.

MITCHELL'S PLAIN WWTW - PILOT PLANT : SCIENTIFIC SERVICES WEEKLY LAB. REPORT

Date : 10 April 2000

SAMPLE	UNITS	MODULES A & B INFLUENT	MODULE A MIXED LIQUOR / ACTIVATED SLUDGE							MODULE B MIXED LIQUOR / ACTIVATED SLUDGE							MODULE A EFFLUENT	MODULE B EFFLUENT
			Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle		
Unfiltered COD	mg COD/l	673.00															58.00	34.00
Filtered COD	mg COD/l	313.00															48.00	34.00
Unfiltered TKN	mg N/l	118.20																
Filtered TKN	mg N/l																	
Flocculated/Filtered TKN	mg N/l																	
Filtered FSA	mg N/l	73.20															0.10	0.10
Filtered NO_3	mg N/l																	
Filtered NO_2	mg N/l																	
Filtered $NO_3 + NO_2$	mg N/l																13.80	13.88
Unfiltered Total P	mg P/l	19.10																
Filtered Total P	mg P/l																	
Filtered Ortho P	mg P/l																11.00	9.00
pH		7.30				6.30							5.50				6.70	6.60
Alkalinity	mg/l as $CaCO_3$	420.00															39.00	50.00
TSS	mg MLSS/l	158.00				2540.00							3680.00				5.00	1.00
VSS	mg MLVSS/l					2250.00							3090.00					
SVI	ml/g					83.00							98.00					
DSVI	ml/g					79.00							82.00					

Notes :
1. The influent and effluent samples are composite samples. All other samples are grab samples.

Table 4.5: Sampling procedure and sample analysis implemented every second day - "site" samples

MITCHELL'S PLAIN WTW PILOT PLANT : SAMPLING & LABORATORY TESTING

SAMPLE	MEASUREMENT PARAMETER										
	COD	**TKN**	**TP**	**NO_3**	**NO_2**	**FSA**	**OrthoP**	**VSS & TSS**	**DO**	**SVI & DSVI**	**pH & ALK**
Influent[1]	i.) Unfiltered ii.) Floc./filt. (0.45μm)	i.) Unfiltered ii.) Filtered (0.45μm)	i.) Unfiltered ii.) Filtered (0.45μm)	i.) Filtered (0.45μm)	i.) Filtered (0.45μm)	i.) Filtered (Whatman's No. 1)	i.) Filtered (Whatman's No. 1)	i.) Influent samples			i.) Influent pH ii.) Influent alkalinity
Anaerobic			i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]						
Anoxic			i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]						
Aerobic			i.) Unfiltered ii.) Filtered (What's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]			i.) Reactor samples	i.) Reactor sample	i.) Reactor sample	i.) Reactor pH
Effluent[1]	i.) Unfiltered ii.) Floc./filt. (0.45μm)	i.) Unfiltered ii.) Floc./filt. (0.45μm)	i.) Unfiltered ii.) Filtered (0.45μm)	i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)	i.) Filtered (Whatman's No. 1)				i.) Effluent pH ii.) Effluent alkalinity
R - recycle[4]				i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]						
A - recycle[4]				i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]				i.) Channel sample		
S - recycle[4]				i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]				i.) Channel sample		
Anoxic-Aerobic Transition[3]				i.) Filtered (Whatman's No. 1)[2]	i.) Filtered (Whatman's No. 1)[2]						

Notes :
1. Influent and effluent samples to be composite samples. All other samples to be grab samples.
2. All Whatman's No. 1 paper filtering, with the exception of the FSA & OrthoP samples, to be done at time of sampling to prevent denitrification.
3. The anoxic - aerobic transition sample to be a composite filtrate of grab samples taken at the upper, middle & lower sections on aerobic side of baffle.
4. The A, R & S - recycle samples to be taken in the channels close to the end of the pipework.
5. Shaded areas are CRITICAL i.t.o. sampling & testing.
6. Filament identification to be done once a month.
7. Other measurement parameters to be taken are all flows, wasting, temperature & rainfall.

Table 4.6 : Typical sample sheet for "site" sampling and analysis. Sampling done every second day, excluding Sundays.

MITCHELL'S PLAIN WWTP - STAGE 1 : LABORATORY REPORT

Date : 29-08-2000

SAMPLE	UNITS	MODULES A & B INFLUENT	MODULE A MIXED LIQUOR / ACTIVATED SLUDGE							MODULE B MIXED LIQUOR / ACTIVATED SLUDGE							MODULE A EFFLUENT	MODULE B EFFLUENT
			Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle		
Unfiltered COD	mg COD/l	541.00															41.00	37.00
Flocculated/Filtered COD	mg COD/l	220.00															37.00	32.00
Unfiltered TKN	mg N/l	95.50															1.10	1.00
Filtered TKN	mg N/l	86.00																
Flocculated/Filtered TKN	mg N/l																2.70	0.70
Filtered FSA	mg N/l	65.00															2.00	0.50
Filtered NO_3	mg N/l	0.182	0.167	[illegible]	4.849	11.539	4.198	10.474	8.993	0.087	6.457	5.768	6.527	7.666	16.634	15.644	10.910	16.855
Filtered NO_2	mg N/l	0.059	0.202	0.154	0.110	0.082	0.101	0.053	0.070	0.006	0.447	0.142	0.042	0.225	0.019	0.021	0.125	0.064
Filtered $NO_3 + NO_2$	mg N/l	0.100															10.200	15.800
Unfiltered Total P	mg P/l	12.50				225.00							267.00				0.20	0.50
Filtered Total P	mg P/l	10.30	13.90	9.00		0.10				25.48	7.20		0.10				0.10	0.20
Filtered Ortho P	mg P/l	8.90															0.10	0.20
pH		7.24				6.63							6.51				6.65	6.55
Alkalinity	mg/l as $CaCO_3$	300.00															67.00	35.00
TSS	mg MLSS/l	134.00				3782.00							3917.00					
VSS	mg MLVSS/l	115.00				2876.00							3053.00					
SVI	ml/g					120.00							105.00					
DSVI	ml/g					95.00							87.00					

Notes :

1. The influent and effluent samples are composite samples. All other samples are grab samples.

parameters and the corresponding figure numbers of graphs found in Appendices B & C are given in Table 4.8.

Table 4.7 : Analytical methods applied to test parameters.

Test Parameter	Analytical Method
COD	Standard Methods (1985)
TKN	Standard Methods (1985)
Total P	Lachat 8000 Flow Injection Analysis (FIA) colorimeter - QuikChem® Method 10-115-01-1-E10-115-01-1-E (Acid-Persulphate Digestion)
Ortho P	FIA colorimeter - QuikChem® Method 10-115-01-1-A
NO_3, NO_2	HP LC Auto Analyser
FSA - Low/High	FIA colorimeter - QuikChem® Method 10-107-06-1-A/H
VSS, TSS	Solids separation by centrifugation, drying in a crucible at 105 °C, incinerating at 600 °C
SVI, DSVI	Lee *et al.* (1983) or Ekama and Marais (1984)
pH	Schott Gerate Digital Lab. pH meter CG 825
Alkalinity	FIA colorimeter - QuikChem® Method 10-303-31-1-A
Flocculation - influent and effluent samples	1l sample subjected to 10ml of 0.25M Aluminium Sulphate flocculant concentration and allowed to settle for 1hr.
Filtration - reactor samples	Filtered through Whatman® GF/C glass microfibre filters.
Filtration - effluent samples	Filtered through Millipore 0.45μm sterile membrane filters.
DO - aerobic zone	Zullig Model DO94 and GLI Int. model D53 fixed DO meters.
DO - various	Yellow Springs Int.(YSI) Model 55 portable DO meter

4.3 Measured System Performance

For each "steady state" period given in Table 4.1, the appropriate data were averaged and are presented below. For Period I (the first 224 days of the investigation) only the "CMC" data were examined to monitor the system performance of the full-scale plants, because the "site" data monitoring programme started only in Long Term Period II.

Table 4.8 : Measured parameters with corresponding figure numbers.

Test	Appendices B and C	Test	Appendices B and C
COD	Figure B1/B4 and Figure C1	Total P	Figure B3/B6 and Figure C3
TKN	Figure B2/B5 and Figure C2	Ortho P	Figure B3 and Figure C3
FSA	Figure B7 and Figure C2	VSS/TSS	Figure B9/B10 and Figure C5
NO_x	Figure B8 and Figure C4	DSVI	Figure B11 and Figure C6

4.3.1 Influent Data

The influent data averaged for each of the long term periods in Table 4.1 are given in Table 4.9 below, for both the weekly "CMC" analysis and the more detailed bi-daily "site" analysis.

From Table 4.9 :

- The influent COD concentrations (averages 653 and 614 mg/ℓ) are much lower than the expected 861 mg/ℓ (Section 3.3.1) determined for the design. For this reason the influent flow rates to the full-scale plants were increased from 1.4 and 2.1 Mℓ/d for Modules A and B respectively, to 1.6 and 2.4 Mℓ/d respectively from Period II (Section 4.1 above).
- The average flow rates (1.60 and 2.16 Mℓ/d for Modules A and B respectively) indicate that the desired flow rates above were closely achieved.
- The influent TKN (averages 95.3 and 98.0 mgN/ℓ) is very similar to that determined for the design (96 mgN/ℓ).
- The high influent TKN concentration together with the reduced COD concentration, indicates that the PST removals were better than expected (COD removal in primary sedimentation is higher than TKN removal, due to the large soluble free and saline ammonia (FSA) fraction in the TKN). This caused the influent TKN/COD ratio to be considerably higher than expected, 0.15 to 0.16 mgN/mgCOD compared to 0.11 mgN/mgCOD (see Section 3.3.1).
- The influent total phosphorus (P) concentrations (averages 14.4 and 12.7 mgP/ℓ) are significantly lower than the concentration accepted for the design (19.2 mgP/ℓ). This is unexpected since a large proportion of the P is soluble and should not be influenced by the better than expected primary sedimentation.

- Influent nitrate + nitrite measurements (not shown here, see Table 4.11) were < 0.5mgN/ℓ indicating these to be present in the influent at negligible concentrations, as expected.

Table 4.9 : Averaged influent data for steady state periods; averages are for "CMC" (weekly) and "site" (bi-daily) data.

Long Term Period No.	Flow Rate (Mℓ/d)		COD (mgCOD/ℓ)			TKN (mgN/ℓ)			FSA (mgN/ℓ)		Total P (mgP/ℓ)	
	Mod. A	Mod. B	CMC data	Site data	Floc/ Filt	CMC data	Site data	Filt	CMC data	Site data	CMC data	Site data
I	1.40	2.10	666	N/A	N/A	90.4	N/A	N/A	72.3	N/A	14.8	N/A
II	1.47	2.24	664	567	254	96.4	94.8	81.6	75.3	68.8	14.8	13.1
III	1.52	2.14	634	612	268	98.8	98.0	85.9	76.1	67.8	13.8	13.0
IV	1.13	1.57	649	653	302	87.8	92.2	80.1	67.6	65.4	14.0	12.8
V	1.63	2.12	640	676	427	92.9	97.6	86.0	75.2	67.6	13.4	12.7
VI	1.91	2.28	630	653	292	100.8	99.9	85.7	77.2	70.0	13.9	12.4
VII	1.70	2.20	631	612	230	103.4	101.2	88.9	82.8	69.6	13.8	12.2
VIII	1.90	2.22	648	616	239	105.3	104.2	90.5	84.5	66.7	14.1	12.3
Ave.	1.61	2.17	653	614	278	95.3	98.0	83.2	75.4	68.3	14.4	12.7

Note : Influent COD, TKN, FSA and Total P = unfiltered. FSA = free and saline ammonia. CMC averages include Period I, whereas site averages do not (N/A). Flocculated/filtered influent TKN was not measured, but 0.45 μm filtered was (see Table 4.6).

4.3.2 Reactor Parameters

The various averaged reactor concentrations for the steady state periods are listed in Tables 4.10 and 4.11 below. In Table 4.11 only the "site" data is listed as the "CMC" data did not include these measurements.

The averaged reactor concentrations will be discussed in more detail in Section 5, but immediately apparent from Tables 4.10 & 4.11 and Figures 4.1 to 4.14 below, are:

- Nitrite concentrations were negligible throughout the plant.

- Anoxic nitrate concentrations were high for both modules, except when nitrification failed, Module A Periods IV and V in particular (see Section 5.2.2 below).
- An apparent anomaly in the nitrate data exists; anoxic reactor nitrate concentrations were high, yet effluent nitrate concentrations were relatively low. It became evident during the investigation that the main cause for this was inadequate aeration and significant back mixing of aerobic reactor mixed liquor into the anoxic reactors resulting in quasi anoxic quasi aerobic conditions in both the anoxic and aerobic reactors leading to simultaneous nitrification-denitrification in these reactors, particularly in Module A (see Section 5.2.3 below).
- The reactor P concentrations follow the typical biological P removal pattern, with anaerobic P release followed by subsequent P uptake in the anoxic and/or aerobic reactors (see Section 5.3.2 below).
- The overall average TSS and VSS concentrations in the 2 modules are similar, as required.
- The DSVI is consistently low (see Section 5.3.5.1 below).

Table 4.10 : Averaged reactor mixed liquor data for steady state periods; averages are for "site" data which excludes Period I (N/A) and "CMC" data.

Long Term Period No.	Site TSS (mgTSS/ℓ)		CMC TSS (mgTSS/ℓ)		Site VSS (mgVSS/ℓ)		CMC VSS (mgVSS/ℓ)		Site DSVI (mℓ/gTSS)		CMC DSVI (mℓ/gTSS)	
	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B
I	N/A	N/A	4257	5473	N/A	N/A	3824	5142	N/A	N/A	97.4	116.1
II	3604	4082	3760	4236	2621	3146	N/A	N/A	99.8	89.2	103.6	87.9
III	3150	3829	3580	3719	2322	2893	N/A	N/A	86.8	87.0	93.0	89.7
IV	2503	4321	3217	4345	2085	3204	N/A	N/A	109.2	93.7	106.0	91.3
V	5006	2819	3240	3374	3787	2123	N/A	N/A	98.7	101.7	126.2	109.4
VI	3878	3914	3964	2228	2860	2958	N/A	N/A	96.6	98.6	94.3	95.3
VII	3343	3330	3161	3110	2593	2580	N/A	N/A	88.6	92.4	89.3	61.5
VIII	3626	3012	3445	2877	2702	2249	2825	2390	105.3	96.8	112.8	91.8
Average	3622	3661	3808	4265	2710	2787	3049	3826	97.1	92.5	97.8	88.7

Note : CMC average VSS for Periods I and VIII only.

Table 4.11 : Averaged filtered concentrations for steady state periods; averages are for "site data". (See also Figures 4.1 to 4.14 below).

Parameter (mg/ℓ)	**Module**	**Long Term Period No.**						
		II	**III**	**IV**	**V**	**VI**	**VII**	**VIII**
Influent NO_3	A & B	0.22	0.17	0.05	0.15	0.51	0.08	0.24
Influent NO_2	A & B	0.04	0.11	0.03	0.22	0.17	0.14	0.13
Influent Total P	A & B	10.75	11.09	11.09	10.66	10.64	10.26	9.86
Anaerobic NO_3	A	1.40	0.21	0.11	0.21	0.51	0.48	0.18
	B	0.39	0.18	0.13	0.10	0.27	0.14	0.26
Anaerobic NO_2	A	0.08	0.14	0.16	0.13	0.15	0.53	0.19
	B	0.06	0.06	0.08	0.10	0.11	0.20	0.16
Anaerobic Total P	A	18.60	29.99	13.03	34.10	25.69	23.92	24.48
	B	22.22	31.49	27.85	28.25	31.33	20.39	31.02
Anoxic NO_3	A	7.22	3.39	0.07	0.13	6.94	6.73	8.32
	B	8.01	5.17	5.01	3.29	5.34	1.67	4.44
Anoxic NO_2	A	0.13	0.25	0.03	0.04	0.28	0.20	0.22
	B	0.20	0.21	0.07	0.46	0.42	0.18	0.24
Anoxic Total P	A	6.04	11.14	9.24	12.66	10.26	10.05	7.25
	B	9.38	13.33	15.05	10.21	13.05	13.03	16.19
Aerobic NO_3	A	11.75	10.00	2.00	1.59	11.73	10.09	13.51
	B	14.78	14.91	10.57	11.07	15.03	9.51	13.58
Aerobic NO_2	A	0.08	0.23	0.15	1.81	0.12	0.15	0.09
	B	0.05	0.04	0.06	0.37	0.09	1.01	0.58
Aerobic Total P	A	2.20	1.55	0.44	3.78	3.61	5.87	2.17
	B	4.45	1.26	7.56	1.74	3.43	2.06	5.06
Effluent NO_3	A	12.50	8.69	0.28	1.27	12.61	11.25	13.58
	B	16.12	16.09	12.42	11.05	15.00	8.78	14.77
Effluent NO_2	A	0.13	0.22	0.21	1.38	0.13	0.23	0.16
	B	0.05	0.08	0.09	0.36	0.12	0.97	0.70
Effluent Total P	A	1.71	0.45	7.18	1.50	3.87	4.90	2.32
	B	4.67	1.52	7.90	3.34	3.51	2.61	0.99

Note : Influent, anaerobic, anoxic, aerobic & effluent Total P = filtered Total P concentration.

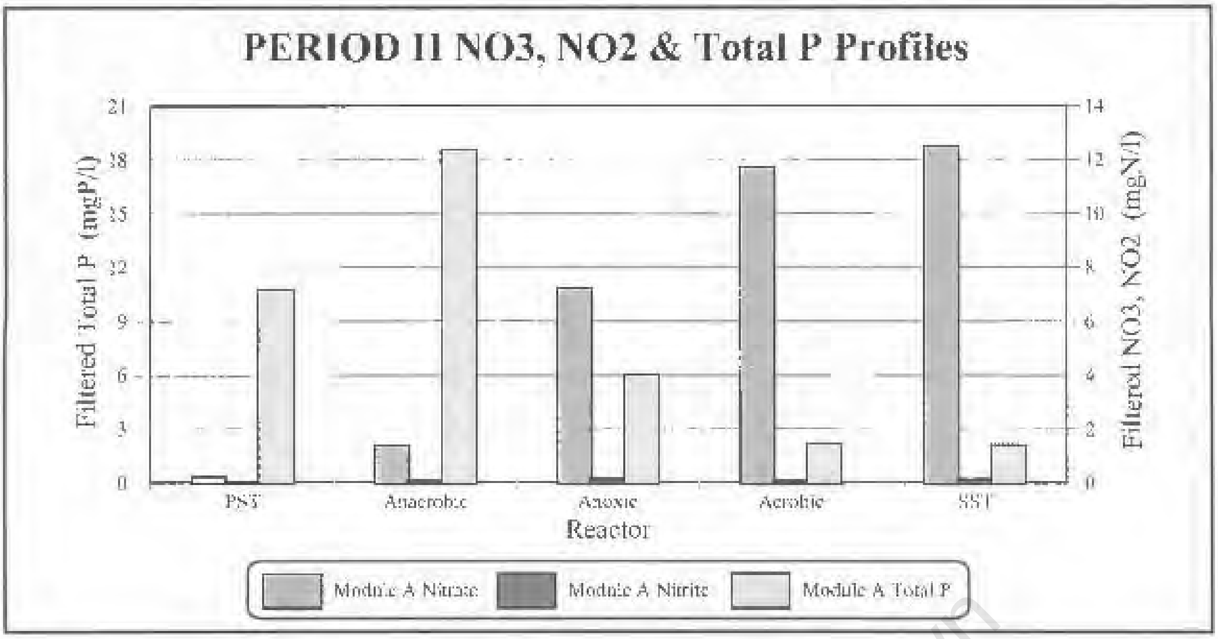


Figure 4.1 : Long Term Period No. II nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module A.

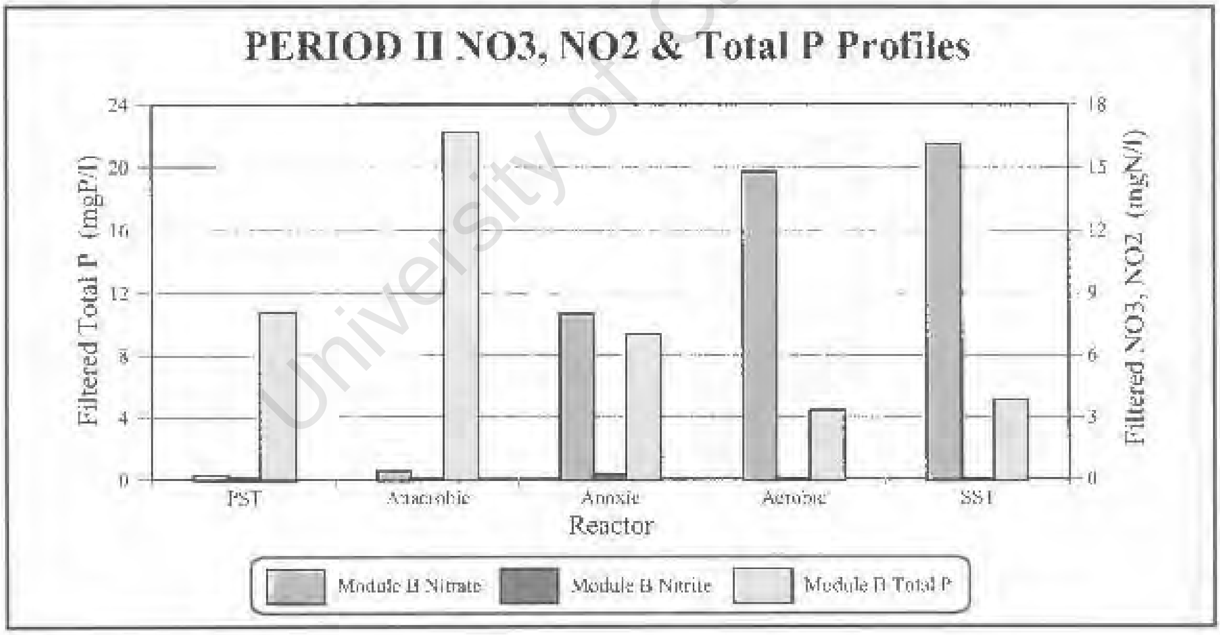


Figure 4.2 : Long Term Period No. II nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module B.

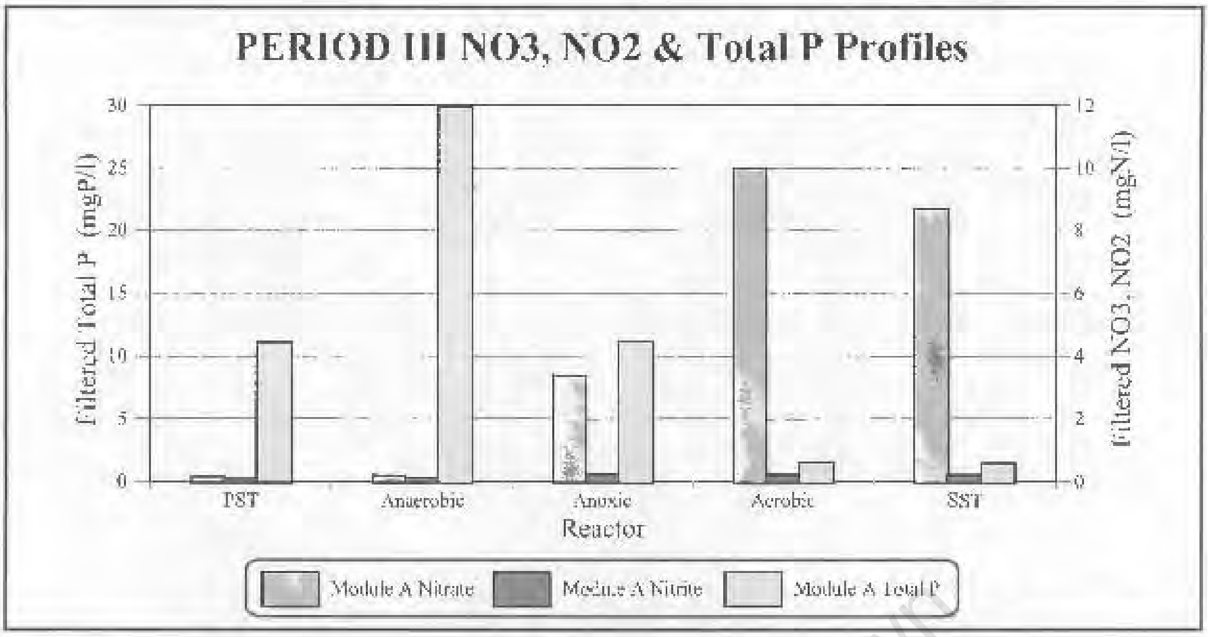


Figure 4.3 : Long Term Period No. III nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module A.

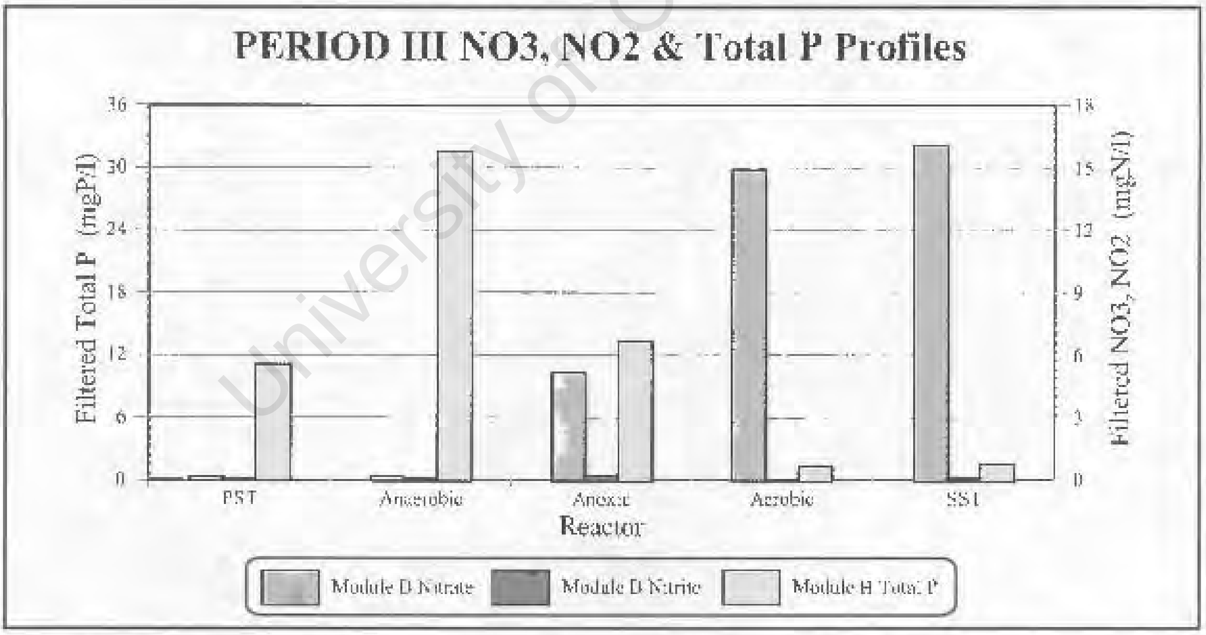


Figure 4.4 : Long Term Period No. III nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module B.

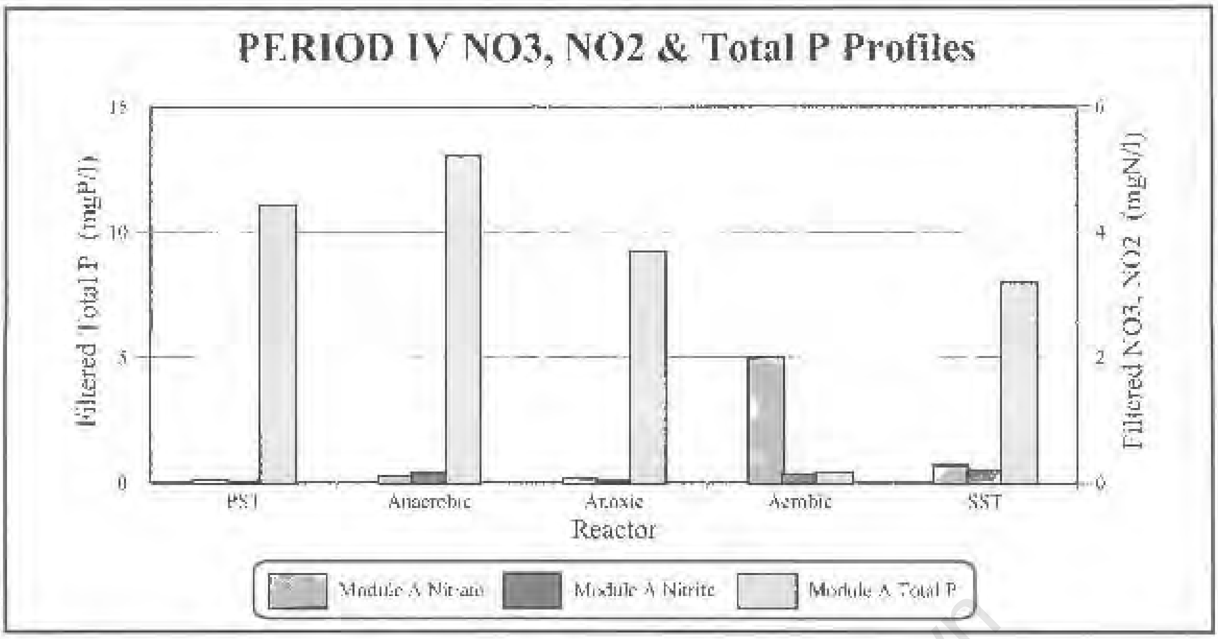


Figure 4.5 : Long Term Period No. IV nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module A.

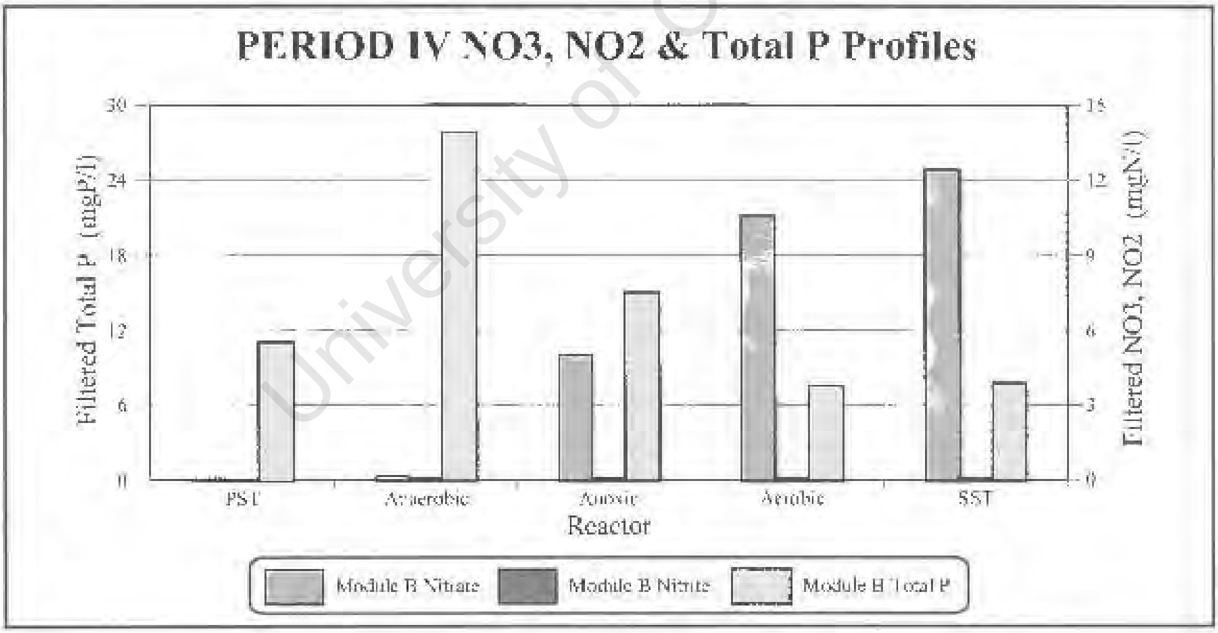


Figure 4.6 : Long Term Period No. IV nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module B.

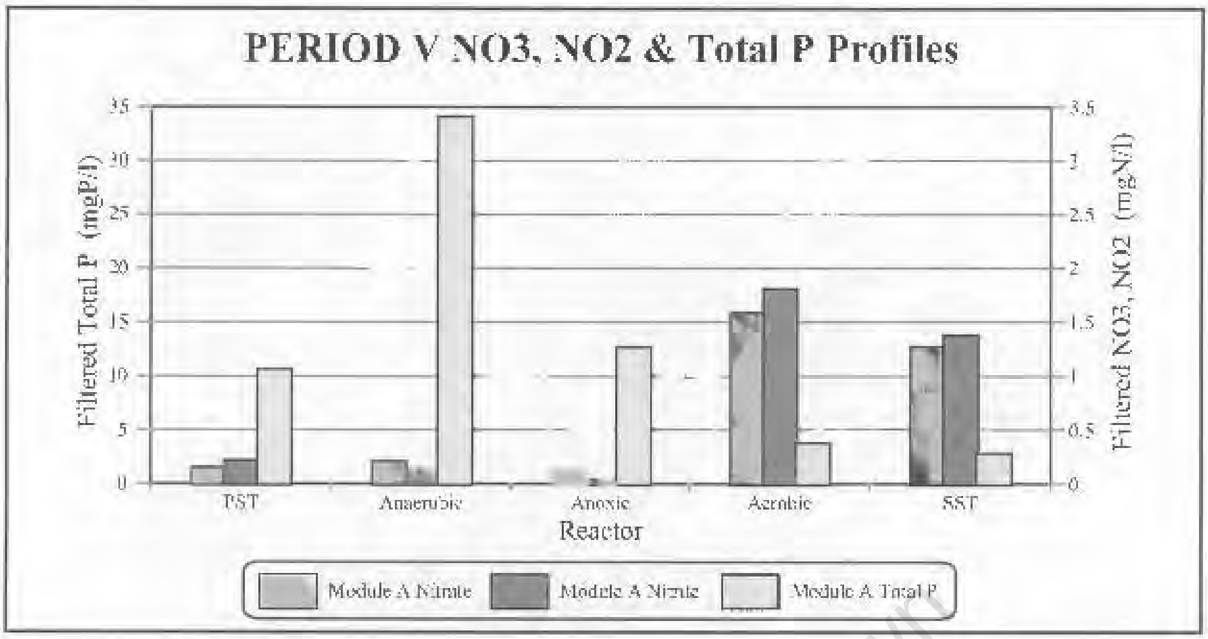


Figure 4.7 : Long Term Period No. V nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module A.

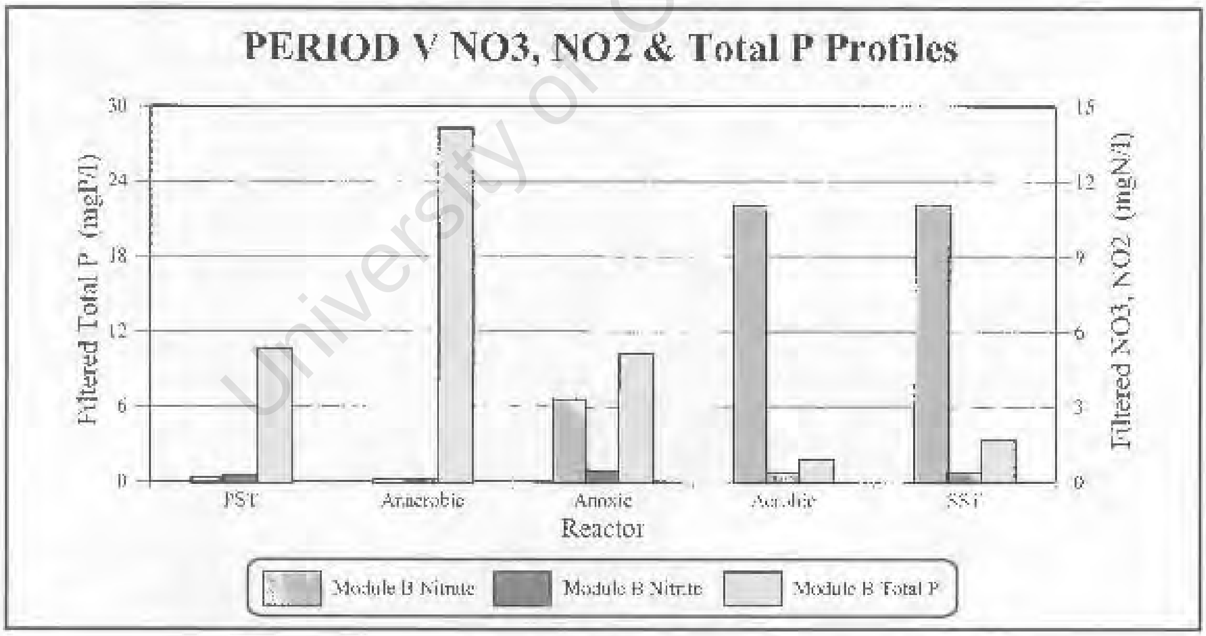


Figure 4.8 : Long Term Period No. V nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module B.

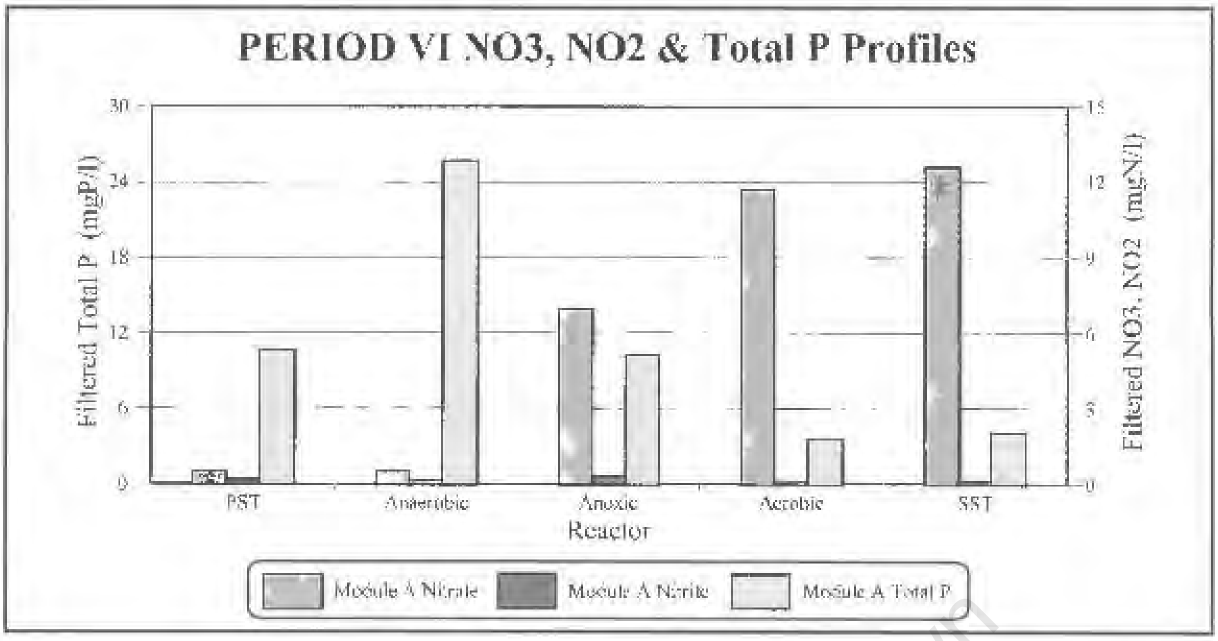


Figure 4.9 : Long Term Period No. VI nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module A.

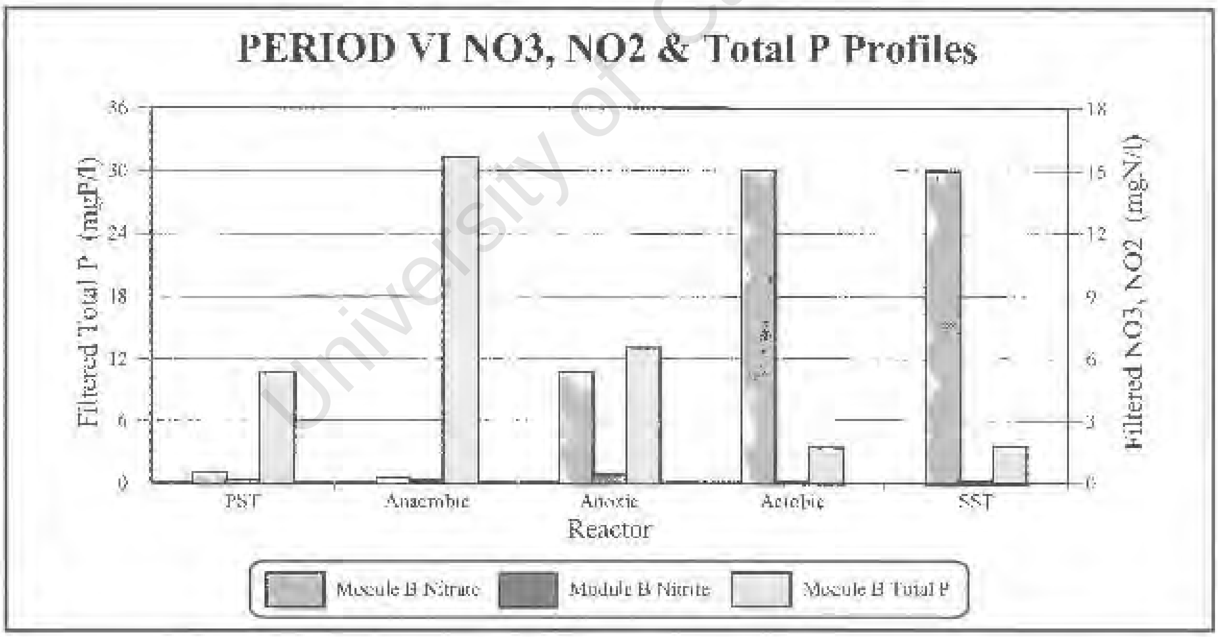


Figure 4.10 : Long Term Period No. VI nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module B.

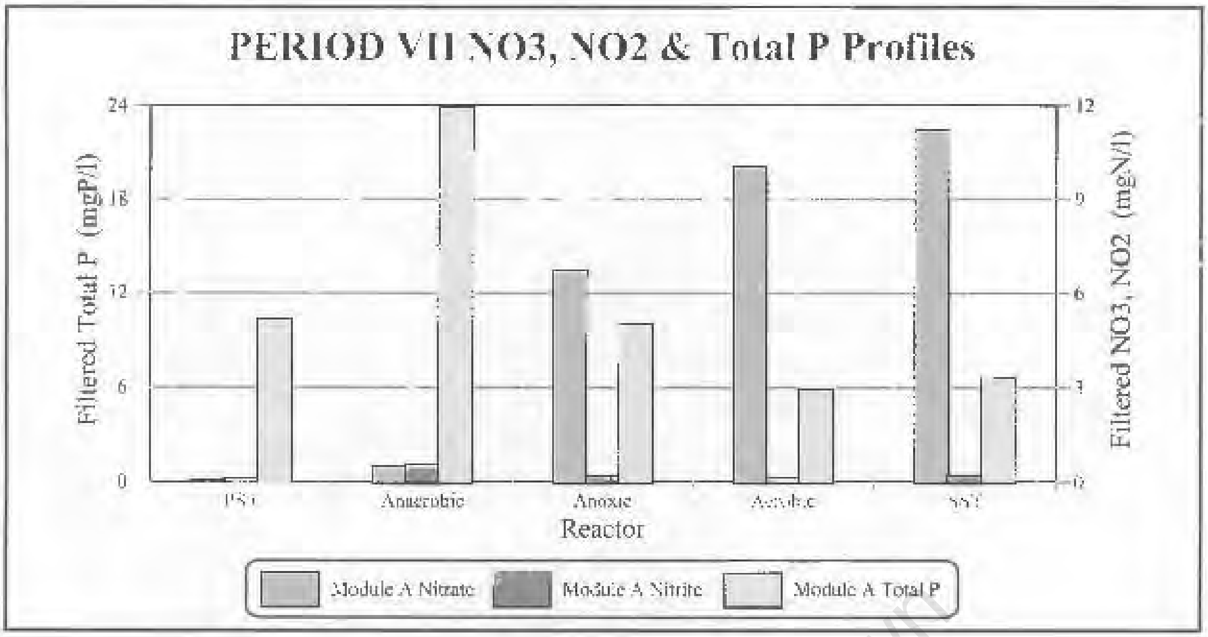


Figure 4.11 : Long Term Period No. VII nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module A.

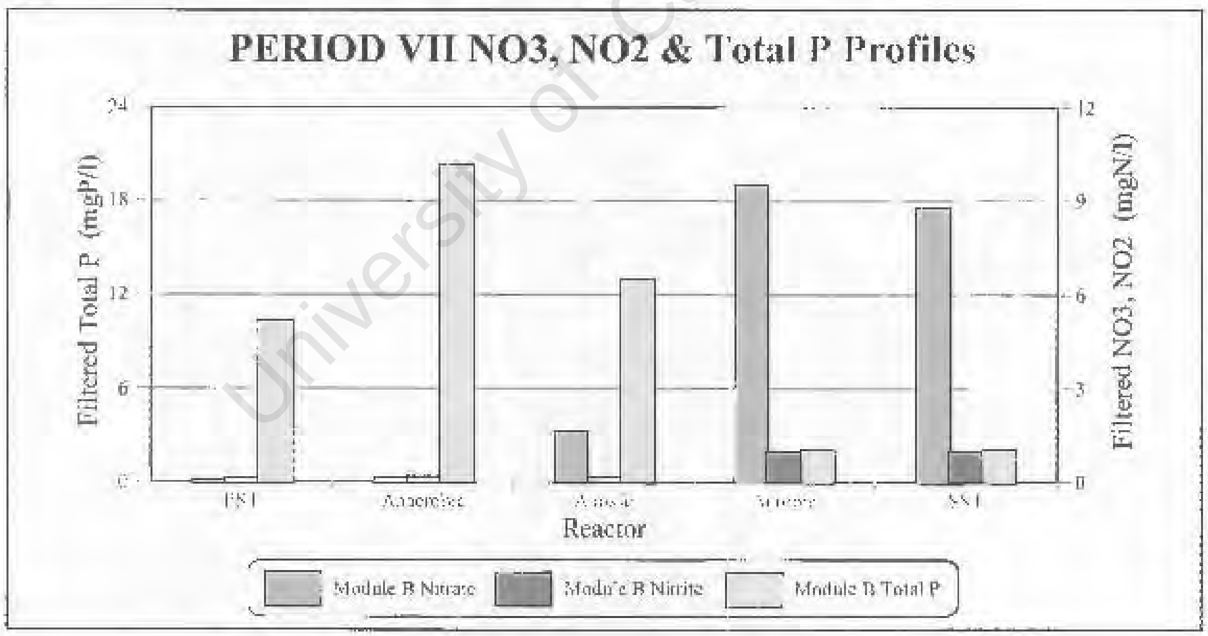


Figure 4.12 : Long Term Period No. VII nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module B.

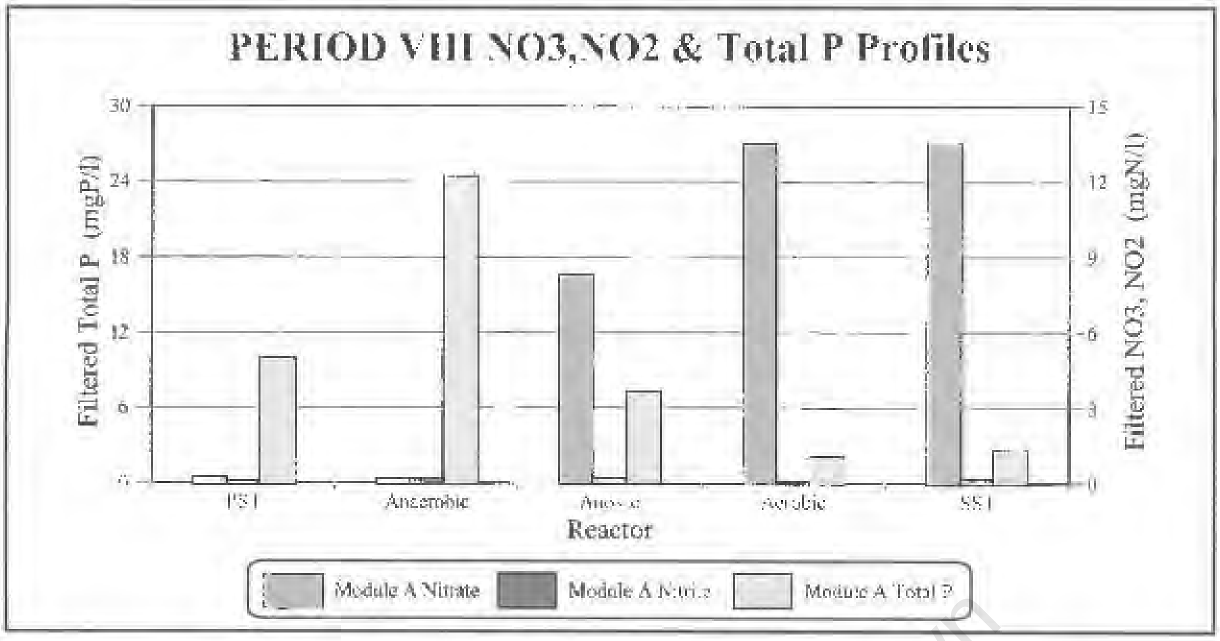


Figure 4.13 : Long Term Period No. VIII nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module A.

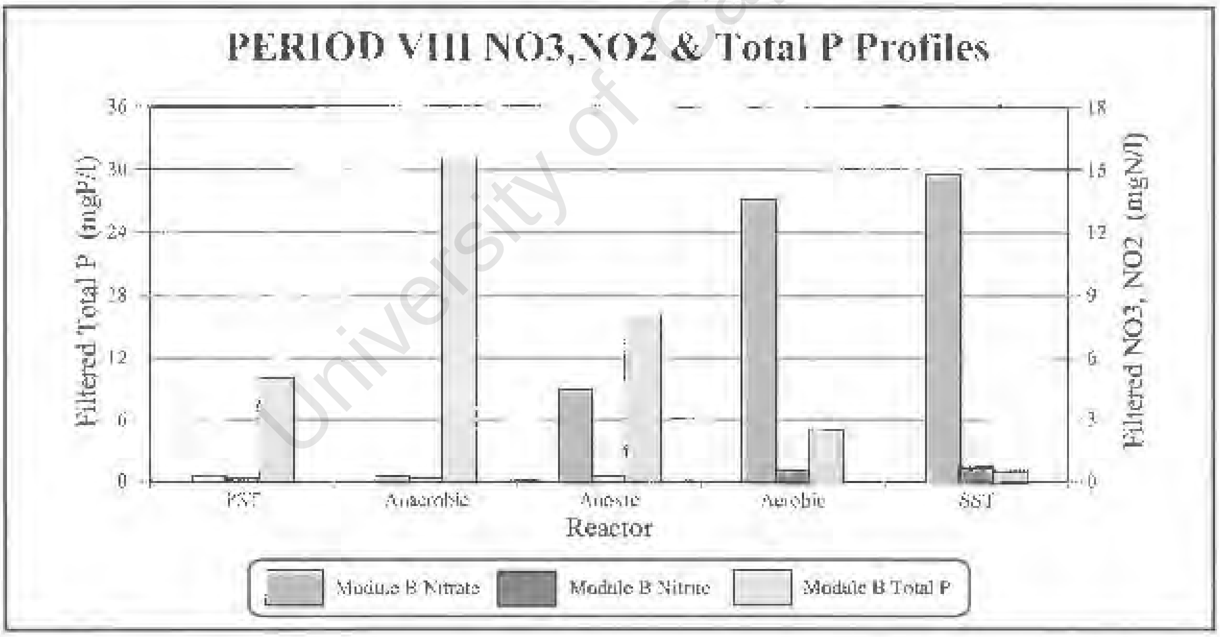


Figure 4.14 : Long Term Period No. VIII nitrate (NO_3), nitrite (NO_2) and filtered Total P concentrations as measured in the various reactors and SST of Module B.

4.3.3 Effluent Quality

The averaged effluent concentrations for the steady state periods are listed in Table 4.12 below. For the effluent data the averages are weighted averages taking into account the number of days of operation for a particular period and excludes all outliers within the data sets.

Table 4.12 : Averaged effluent data for steady state periods; averages from "site data" and "CMC" data.

Long Term Period No.	Site COD (mgCOD/ℓ)		CMC COD (mgCOD/ℓ)		Floc/filt COD (mgCOD/ℓ)		Site TKN (mgN/ℓ)		Floc/filt TKN (mgN/ℓ)		Site Total P (mgP/ℓ)	
	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B
I	N/A	N/A	43.6	39.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
II	37.3	40.4	39.8	37.4	32.1	33.4	3.3	2.1	2.5	1.5	1.8	5.1
III	46.3	54.0	46.5	35.5	42.2	47.0	13.8	4.8	11.3	3.3	0.5	1.9
IV	260.7	54.7	238.0	53.3	120.9	48.7	90.1	2.3	74.7	1.6	8.5	8.4
V	74.6	70.4	48.2	50.8	64.6	58.3	30.6	8.0	27.5	7.4	1.7	3.8
VI	51.1	60.4	36.0	37.6	47.4	57.0	7.0	5.2	4.3	3.9	4.1	3.7
VII	64.6	102.1	71.2	48.3	59.1	79.5	7.8	38.0	7.6	35.3	5.2	3.4
VIII	70.6	112.5	53.7	78.6	65.6	83.5	14.1	21.1	11.9	13.4	2.5	2.5
Ave.	66.4	66.4	54.0	43.2	52.5	54.5	15.8	11.2	13.3	9.4	2.9	4.0

Long Term Period No.	Site FSA (mgN/ℓ)		CMC FSA (mgN/ℓ)		Site NO_x (mgN/ℓ)		CMC NO_x (mgN/ℓ)		Site Ortho P (mgP/ℓ)		CMC Ortho P (mgP/ℓ)	
	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B
I	N/A	N/A	0.3	0.6	N/A	N/A	13.0	14.6	N/A	N/A	6.1	6.3
II	1.9	0.7	1.1	1.1	12.5	15.8	13.4	15.4	1.2	3.8	1.3	3.5
III	10.4	2.4	15.8	5.4	10.0	16.2	9.9	11.1	0.4	1.3	0.5	0.9
IV	61.8	1.0	54.9	1.2	0.5	13.6	0.2	14.1	6.9	7.5	7.6	7.1
V	24.2	5.2	23.1	10.2	1.6	13.2	3.6	10.8	1.5	3.3	0.8	0.3
VI	5.2	1.2	2.7	1.9	14.1	17.0	12.3	16.0	3.9	3.4	5.4	4.5
VII	3.1	28.0	1.9	24.7	15.3	7.3	15.8	7.9	4.9	2.0	4.1	3.7
VIII	5.0	5.7	4.2	5.4	12.5	17.2	13.5	16.4	2.0	0.8	3.3	1.5
Ave.	10.5	6.4	6.3	4.6	10.7	14.3	11.9	13.7	2.4	3.0	3.9	4.2

Note : Effluent COD, TKN & Total P = unfiltered. FSA = free and saline ammonia; NO_x = nitrate + nitrite. The floc/filt COD and TKN values are "site" values. "CMC" averages include Period I, whereas "site" averages do not (N/A).

These data will be discussed in more detail in Chapter 5 below. However, immediately apparent is that:

- With the exception of Module A Period IV, effluent CODs were consistently low.
- Nitrification failed for Module A Period IV, and partially failed for Module A Period V and Module B Period VII.
- With the exception of Module A Period III, effluent ortho P > 0.5 mgP/ℓ, indicating P removal was not limited by the influent P concentration. However, effluent P concentrations are higher than those predicted with UCTPHO (Section 3.5 above), indicating lower biological P removal than predicted probably due to nitrate recycle to the anaerobic reactors from the anoxic reactors (see Section 5.3.2.3 below).
- Even with the lower implemented 'a-recycle' ratios, effluent nitrate + nitrite (NO_x) concentrations are lower than predicted with UCTPHO (Section 3.5 above), indicating possibly better denitrification than predicted, possible errors in nitrate measurement or simultaneous nitrification-denitrification (see Sections 5.2.2 and 5.2.3 below).
- The sum of the "site" effluent nitrate (NO_3) and "site" effluent nitrite (NO_2) in Table 4.11 is reasonably close to the "site" effluent nitrate + nitrite (NO_X) given in Table 4.12. The NO_X concentrations (Table 4.12) were measured independently as a cross-check on the sum of the separately measured NO_3 and NO_2 concentrations (Table 4.11).

From the influent, reactor and effluent data a reasonable correlation is achieved between the "CMC" and "site" tested data. Similar correlations were achieved for the other parameters duplicated in the two sets of results. This indicated that the sampling and analytical procedures were reasonable. Because the "CMC" data are once weekly, and the "site" tested data three times weekly, the "site" tested data are accepted to be more reliable. Thus, the "site" tested data will be evaluated in greater depth and presented further in this report. However, where possible, the "CMC" data will be used as a cross check on the "site" data.

4.4 Laboratory-Scale UCT System

From February 2001 (day 470) a parallel laboratory-scale UCT system with the same design and operating parameters as the full-scale plants was set up in the Water Research Laboratory at the

University of Cape Town. The principal aim of this laboratory system was to investigate the cause(s) of the poor N mass balances achieved with the full-scale plants and to characterise the settled wastewater feed, in particular measure the unbiodegradable particulate COD concentration which affects the VSS concentration in the full-scale plants (see Section 5.2.3).

4.4.1 Experimental Set-up and Control

The laboratory system was set-up and operated in the same way as the Module A full-scale plant *i.e.* to limit the anoxic nitrate/nitrite concentrations to < 1 mgN/ℓ in order to achieve a good settling sludge. Hence, the 'a-recycle' ratio was set to 0:1 w.r.t. influent flow to ensure a nitrate load on the anoxic reactor below its denitrification potential thus controlling the nitrate concentration in the anoxic reactor immediately prior to the aerobic reactor to < 1 mgN/ℓ.

A schematic layout of the laboratory-scale UCT system is given in Figure 4.15 and the design and operating parameters given in Table 4.13. The system consisted of three completely mixed reactors (anaerobic, anoxic and aerobic) with a total physical volume of 20.4 litres (ℓ) and an inclined tubular secondary settling tank of 1.5 ℓ in series. These reactor dimensions were in proportion to those of the Module A full-scale plant. The system had a 's-recycle' (RAS) ratio and 'r-recycle' ratio, both at 1:1 w.r.t. influent flow.

The influent sewage fed to the laboratory-scale UCT system was settled sewage collected after the Stage 1 PST at the Mitchell's Plain Wastewater Treatment Plant. Thus the laboratory-scale system received the same wastewater as influent as the full-scale plants. During this investigation which lasted 163 days from day 470 to day 632 (the full-scale plants were decommissioned on day 589), the system received four batches of sewage. These batches of settled sewage collected approximately every four to six weeks, were first macerated and then stored in stainless steel tanks in the laboratory cold room at 4 °C. The system received a constant influent flow of 24 ℓ/d and the sludge age was controlled hydraulically at 15 days by wasting 1.25 ℓ/d from the aerobic reactor, taking due account of the volume of the samples taken for analysis. The system was operated at a constant laboratory controlled ambient temperature of 20 °C.

4.4.2 System Performance Monitoring

System performance monitoring commenced on 12 February 2001 (day 470). To monitor the performance and operation, samples were taken virtually daily from the reactors and SST for analysis. A sampling and analysis schedule is given in Table 4.14; these analyses will be termed "UCT" data. All samples taken from the influent, reactor and effluent were grab samples. All mixed liquor grab samples from the various reactors were filtered immediately to prevent further biological activity. A table and graphs of the daily "UCT" data are given in Appendix I.

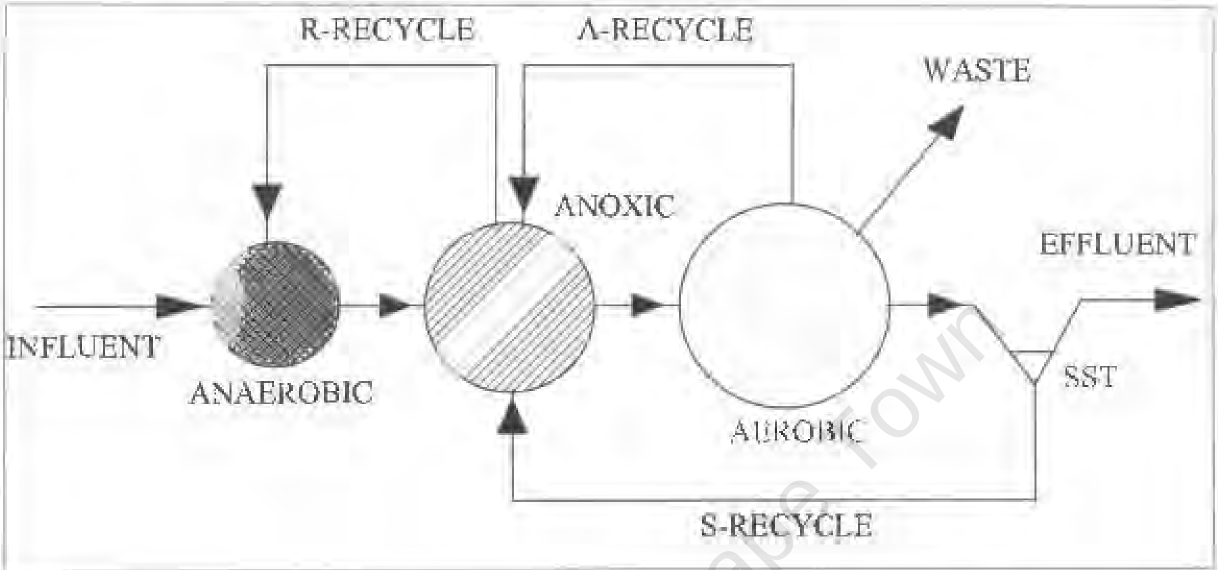


Figure 4.15 : Schematic layout of the laboratory-scale UCT system.

4.4.3 Experimental Results

For each sewage batch, the appropriate data were averaged and are presented below. A detailed comparison with the Module A full-scale plant is given in Chapter 5.

4.4.3.1 Influent data

The influent data averaged for each batch are given in Table 4.15 below. From Table 4.15 :

- The influent COD concentrations were low; overall average 522 mgCOD/ℓ compared with 621 mgCOD/ℓ fed to the full-scale plants over roughly the same period.
- The influent TKN concentrations were consistent for each batch at around 85 mgN/ℓ compared to 102 mgN/ℓ fed to the full-scale plants, giving an average influent TKN/COD ratio of 0.164 mgN/mgCOD for the settled sewage, the same as for the full-scale plants.
- The influent Total P concentrations were consistent for each batch at around 13 mgP/ℓ compared to 12 mgP/ℓ fed to the full-scale plants, giving an average influent TP/COD ratio of 0.026 mgP/mgCOD for the settled sewage, compared to 0.019 for the full-scale plants.

- The average influent FSA concentration of 65 mgN/ℓ compared to 69 mgN/ℓ fed to the full-scale plants over the same period, gave an FSA/TKN ratio of 0.76 compared to 0.68 for the full-scale plants.

Table 4.13 : Laboratory-scale UCT system design and operating parameters.

System Parameter	Sewage Batch 1	Sewage Batch 2	Sewage Batch 3	Sewage Batch 4
Period (2001)	12/02-19/03	20/03-19/04	20/04-04/06	05/06-24/07
Day numbers	470-497	498-528	529-574	575-632
Number of days (d)	28	31	45	49
Number of sampling days (d)	26	17	28	37
Total system volume (ℓ)	20.4	20.4	20.4	20.4
Total effective volume (ℓ)*	18.7	18.7	18.7	18.7
Anaerobic volume (ℓ)	3.4	3.4	3.4	3.4
Anaerobic effective volume (ℓ)*	1.7	1.7	1.7	1.7
Anoxic volume (ℓ)	6.5	6.5	6.5	6.5
Aerobic volume (ℓ)	10.5	10.5	10.5	10.5
Anaerobic Mass Fraction	0.091	0.091	0.091	0.091
Anoxic Mass Fraction	0.350	0.350	0.350	0.350
Aerobic Mass Fraction	0.559	0.559	0.559	0.559
Sludge age (d)	15	15	15	15
Temperature (°C)	20	20	20	20
pH of mixed liquor	7.0-7.5	7.0-7.5	7.0-7.5	7.0-7.5
Aerobic reactor DO (mgO/ℓ)	2.0-5.0	2.0-5.0	2.0-5.0	2.0-5.0
Influent TKN/COD ratio	0.12-0.21	0.12-0.22	0.12-0.23	0.14-0.24
Influent TP/COD ratio	0.02-0.03	0.02-0.04	0.02-0.04	0.02-0.06
Influent (ℓ/d)	24.0	24.0	24.0	24.0
Waste (ℓ/d)	1.25	1.25	1.25	1.25
'S-recycle' ratio	1:1	1:1	1:1	1:1
'A-recycle' ratio	0:1	0:1	0:1	0:1
'R-recycle' ratio	1:1	1:1	1:1	1:1

* Volume adjusted to account for the dilution of the anaerobic reactor mixed liquor in the UCT NDBEPR system.

4.4.3.2 Reactor mixed liquor data

The averaged reactor concentrations for each sewage batch are given in Table 4.16 below.

Table 4.14 : Daily sampling procedure and sample analysis; "UCT" samples.

SAMPLE	MEASUREMENT PARAMETER								
	COD[1]	TKN[2]	FSA[3]	NO_x[4]	TP[5]	OUR[6]	DSVI[7]	VSS[8]	TSS[9]
Influent	◆	◆	✣		◆				
Anaerobic				✣	✣				
Anoxic				✣	✣				
Aerobic	◆	◆		✣	✣	✓	✓	✓	✓
Effluent	◆✣	◆✣	✣	✣	✣				

Key :

✓ Measurement taken.

◆ Unfiltered sample.

✣ Filtered through Whatman® GF/C glass microfibre filters.

1,2,3 Method according to Standard Methods (1985).

4 According to Technicon Auto Analyser Industrial Method No 33.69W.

5 Sulphuric acid/persulphate digestion at 100 °C followed by molybdate-vanadate colour.

6 With Yellow Springs DO probe and Randall *et al.* (1991) OUR box. The daily OUR is the mean of ~150 OUR readings over a 24h period.

7 According to Lee *et al.* (1983) or Ekama and Marais (1984).

8,9 By separation with centrifugation, drying in a crucible at 105 °C and incineration at 600 °C .

Table 4.15 : Averaged influent data for sewage batches; averages are for "UCT" data (daily).

Sewage Batch No.	Influent COD (mgCOD/ℓ)	Influent TKN (mgN/ℓ)	Influent FSA (mgN/ℓ)	Influent Total P (mgP/ℓ)
1	523.3	82.1	61.4	14.2
2	540.9	86.5	65.7	14.3
3	513.3	82.5	63.9	12.3
4	520.3	89.3	68.3	14.0
Average	522.3	85.5	65.3	13.7

Table 4.16 : Averaged reactor mixed liquor data for sewage batches; averages for "UCT" data.

Sewage Batch No.	VSS (mg/ℓ)	TSS (mg/ℓ)	Anaer NO_x (mgN/ℓ)	Anox NO_x (mgN/ℓ)	Aero NO_x (mgN/ℓ)	Anaer Total P (mgP/ℓ)	Anox Total P (mgP/ℓ)	Aero Total P (mgP/ℓ)	OUR (mgO/ℓ/h)	DSVI (mℓ/g)
1	1930	2312	0.1	0.6	25.2	23.5	17.1	6.7	39.4	168
2	2095	2411	0.6	3.3	30.4	20.7	14.1	9.4	42.7	266
3	1852	2109	0.2	2.1	39.5	14.7	10.6	7.6	29.5	346
4	1592	1841	0.2	2.7	37.3	15.1	12.0	9.1	36.0	181
Ave.	1817	2111	0.2	2.1	34.0	17.9	13.2	8.2	37.5	234

Note : Anaerobic, anoxic & aerobic Total P = filtered Total P concentration. NO_x = nitrate + nitrite.

Immediately apparent from Table 4.16 :

- The VSS and TSS concentrations were fairly consistent throughout the investigation except for Sewage Batch 4 in which they were considerably lower.
- The NO_x concentrations in the anaerobic zone were consistently low at < 1 mgN/ℓ.
- With the exception of Sewage Batch 1, NO_x concentrations in the anoxic zone were > 1 mgN/ℓ.
- The NO_x concentrations in the aerobic zone were consistently high (25 to 40 mgN/ℓ).
- The DSVIs were consistently high (> 150 mℓ/g) throughout the investigation but increase further when anoxic NO_x increased- this conforms to the AA filament bulking hypothesis.
- The OUR was around 37 mgO/ℓ/h except for Sewage Batch 3, for which it was considerably lower.

4.4.3.3 Effluent quality

The averaged effluent concentrations for each sewage batch is given in Table 4.17. These data will be discussed in more detail in Chapter 5. However, immediately apparent is that :

- The effluent COD concentrations were consistently low.
- With the exception of Sewage Batch 1, the effluent FSA concentrations were > 1 mgN/ℓ.
- The effluent NO_x concentrations were consistently high.
- The effluent soluble P concentrations are high throughout (> 5 mgP/ℓ).

Table 4.17 : Averaged effluent data for sewage batches; averages are for "UCT" data.

Sewage Batch No.	Effluent COD (mgCOD/ℓ)	Effluent TKN (mgN/ℓ)	Effluent FSA (mgN/ℓ)	Effluent NO_x (mgN/ℓ)	Effluent Soluble P (mgP/ℓ)
1	51.6	2.4	0.8	33.2	5.9
2	49.7	1.8	0.4	36.3	8.8
3	61.1	4.4	1.7	44.9	7.1
4	58.8	5.1	2.5	37.0	8.7
Average	56.4	3.7	1.6	38.1	7.6

4.5 FILAMENT IDENTIFICATIONS

Throughout the 589 day investigation filament identifications were done once monthly on the full-scale plants and the UCT laboratory-scale unit using the microscopic techniques of Eikelboom and van Buijsen (1981) and Jenkins *et al.* (1984). Samples for identification were collected at the end of the aerobic reactor and examined on the same day. Detailed identification results are listed in Appendix H. A summary of the results is given in Table 5.14 where this aspect is discussed. The AA (low F/M) filaments *M. parvicella*, types 0092 and 1851 were dominant in both modules as well as in the laboratory-scale system throughout the investigation.

CHAPTER 5

DATA ANALYSIS AND DISCUSSION

Bulking in NDBEPR plants is inextricably linked to the nutrient removal performance (Casey *et al.*, 1992a, 1994). Hence, in this chapter the COD, N and P removal performance is analysed and presented. Further, to assess the validity of the measured data, N and P mass balances are calculated for the steady state periods. COD balances could not be done because the OUR was not measured except on two occasions during the two 24h tests, which are discussed later in this chapter. The sludge settleability and filamentous organisms are presented and a comparison between Module A and a laboratory scale system is given at the end of the chapter. The modules are also simulated with two biological N & P removal programmes, *UCTPHO* which is COD conservative and *BIOWIN* which includes COD loss in some of the anaerobic processes.

5.1 COD Removal Performance

5.1.1 Influent and Effluent unfiltered COD Concentrations

The averaged unfiltered influent and effluent COD concentrations for Modules A and B are listed in Tables 4.9 and 4.12 respectively, and are shown plotted in Figures 5.1 and 5.2 for the "site" and "CMC" data respectively. For the eight long term periods of the investigation, a reasonable correlation for the unfiltered COD concentrations is achieved for the "site" and "CMC" data. For the site data, it can be seen that the influent COD concentration varied between 567 and 676 mgCOD/ℓ. The effluent COD concentration varied substantially between 37 and 261 mgCOD/ℓ. However, with the exceptions of Period IV Module A and Periods VII and VIII Module B, consistently good COD removals were achieved with unfiltered effluent COD concentrations < 75 mgCOD/ℓ. During Period IV Module A, the 's-recycle' (RAS) failed, and as a result the air supply and influent flow were switched off for two days (see Table 4.3). When the system was restarted, the sludge accumulated in the SST, some of which floated on the surface due to denitrification, first had to be returned to the bioreactor before the system could function adequately. A very high unfiltered COD concentration was measured for a few days following this event. Because aeration was off during this two day breakdown, it is also reflected in the nitrification (see below). As mentioned earlier, towards the end of the investigation for Periods

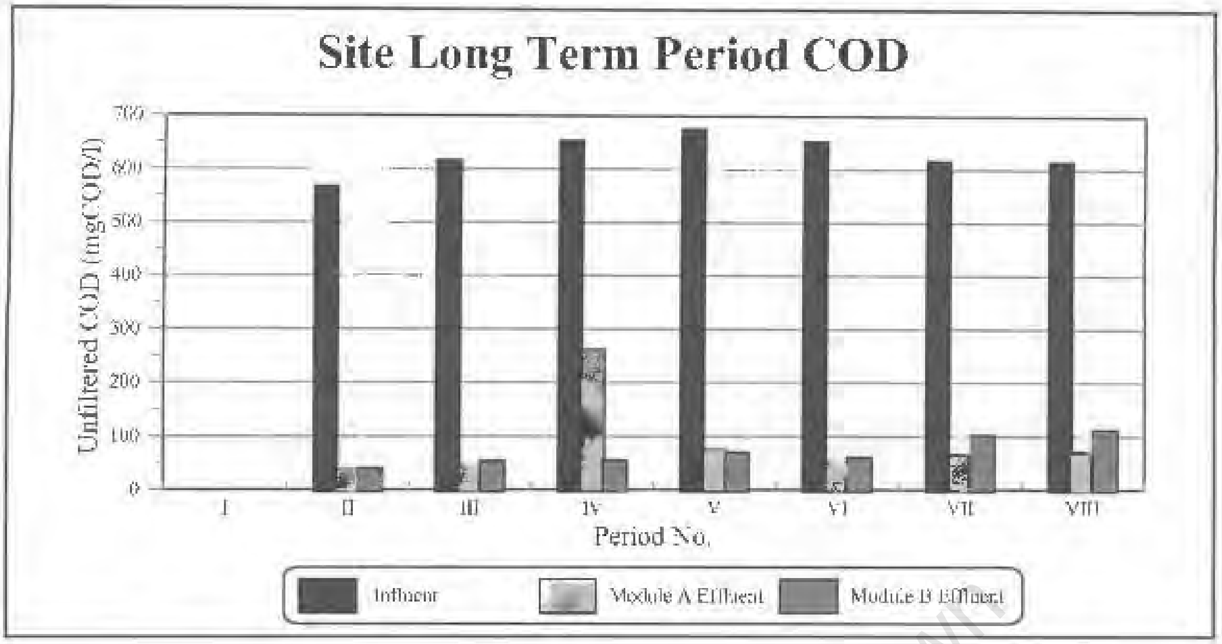


Figure 5.1 : Averaged influent and effluent unfiltered COD concentrations for steady state periods; "site" averages do not include Period I.

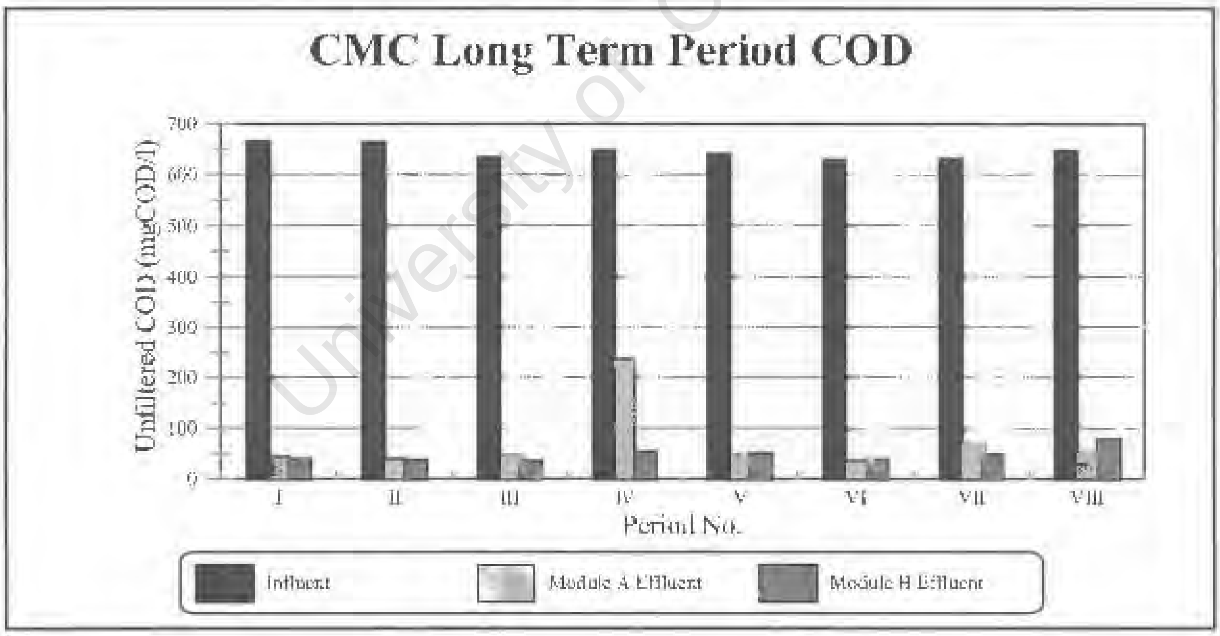


Figure 5.2 : Averaged influent and effluent unfiltered COD concentrations for steady state periods; averages are for "CMC" data.

VII and VIII and particularly in Module B, considerable difficulties were experienced with the aeration system due to blockages of the ceramic diffuser domes. This resulted in inadequate aeration in Module B during these periods. Again this is reflected in the poor nitrification performance during these periods (see below).

5.1.2 Filtered COD Concentrations

Flocculated/filtered influent and effluent COD concentrations were also measured in the "site" data set. These were done to determine the soluble COD concentration of the influent and effluent from which (i) the effluent value is the unbiodegradable soluble (US) COD concentration (S_{use}) and (ii) their difference is approximately the influent readily biodegradable (RB) COD concentration (RBCOD). The influent and effluent flocculated/filtered COD concentrations are given in Chapter 4, Tables 4.9 and 4.12 respectively and Figure 5.3 below. Table 5.1 below gives S_{use}, RBCOD, the USCOD fraction with respect to the total influent COD ($f_{S,us}$) and the RBCOD fraction with respect to the total influent COD (f_{ts}). From Table 5.1 it can be seen that $f_{S,us}$ ranged from 0.06 to 0.12 with an overall average of 0.086, which is in the expected range for typical municipal settled wastewaters (*i.e.* 0.05 - 0.20). From Table 5.1 it can also be seen that f_{ts} ranged from 0.258 to 0.538 with an overall average of 0.354. The influent RBCOD for Long Term Period V is very high at 364 mgCOD/ℓ, yielding the high f_{ts} value of 0.538.

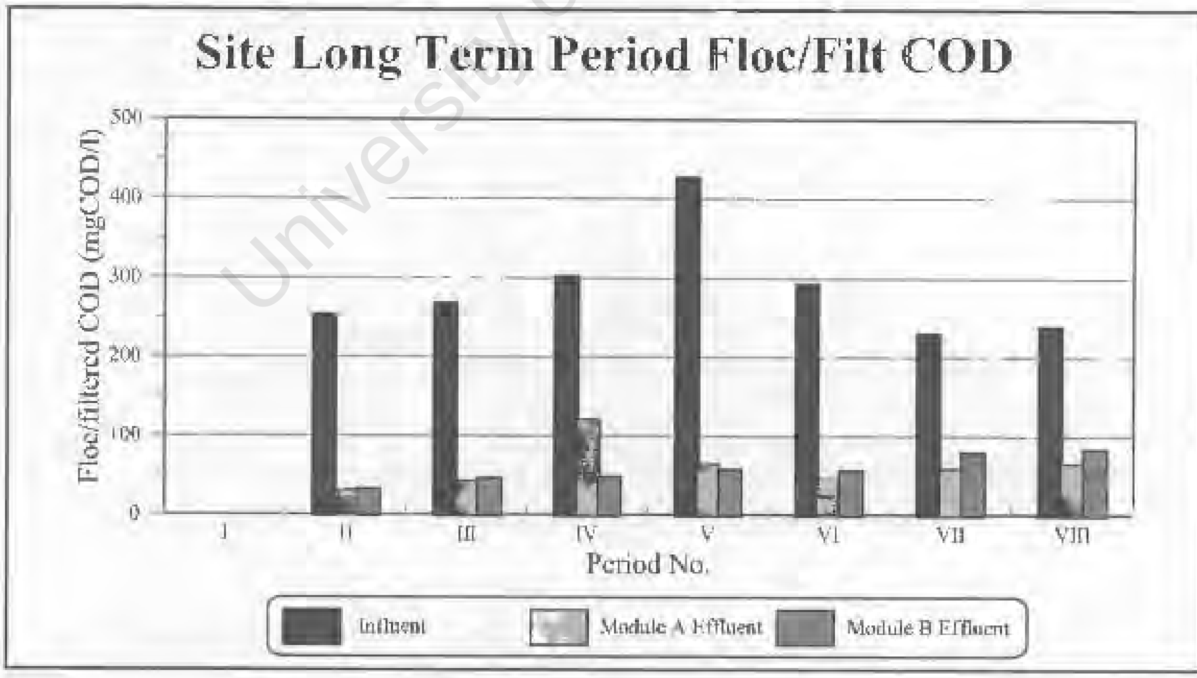


Figure 5.3 : Averaged influent and effluent flocculated/filtered COD concentrations for steady state periods; "site" averages do not include Period I.

Table 5.1 : Average unbiodegradable soluble and readily biodegradable COD concentrations and fractions for steady state periods; averages are for "site" data which excludes Period I.

Long Term Period	USCOD (mgCOD/ℓ)	$f_{S,us}$	RBCOD (mgCOD/ℓ)	f_{bs}
I	N/A	N/A	N/A	N/A
II	34.0	0.060	221.4	0.390
III	42.8	0.070	222.8	0.364
IV	65.3	0.100	238.0	0.364
V	60.8	0.090	364.0	0.538
VI	52.2	0.080	238.7	0.366
VII	73.4	0.120	157.7	0.258
VIII	73.9	0.120	162.9	0.264
Average	52.8	0.086	217.3	0.354

Note : For Long Term Period I, the influent and effluent flocculated/filtered COD concentrations were not measured (N/A).

5.1.3 Effluent Suspended Solids

Due to the mostly very low effluent suspended solids (SS) concentrations, it was not possible to measure it accurately. In this investigation, the effluent SS (VSS and TSS) was calculated from the difference between the effluent unfiltered and filtered COD concentration, divided by the COD/VSS and VSS/TSS ratios of the activated sludge in the biological reactor. The results so obtained are listed in Table 5.2. From Table 5.2, with the exception of Module A Period IV and Module B Periods VII and VIII, the calculated effluent VSS and TSS concentrations are low (< 9 mgVSS/ℓ and <11 mgTSS/ℓ). The overall average effluent SS are very similar for Modules A and B.

Table 5.2 : Average effluent VSS and TSS of Modules A and B for steady state periods; averages are for "site" data which does not include Period I.

Long Term Period	ΔCOD (mgCOD/ℓ)		COD /VSS ratio	VSS/TSS ratio		Effluent VSS (mgVSS/ℓ)		Effluent TSS (mgTSS/ℓ)	
	Mod A	Mod B		Mod A	Mod B	Mod A	Mod B	Mod A	Mod B
I	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
II	5.20	6.95	1.48	0.73	0.77	3.51	4.70	4.83	6.10
III	4.05	6.91	1.48	0.74	0.76	2.74	4.67	3.72	6.18
IV	139.78	6.00	1.48	0.83	0.74	94.44	4.05	113.38	5.47
V	10.0	12.14	1.48	0.76	0.75	6.76	8.21	8.93	10.90
VI	3.33	3.38	1.48	0.74	0.76	2.25	2.28	3.05	3.02
VII	5.50	22.56	1.48	0.79	0.75	3.72	15.24	4.73	20.40
VIII	5.03	28.92	1.48	0.75	0.75	3.40	19.54	4.56	26.18
Average	13.90	11.87	1.48	0.75	0.76	9.39	8.02	11.75	10.66

Note : ΔCOD is the difference between the effluent unfiltered and flocculated/filtered COD concentrations. The COD/VSS ratio of 1.48 is assumed, as the COD of the sludge in the reactors were not measured. For Long Term Period I, the effluent flocculated/filtered COD concentrations were not measured (N/A).

5.1.4 COD Removal

For the eight steady state periods, the COD removal of the two modules is shown plotted together with the soluble and particulate effluent COD in Figures 5.4 and 5.5, where the total height of the stacked bar represents the unfiltered influent COD concentration. Table 5.3 below lists, for each steady state period, the percentage COD removal (based on unfiltered and filtered effluent COD) of the systems. From Table 5.3, with the exceptions of Period IV Module A and Periods VII and VIII Module B, it is evident that good COD removal was attained with percentage COD removal based on the unfiltered COD > 89% and an average for the investigation of 87 and 89 % for Modules A and B respectively. The low 60 % removal occurred in Period IV Module A, which as stated above, was due to the air being switched off for two days. The COD removal based on filtered effluent COD ranged from 81 to 94 % with an average for the investigation of 90 and 91 % for Modules A and B respectively.

Table 5.3 : Average percentage COD removal based on unfiltered and filtered effluent COD for steady state periods; averages are for "site" data except Period I, which is based on "CMC" data.

Long Term Period No.	Module A COD Removal (%)		Module B COD Removal (%)	
	Unfiltered COD	Filtered COD	Unfiltered COD	Filtered COD
I	93	N/A	94	N/A
II	93	94	93	94
III	92	93	91	92
IV	60	81	92	93
V	89	90	90	91
VI	92	93	91	91
VII	90	90	83	87
VIII	89	89	82	86
Average	87	90	89	91

Note : For Long Term Period I, the effluent flocculated/filtered COD concentrations were not measured (N/A).

From Figures 5.4 and 5.5 below which shows the COD removal and effluent soluble and particulate COD as a stacked bar equal to the influent unfiltered COD concentration, it can be seen that the COD removal performance for the two modules, with the exception of Long Term Period IV, was very similar. Also, with the exception of Module A Period IV, the effluent particulate COD concentrations were very small (< 15 mgCOD/ℓ).

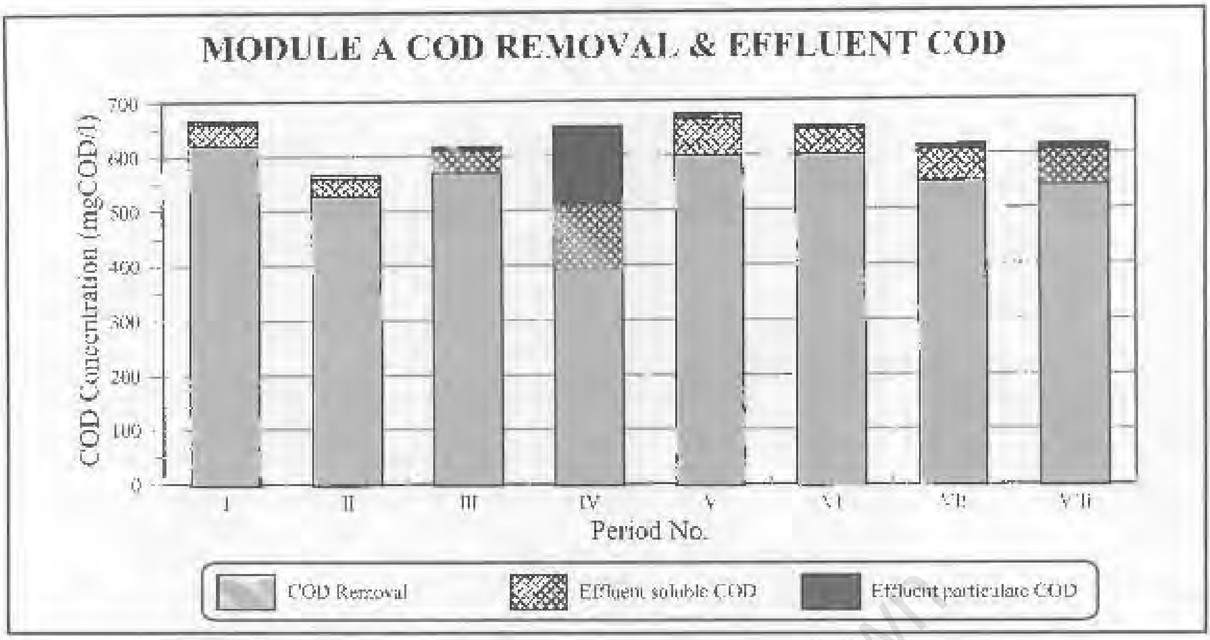


Figure 5.4 : Module A average COD removal (based on unfiltered effluent COD) and effluent soluble and particulate COD for steady state periods; averages are for "site" data.

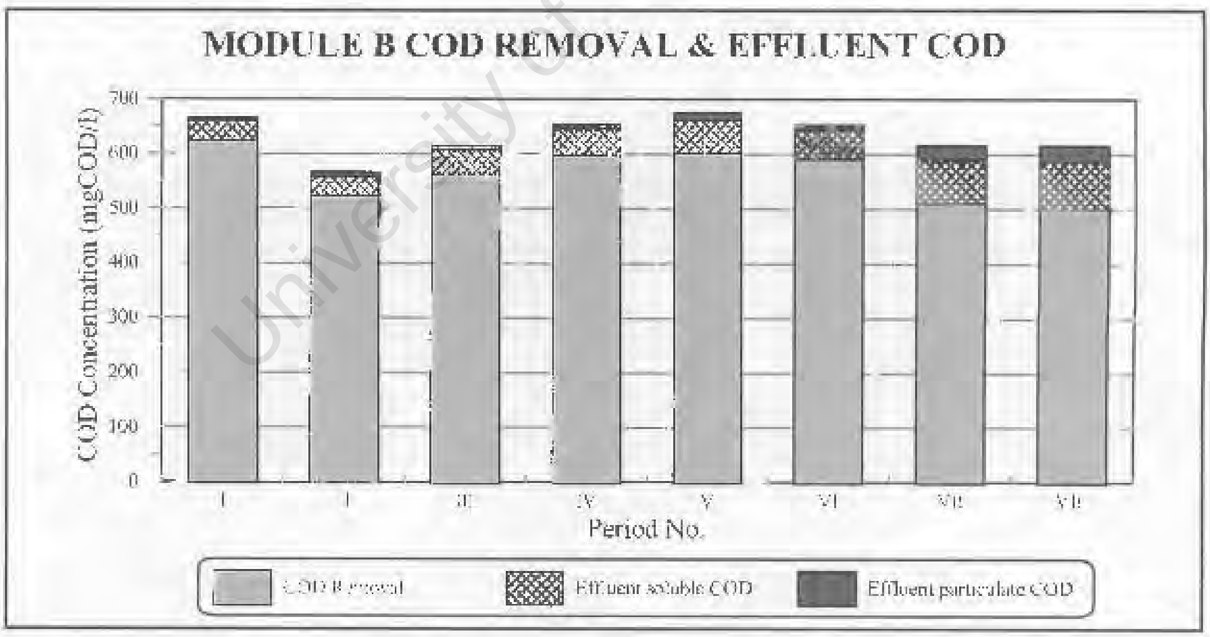


Figure 5.5 : Module B average COD removal (based on unfiltered effluent COD) and effluent soluble and particulate COD for steady state periods; averages are for "site" data.

5.2 NITROGEN REMOVAL PERFORMANCE

5.2.1 Unfiltered & Filtered Influent and Effluent Nitrogen Concentrations

The averaged unfiltered & filtered influent and effluent TKN and FSA concentrations for Modules A and B are listed in Tables 4.9 and 4.12 respectively, and are shown plotted in Figures 5.6 to 5.8 and Figure 5.9 for the "site" and "CMC" data respectively. From Tables 4.9 & 4.12 and Figures 5.6 to 5.9 for the eight long term periods of the investigation, a reasonable correlation for the unfiltered TKN and FSA concentrations is achieved for the "site" and "CMC" data. For the "site" data, the unfiltered influent TKN concentration varied between 92 and 104 mgN/ℓ, the filtered influent TKN between 80 and 91 mgN/ℓ and the influent FSA between 65 and 70 mgN/ℓ. This yielded an average influent TKN/COD ratio of about 0.16 and an average influent FSA/TKN ratio of about 0.70. Detailed characterisation of the influent TKN is given in Appendix A. Excluding Period IV for Module A during which time the aeration system was off, the unfiltered effluent TKN concentration varied between 2 and 38 mgN/ℓ. Similarly, the effluent FSA concentration varied between 1 and 28 mgN/ℓ. The periods identified above with reduced COD removal and Period V Module A, also exhibited partial nitrification performance (effluent TKN > 20mgN/ℓ), for the same reason.

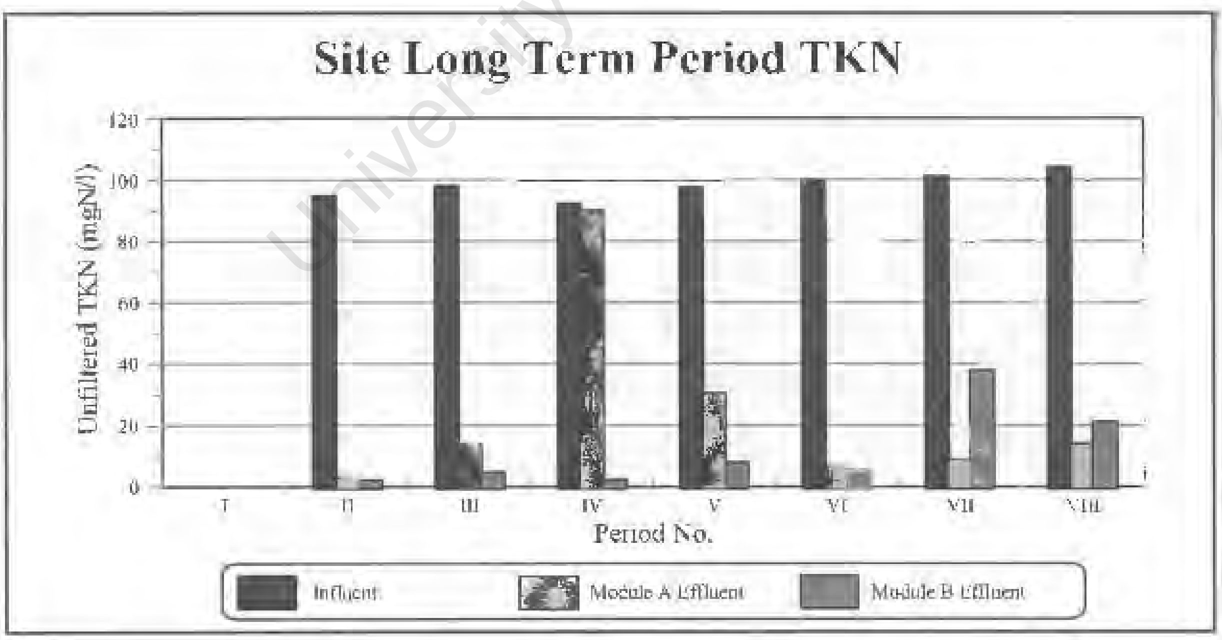


Figure 5.6 : Averaged influent and effluent unfiltered TKN concentrations for steady state periods; "site" averages do not include Period I

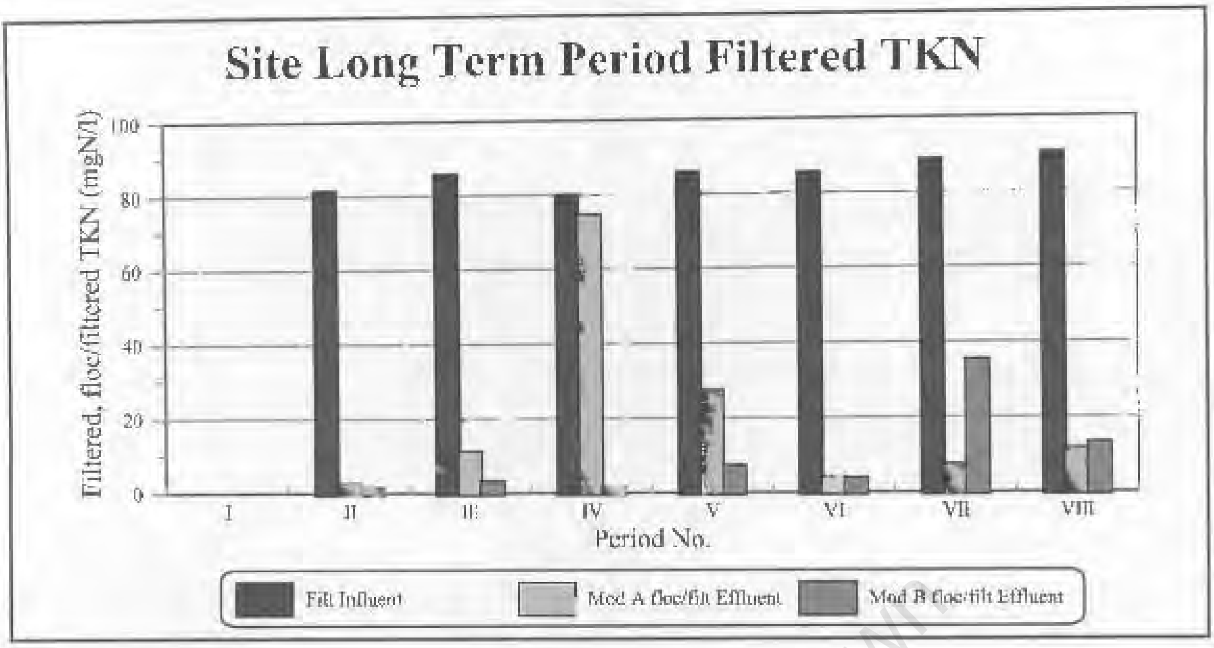


Figure 5.7 : Averaged filtered influent and flocculated/filtered effluent TKN concentrations for steady state periods; "site" averages do not include Period I.

The problem hinged around the limited capacity of the aeration system, even with both blowers in operation. This problem became worse as the investigation proceeded due to increasing blockage of the ceramic diffuser domes. Also it was difficult to share the available air supply equitably between Modules A and B. In the first part of the investigation it became clear that Module B received more air than Module A, hence its better nitrification performance. From Period V, the air supply to Module A was increased at the expense of Module B, which improved the nitrification performance in Module A for Period VI but led to poor nitrification performance in Module B in Period VII. So clearly the effluent TKN and FSA concentrations were directly related to the limited air supply of the aeration system.

Table 5.4 : Average effluent TKN concentrations of Modules A and B for steady state periods; averages are for "site" data which excludes Period I.

Long Term Period No.	Unfiltered TKN (mgN/ℓ)		Floc/filtered TKN (mgN/ℓ)		Filtered FSA (mgN/ℓ)		*Soluble Organic N (mgN/ℓ)		TKN of effluent SS (mgN/ℓ)		#TKN/VSS of effluent SS (mgN/ℓ)	
	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B
I	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
II	3.3	2.1	2.5	1.5	1.9	0.7	0.7	0.8	0.7	0.6	0.2	0.1
III	13.8	4.8	11.3	3.3	10.4	2.4	0.9	0.9	2.5	1.5	0.9	0.3
IV	90.1	2.3	74.7	1.6	61.8	1.0	12.9	0.6	15.4	0.7	0.2	0.2
V	30.6	8.0	27.5	7.4	24.2	5.2	3.3	2.2	3.1	0.6	0.5	0.1
VI	7.0	5.2	4.3	3.9	0.6	1.2	3.7	2.7	2.7	1.2	1.2	0.5
VII	7.8	38.0	7.6	35.3	3.1	28.0	4.4	7.3	1.6	2.8	0.4	0.2
VIII	14.1	21.1	11.9	13.4	5.0	5.7	6.9	7.6	2.3	7.7	0.7	0.4
Ave.	15.9	11.2	13.3	9.3	10.0	6.4	3.3	2.9	2.7	1.9	0.4	0.2

* This soluble TKN is soluble unbiodegradable organic N, N_{ousi}. # Calculated from effluent VSS concentration from Table 5.2.

In Table 5.4 the unfiltered and 0.45 µm membrane filtered effluent TKN and FSA concentrations for Modules A and B for the eight long term periods are given. From these values, the soluble and particulate organic N concentrations are calculated, as well as the TKN/VSS of the particulate organic N from Table 5.2. From these results :

- With the exception of Module A Period IV, the average soluble unbiodegradable organic N (N_{ousi}) and the TKN of the SS for Modules A & B were similar *i.e.* 3.3 & 2.9 mgN/ℓ and 2.7 & 1.9 mgN/ℓ respectively.
- The effluent TKN/VSS ratios of Modules A and B vary considerably mainly due to the unfiltered effluent COD variation (Table 5.2).

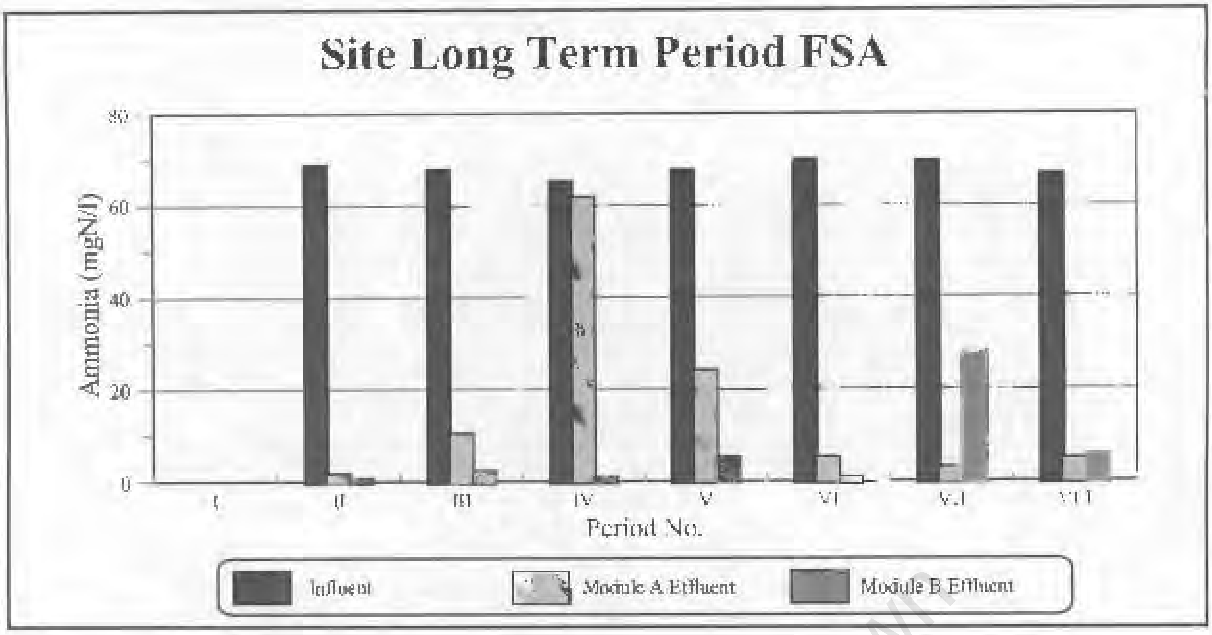


Figure 5.8 : Averaged influent and effluent FSA concentrations for steady state periods; "site" averages do not include Period I.

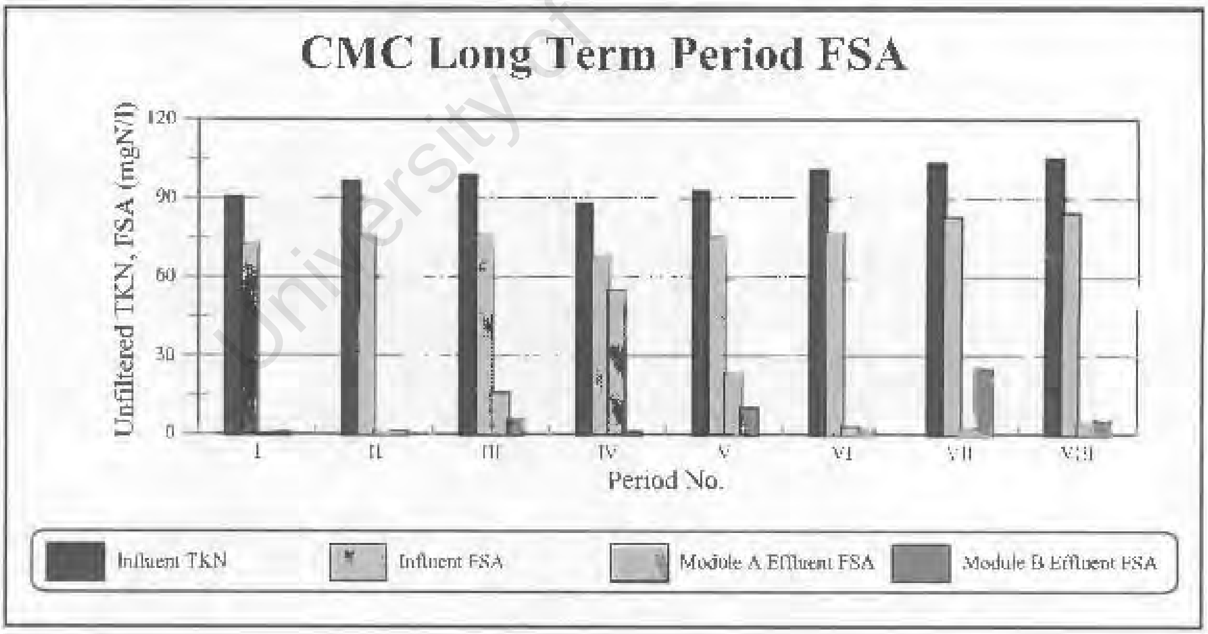


Figure 5.9 : Averaged influent unfiltered TKN and influent and effluent FSA concentrations for steady state periods; averages are for "CMC" data.

5.2.2 Nitrogen Removal

Nitrogen removal is effected by N incorporation into sludge mass and the sequence of nitrification and denitrification.

5.2.2.1 Nitrification

For Periods I and II, nitrification was good, with effluent FSA concentrations at about 1 mgN/ℓ. For all the other periods nitrification was partial only, indicated by the relatively high effluent TKN and FSA concentrations (see Figures 5.6 and 5.8). From Period III to midway Period VI, nitrification was particularly poor in Module A (effluent FSA > 10 mgN/ℓ), which indicated inadequate aeration. In an attempt to improve the aeration to Module A, from day 458 the aeration was gradually increased which improved the nitrification performance. However, the improved nitrification in Module A resulted in a concomitant decrease in nitrification performance in Module B Period VII (see Table 4.12) due to the difficulty in sharing the limited oxygen supply between the two modules. As mentioned in Section 4.1, the blocked ceramic diffuser domes made it difficult to maintain aeration in Modules A and B and eventually resulted in irreparable system failure.

5.2.2.2 Denitrification

Figures 5.10 and 5.11 below, show the effluent nitrate + nitrite (NO_x) concentrations for the "site" and "CMC" analysis respectively. For the eight long term periods of the investigation, a reasonable correlation for the effluent NO_x of the two sets of data was obtained. The various reactor and effluent nitrate (NO_3) and nitrite (NO_2) concentrations are listed in Table 4.11 and shown in Figures 4.1 to 4.14. From these it is evident that the nitrite concentrations were negligible throughout the investigation (< 0.3 mgN/ℓ). For most periods anoxic nitrate concentrations tended to be relatively high in both Modules A and B (overall average of about 5 mgN/ℓ), except for Periods IV and V in Module A when nitrification was partial, as described above. The high nitrate concentration in the anoxic zone of Module B was intended, but for Module A it was not intended - a low (< 1 mgNO_x-N/ℓ) was aimed for. This indicated that for Module A, the proposed control of nitrate in the anoxic zone to low concentrations had not been achieved in practice, even though the 'a-recycle' ratio was set to zero from Period III onwards (see Tables 4.2 and 4.3). Thus, it was not possible to demonstrate the effect of complete anoxic denitrification on sludge settleability, though the effect of incomplete anoxic denitrification could be demonstrated. From the AA filament bulking hypothesis, the expectation from the high nitrate concentrations of the anoxic to aerobic transition is that both modules should develop AA filament bulking sludges but this did not happen. The dominant filaments were indeed AA filaments (*M. parvicella*, types 0092 and 1851) but the 7 day moving average DSVI was below 110 mℓ/g throughout the investigation (see Section 5.4 below).

The high nitrate concentrations in the anoxic zones of Modules A and B indicated an apparent low denitrification performance in these zones, see below. In seeking an explanation for the high reactor nitrate concentrations, it was noted (in Section 4.3.1 and Table 4.2) that the influent TKN/COD ratio varied between 0.10 and 0.24 for the investigation with an average of about 0.16 mgN/mgCOD. As the influent TKN/COD ratio is a measure of the potential mass of nitrate that can be generated in the system through nitrification relative to the potential mass of nitrate that can be removed through denitrification, the influent TKN/COD ratio essentially defines the degree of denitrification possible. At such high TKN/COD ratios, high effluent nitrate concentrations are expected even if denitrification is the best it can be (see below). However, it was also noted that in Module A there was considerable back mixing across the submerged baffle wall between the anoxic and aerobic zones, and that the recycles (RAS for Module A, RAS & 'a-recycle' for Module B) to the anoxic zones of both modules had high dissolved oxygen (DO) concentrations from the Archimedean screw return pumps. While this ingress of DO to the anoxic zones would reduce the denitrification performance, it was initially thought that this was unlikely to be significant. Even though the anoxic nitrate concentrations tended to be relatively high in both modules, it seemed strange the effluent nitrate concentrations were nevertheless low (see Figures 5.10 and 5.11). Also for Module A, the effluent nitrate concentrations were significantly lower (9 to 14 mgN/ℓ) than expected (18 to 20 mgN/ℓ, Table 3.5). To calculate the nitrate concentrations denitrified and generated in the unaerated and aerated reactors, nitrate/nitrite mass balances were done on each reactor.

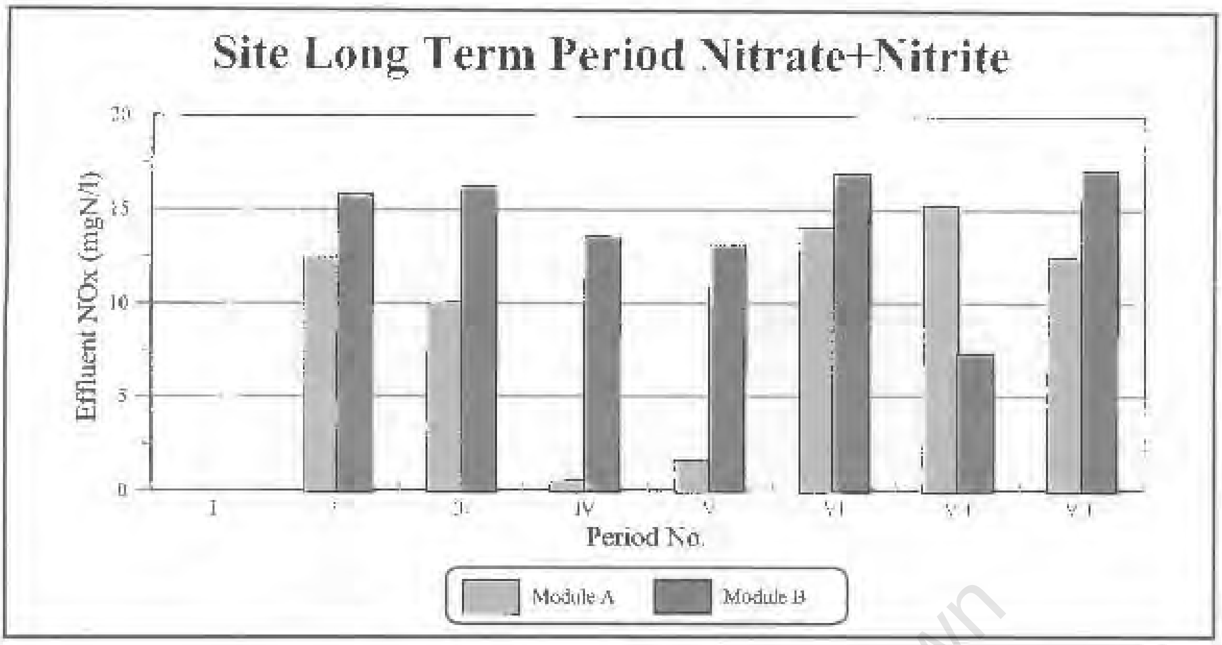


Figure 5.10 : Averaged effluent nitrate + nitrite (NO_X) concentrations for steady state periods; "site" averages do not include Period I.

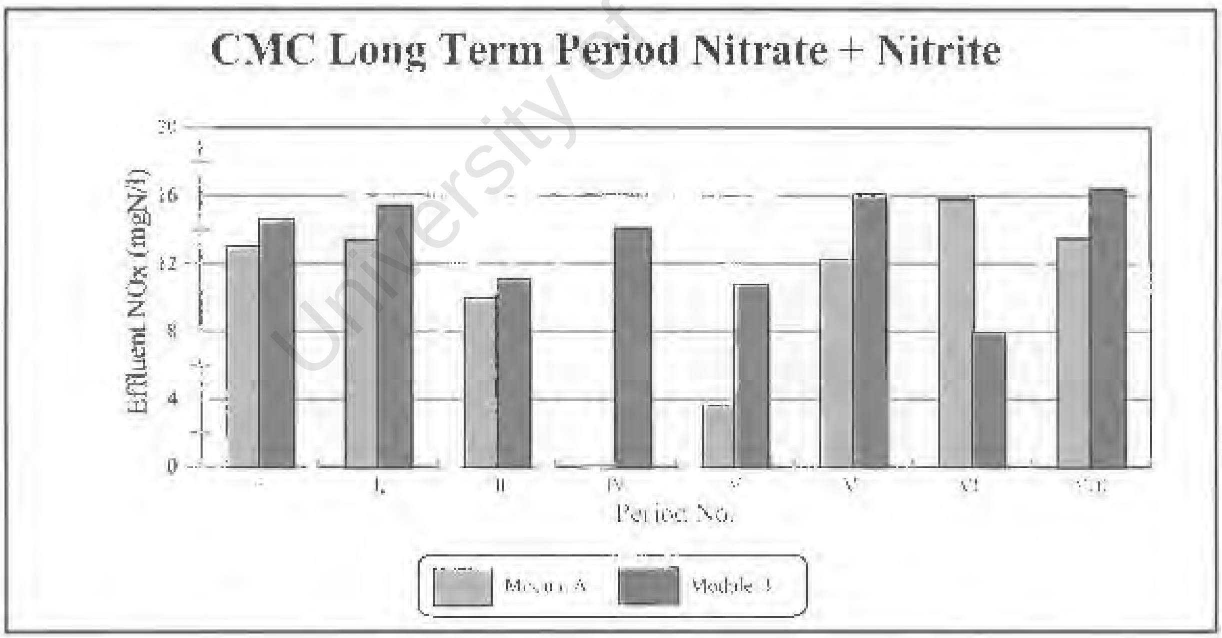


Figure 5.11 : Averaged effluent nitrate + nitrite (NO_X) concentrations for steady state periods; averages are for "CMC" data.

5.2.2.3 Nitrate/nitrite mass balances across reactors and SST

To better understand the nitrification and denitrification performance, nitrate and nitrite mass balances were calculated around each reactor and the SST. Taking due consideration of the flows entering and exiting each reactor and the SST, the change in concentration per litre influent in the reactor and SST is calculated. Figures 5.12 to 5.18 below give the nitrate/nitrite mass balance results (where +ve values indicate nitrification, and -ve denitrification) for Long Term Periods II to VIII. These figures show that the changes in nitrite are negligible as the concentrations were very low. Some nitrification occurs in the SST, but this is small. With the exception of Module A Periods VII and VIII, nitrification occurs mainly in the aerobic reactors, as expected. However, for Periods VII and VIII in Module A, excessive ingress of DO (due to the increased aeration by distributing more air to Module A and less Module B) was probably the cause of the nitrification in the anoxic reactor. In the anoxic reactors, denitrification was low but reasonable in Module B at 23 mgN/ℓ influent but extremely low at 1.5 mgN/ℓ influent for Module A, compared to the influent TKN of 95 to 98 mgN/ℓ. This confirms the poor anoxic reactor denitrification performance described above. Due to the recycling of nitrate (via the 'r-recycle') to the anaerobic reactor, some denitrification (< 3 mgN/ℓ influent) occurred in this reactor for both modules.

Figure 5.19 below gives a comparison of the total (*i.e.* the sum of each of the reactors and SST) nitrification and denitrification as measured in Modules A and B; nitrification is plotted as +ve and denitrification as -ve. From Figure 5.19 it is evident that both total nitrification and total denitrification is much smaller in Module A compared with Module B. Hence, the nitrification and denitrification performance appears generally better in Module B. This was mainly due to (i) greater air supply to Module B than Module A due to (in hindsight) inaccurate DO meters in the modules; and (ii) inadequate total air supply to both modules. An observation that indicates that Module A received less air than Module B is from nitrification-denitrification behaviour - the effluent FSA was higher (less nitrification) and the effluent NO_x lower (more simultaneous denitrification) compared with Module B. Initially it was thought that the anoxic P uptake P removal behaviour in Module A compared with the predominantly aerobic P uptake P removal behaviour in Module B was also a sign that indicated greater air supply to Module B than to Module A. However, this could not be accepted because anoxic P uptake BEPR results in lower P removal which was <u>not</u> observed. This led to the conclusion (described below) that Module A's anoxic reactor was in fact partially aerobic so the P uptake was in fact aerobic P uptake,

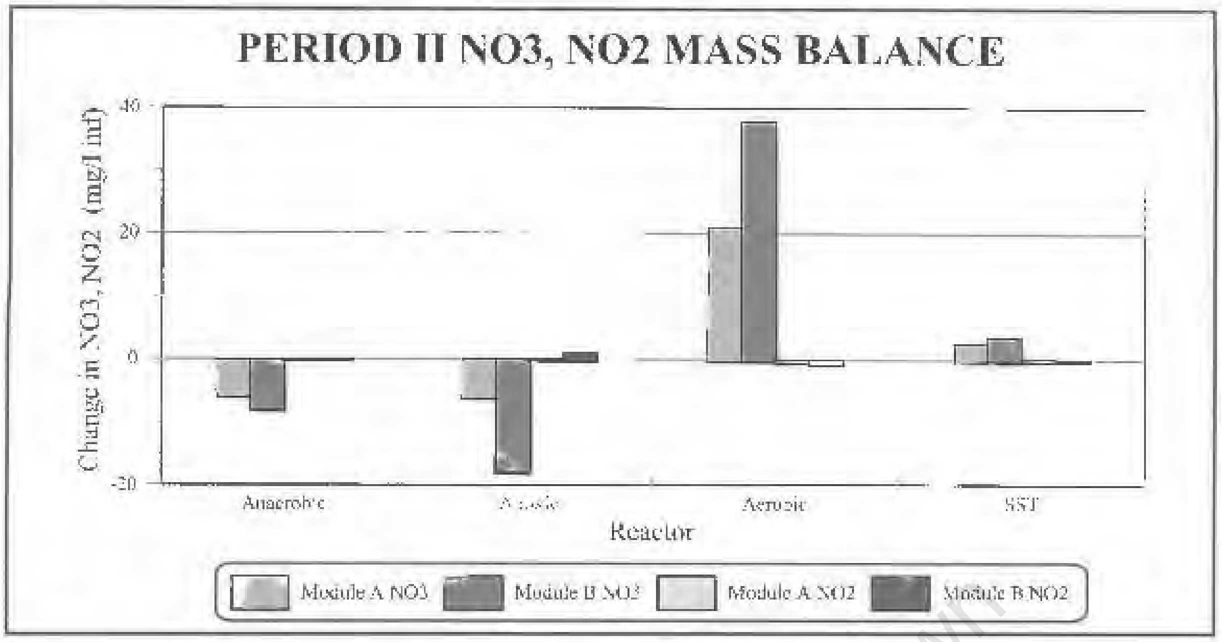


Figure 5.12 : Mass changes in nitrate and nitrite across the various reactors and SST for Modules A and B, Period II.

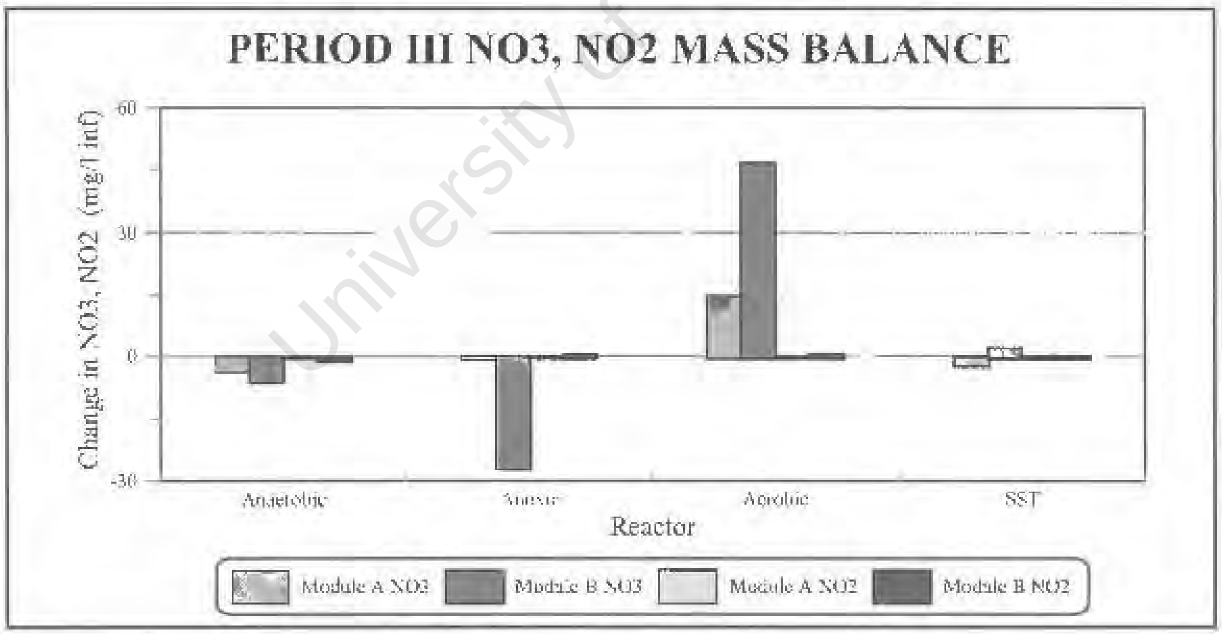


Figure 5.13 : Mass changes in nitrate and nitrite across the various reactors and SST for Modules A and B, Period III.

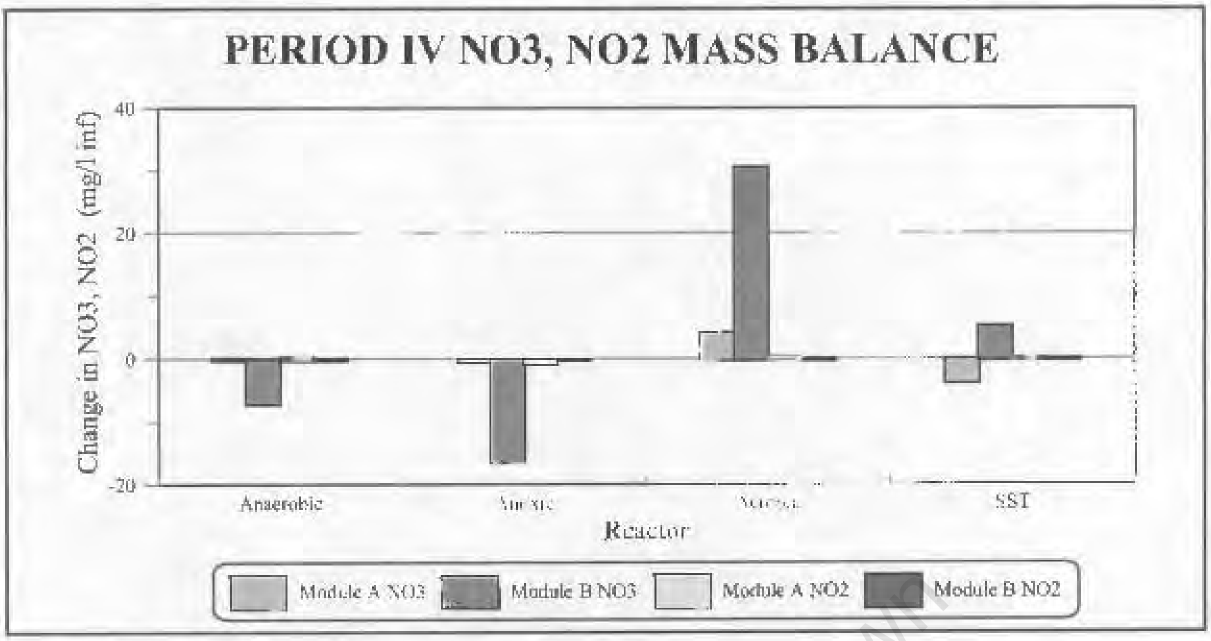


Figure 5.14 : Mass changes in nitrate and nitrite across the various reactors and SST for Modules A and B, Period IV.

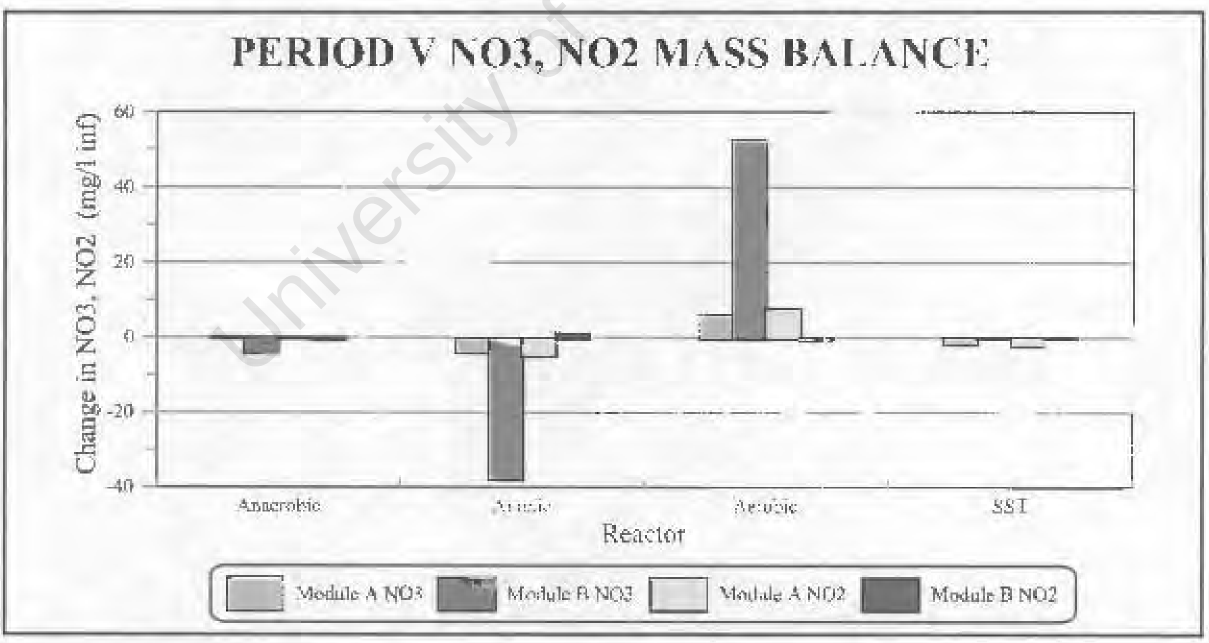


Figure 5.15 : Mass changes in nitrate and nitrite across the various reactors and SST for Modules A and B, Period V.

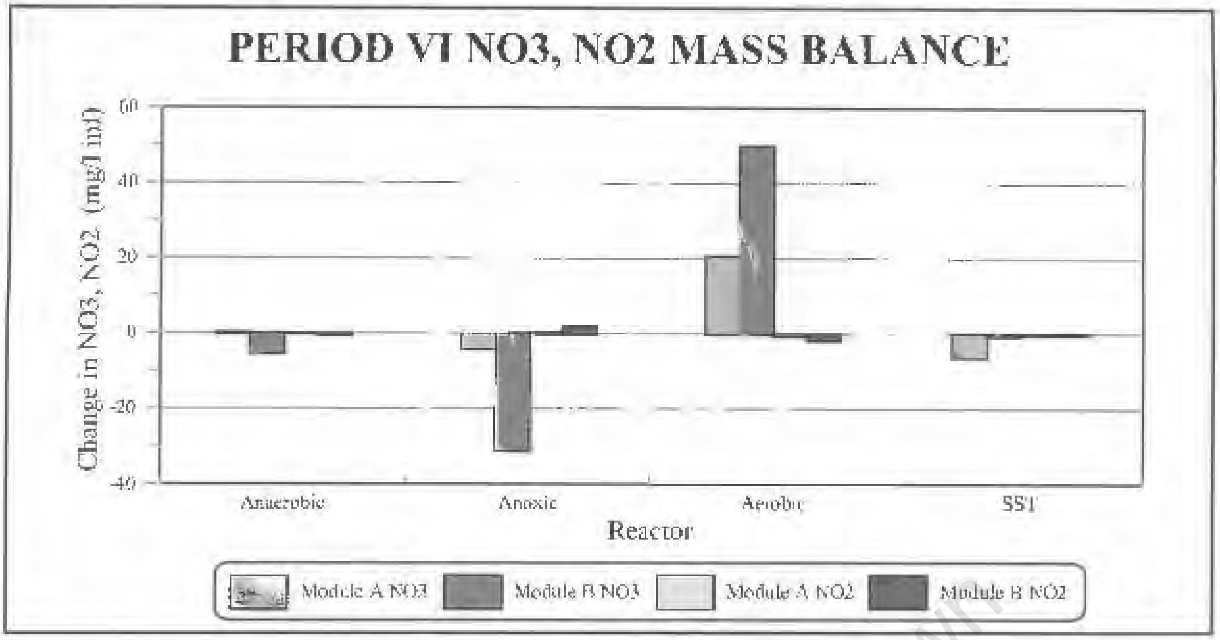


Figure 5.16 : Mass changes in nitrate and nitrite across the various reactors and SST for Modules A and B, Period VI.

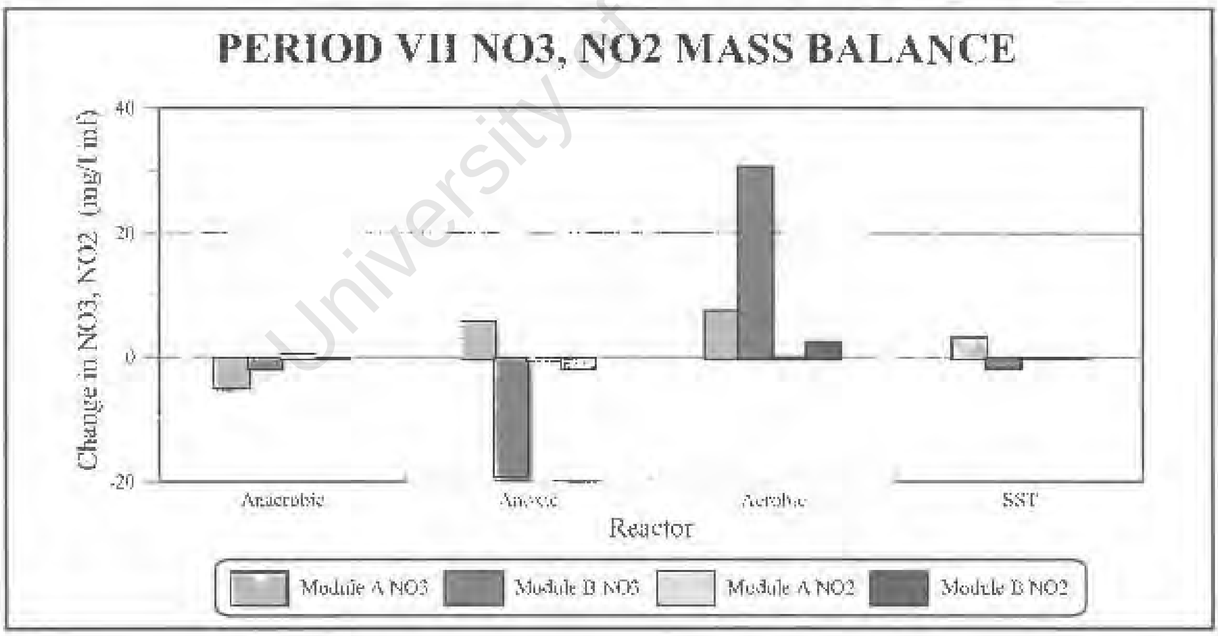


Figure 5.17 : Mass changes in nitrate and nitrite across the various reactors and SST for Modules A and B, Period VII.

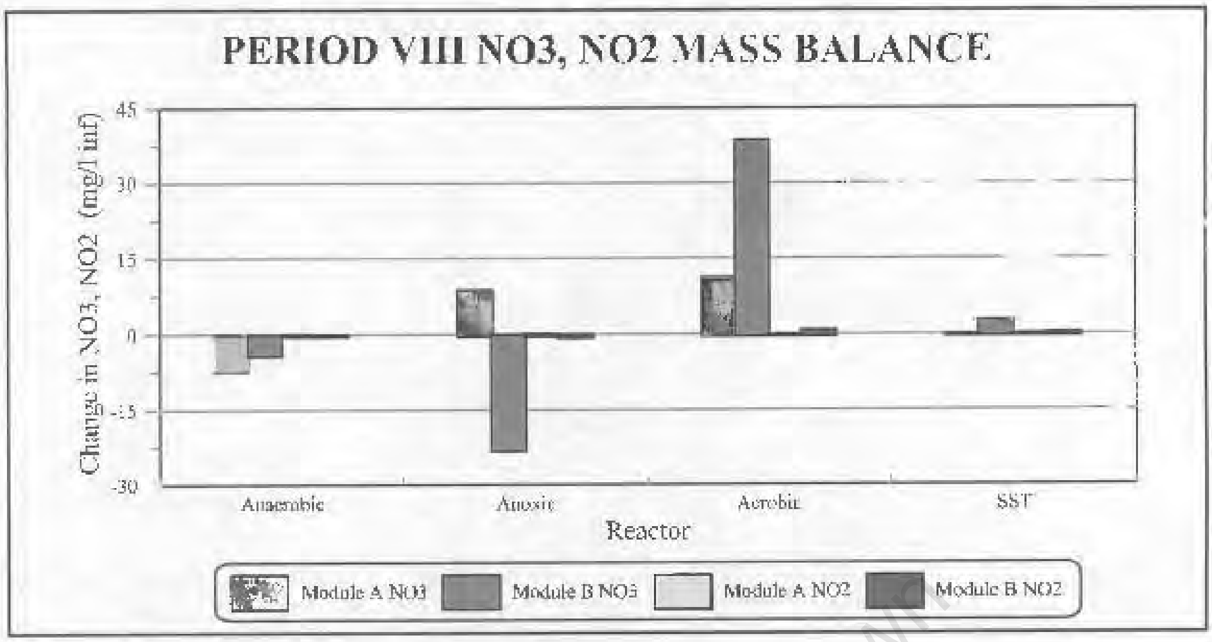


Figure 5.18 : Mass changes in nitrate and nitrite across the various reactors and SST for Modules A and B, Period VIII.

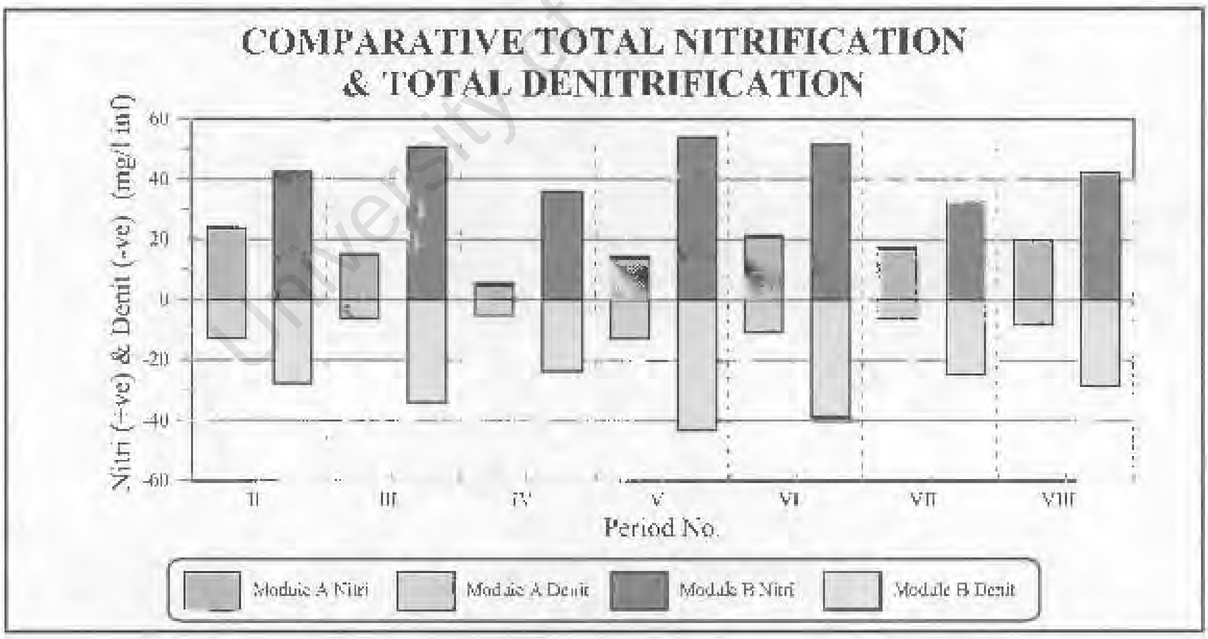


Figure 5.19 : Comparative total nitrification and total denitrification as measured in Modules A and B, "site" data does not include Period I.

which explains also its extremely low denitrification (1.5 mgN/ℓ).

5.2.2.4 N Removal

Based on the measured TKN, FSA and NO_X concentrations on the influent and effluent[5] over the eight steady state periods, the N removals for Modules A and B are shown plotted together with the effluent N in Figures 5.20 and 5.21 respectively, where the total height of the stacked bar represents the influent TKN concentration. Table 5.5 below also lists, for each steady state period, the percentage N removal of the systems. The N removal is via the N in the waste sludge and the NO_x denitrified, and the effluent N is given by the effluent TKN and effluent NO_x. From Figures 5.20 and 5.21 and Table 5.5 it is evident that, with the exceptions of the periods where difficulties were experienced (Module A, Period IV and V to some extent - more air to Module B and less to Module A; Module B, Period VII and VIII to some extent - more air to Module A and less to Module B), the total N concentration removed (via denitrification + N in the waste sludge) was very high, on average at about 74 mgN/ℓ influent for both modules *i.e.* 77 %. Of this N, about 21 and 25 mgN/ℓ influent for Modules A and B respectively was removed with the waste sludge leaving about 53 and 49 mgN/ℓ influent for Modules A and B respectively as nitrate denitrified. Of this nitrate, as noted above only about 3 and 24 mgN/ℓ influent for Modules A and B respectively was denitrified in the anoxic zone, *i.e.* on average about 6 and 49 % respectively. It must therefore be accepted that a large part of the balance of nitrate was denitrified in the aerobic reactor (see Section 5.2.3 below). Such denitrification via this mechanism holds potential for significant N removal which will be increasingly required in terms of the proposed DWAF effluent nitrate limits. However, it would appear that this denitrification does carry a considerable risk to nitrification, indicated by the relatively incomplete nitrification (effluent FSA > 5 mgN/ℓ). Clearly this is an aspect that warrants further investigation.

From Table 5.5, with the exceptions of Period IV and V Module A and Periods VII and VIII Module B, for which the N removal performance was poor for reasons largely related to poor aeration and therefore partial nitrification, it is evident that, although the total N concentration removed in both modules is large, only moderately efficient N removal was attained with percentage N removal between 74 and 85 % and an average for the investigation of 77 % for both modules.

[5] This in effect assumes a 100 % N balance where the N difference between influent N and sum of the N in the effluent and waste flows is the N denitrified.

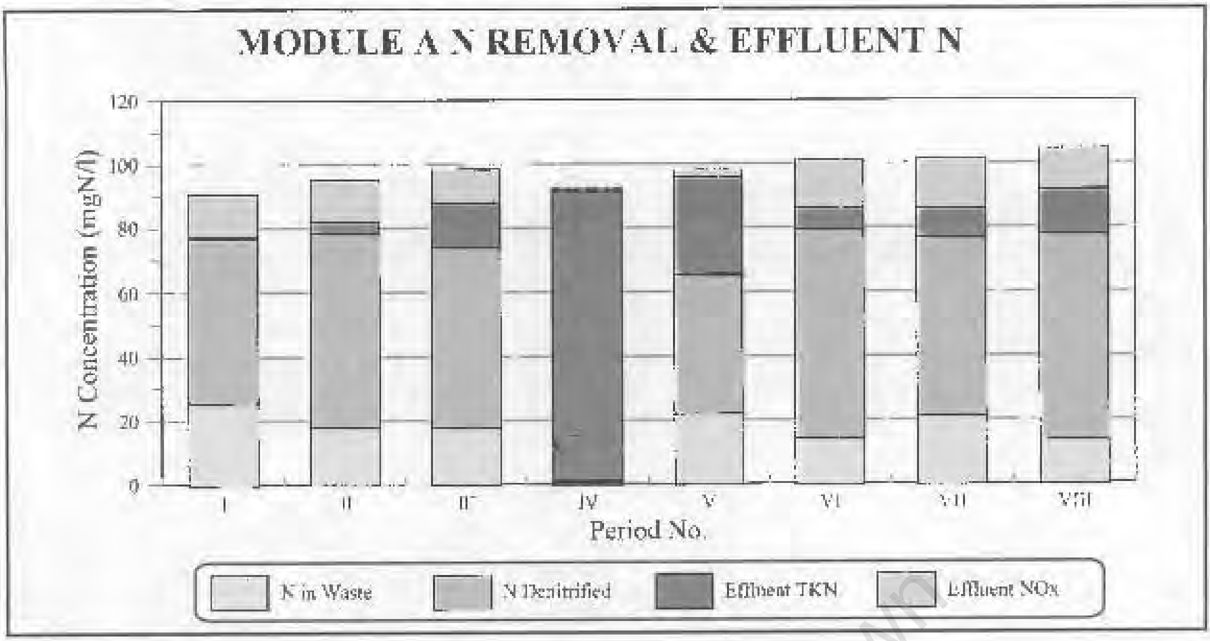


Figure 5.20 : Module A average N removal and effluent N for steady state periods; averages are for "site" data, except Period I which is for "CMC" data.

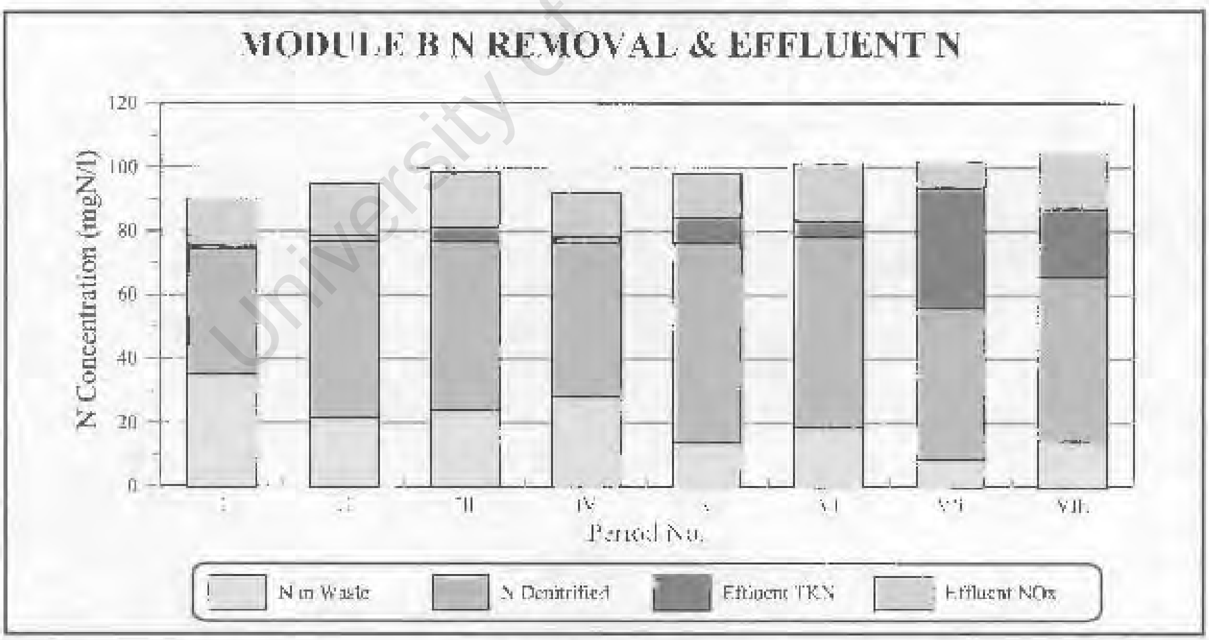


Figure 5.21 : Module B average N removal and effluent N for steady state periods; averages are for "site" data, except Period I which is for "CMC" data.

Table 5.5 : Average percentage N removal for steady state periods; averages are for "site" data, except Period I which is for "CMC" data.

Long Term Period No.	Module A							
	Total influent TKN	Anoxic NO_3 denit.	Balance of NO_3 denit.	Total NO_3 denit.	N in waste sludge	Total N removed	N in effluent	N removal
	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(%)
I	90.4	N/A	N/A	50.8	26.2	77.0	13.4	85
II	94.8	6.1	54.9	61.0	18.3	79.3	15.5	83
III	98.0	0.4	56.0	56.4	18.1	74.5	23.5	75
IV	92.2	0.5	0.3	0.8	0.8	1.6	90.6	2
V	97.6	4.0	39.4	43.4	22.3	65.7	31.9	67
VI	99.9	3.8	61.5	65.3	14.4	79.7	20.2	79
VII*	101.2	0.0	55.5	55.5	21.6	77.1	24.1	76
VIII*	104.2	0.0	64.1	64.1	13.7	77.8	26.4	74
Average	95.1	2.8	50.2	53.0	20.7	73.7	21.4	77
Long Term Period No.	**Module B**							
	Total influent TKN	Anoxic NO_3 denit.	Balance of NO_3 denit.	Total NO_3 denit.	N in waste sludge	Total N removed	N in effluent	N removal
	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(mgN/ℓ)	(%)
I	90.4	N/A	N/A	39.1	35.5	74.6	15.8	82
II	94.8	18.0	37.3	55.3	21.9	77.2	17.6	81
III	98.0	26.9	26.4	53.3	24.0	77.3	20.7	79
IV	92.2	16.3	31.2	47.5	28.9	76.4	15.8	83
V	97.6	37.7	24.7	62.4	14.4	76.8	20.8	78
VI	99.9	31.1	28.8	59.9	18.8	78.7	21.2	78
VII	101.2	19.0	28.3	47.3	8.9	56.2	45.0	55
VIII	104.2	23.0	28.6	51.6	14.6	66.2	38.0	63
Average	95.1	23.7	24.8	48.5	25.0	73.5	21.6	77

* For Module A Periods VII and VIII, net nitrification occurred; anoxic NO_3 denit. set to zero.

The primary settling ahead of the biological nutrient removal activated sludge (BNRAS) process has a detrimental effect on the the influent TKN/COD ratio. The TKN/COD ratio increases due to a higher COD removal compared with TKN (Ekama *et al.*, 1983). Wastewaters with high TKN/COD ratios do not produce high denitrification for most BNRAS process configurations, and if insufficient, can compromise BEPR (Siebritz *et al.*, 1983; Pitman, 1991). The high TKN/COD ratio and incomplete nitrification due to inadequate air supply are the main reasons for the moderate N removal attained. The very low 2 % N removal that occurred in Period IV Module A, as stated in Section 5.1.1 above, was due to the air being switched off for two days. In Table 5.5, the total nitrate denitrified, N in the effluent and total N removal of the two modules are virtually identical, despite the different air distribution between Module A (which received less than Module B for periods I to VI) and Module B (which received less than Module A for periods VII and VIII). This demonstrates the capacity of the activated sludge to accommodate imperfect operation - the lower the air input the greater the simultaneous denitrification in the aerobic reactor, yielding similar N removal as the higher air input system. Of course this accommodating capacity lasts only as long as nitrification is sustained in the system. Interestingly, the BEPR showed a similar accommodating capacity (see Section 5.3.2.2 below) and seems to be able to cope better than nitrification with reduced air supply.

5.2.3 Nitrogen Mass Balance

To assess the data, for the steady state periods nitrogen mass balances were calculated. For the N mass balance, the N exiting the system - with (i) the effluent, as TKN and nitrate/nitrite (both available from direct measurement), (ii) with the waste sludge, as N bound in the sludge mass (the waste sludge VSS concentration and waste flow rate were available from direct measurement; the N/VSS ratio was assumed to be 0.1 mgN/mgVSS, WRC, 1984), and (iii) as N denitrified, calculated from nitrate/nitrite mass balances around each reactor (see Section 5.2.2.3 above) was reconciled with the N entering the system as influent TKN (available from direct measurement). For the mass balances, the closer the mass balance is to 100 %, the more reliable the data provided the designated aerobic processes (such as nitrification) take place only in the aerobic reactor and the designated anoxic processes (such as denitrification) take place only in the anoxic reactor. When this is not the case, as in this investigation, the N measurement can be reliable and poor N balances achieved due to simultaneous nitrification-denitrification in the aerobic reactor. A table of the bi-daily ("site") N mass balances is given in Appendix D. N mass balances for the different periods are listed in Table 5.6 and shown in Figure 5.22 below.

It is evident that for all the steady state periods, the N mass balance for Module B, although not good, was considerably better than Module A. On average over the 589 day investigation the N mass balances for both modules were poor - 57 and 76 % for Modules A and B respectively. This clearly demonstrates simultaneous nitrification-denitrification in the aerobic reactor and probably also in the anoxic reactors, but to assess the extent of this, nitrate analysis accuracy was also checked.

In seeking the cause for the low N mass balances, two possibilities were identified:

(1) Simultaneous nitrification/denitrification:

The aeration in the modules may have been inadequate for long periods of time, resulting in simultaneous nitrification/ denitrification in the anoxic and aerobic reactors. This possibility was supported by:

(a) In the aeration set up, Module B was the first in line to receive air, thereby receiving air in preference to Module A, and had the better N mass balances.

(b) Poor aeration is manifest in the observed incomplete nitrification (effluent FSA > 5 mgN/ℓ).

(c) Equal BEPR in Modules A and B but with apparent anoxic/aerobic P uptake in Module A and predominantly aerobic P uptake in Module B.

(d) When the air supply to Module A was increased in Period V, the anoxic reactor switched from an extremely low denitrification (2mgN/ℓ) to nitrification of 5 mgN/ℓ (Figure 5.17). This confirmed that air ingress to the Module A anoxic reactor was high - from leaks in the air distribution system and back mixing across the anoxic-aerobic dividing wall.

(2) Error in nitrate analysis:

To assess the reliability of the measured nitrate concentrations:

(a) nitrate standards were made up and sent to the "CMC" Scientific Services for analysis,

(b) the same effluent samples were analysed independently by "CMC" Scientific Services and the UCT laboratory on 3 separate occasions.

The results on the standards were mixed, with some analyses correctly reflecting the known standard concentrations and others giving concentrations that were lower than the known. For the effluent samples, on all 3 occasions the UCT laboratory gave effluent nitrate concentrations that were about 65 to 70 % higher than those measured by "CMC" Scientific Services (*e.g.* 25 versus 15 mgN/ℓ). These results indicated that there were some problems with the effluent nitrate analysis but not sufficiently large to explain the low N balance results of the full-scale plants.

Table 5.6 : Average nitrogen mass balance data for steady state periods; averages are for "site" data which does not include Period I.

Long Term Period No.	Total mass N in (kgN/d)		Total mass N out (kgN/d)		Nitrogen Recovery (%)	
	Module A	Module B	Module A	Module B	Module A	Module B
I	N/A	N/A	N/A	N/A	N/A	N/A
II	133.8	211.7	70.1	151.1	54	73
III	156.8	212.7	71.4	162.5	46	76
IV	106.7	146.1	135.7	115.9	126	84
V	151.6	205.0	104.7	178.1	78	89
VI	195.9	231.9	110.0	179.4	56	78
VII	172.3	223.4	99.6	167.9	57	75
VIII	198.6	232.2	93.1	180.4	47	78
Average	157.7	213.5	89.9	162.3	57	76

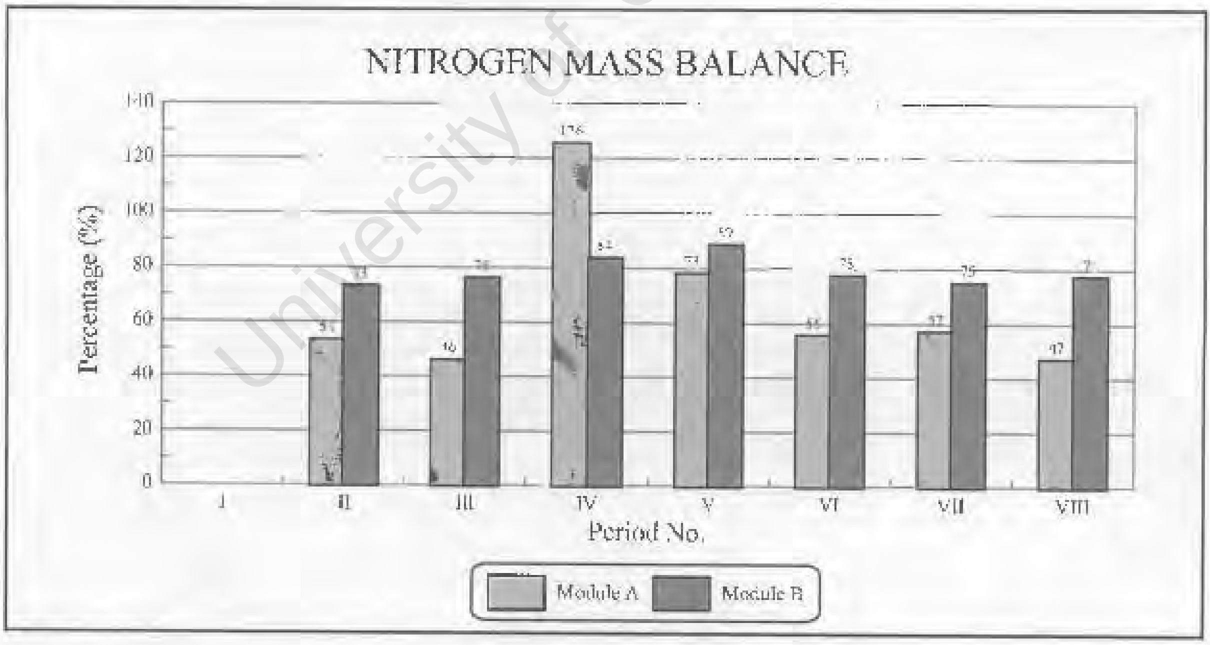


Figure 5.22 : Average nitrogen mass balance for steady state periods; averages are for "site" data which excludes Period I.

To investigate the poor N mass balances further, a parallel laboratory-scale UCT system was set up with the same operational parameters as for the two full-scale plants receiving the same wastewater. This system gave significantly higher effluent nitrate concentrations than the full-scale plants, on average about 32mgN/ℓ versus 10 to 15mgN/ℓ (see Section 5.5.1.3). Also, the N mass balances in the laboratory-scale unit were significantly better (99 %) than in the full-scale plants (see Section 5.5.2). Unfortunately, these results do not enable a definitive judgement to be made as to which of the two possibilities above is the likely explanation for the poor N mass balances. However, comparing the laboratory-scale UCT system effluent nitrate concentrations with those determined for the full-scale plants by the UCT laboratory, the lab-scale system had consistently higher effluent nitrate concentrations. This indicates that most likely both possibilities apply with simultaneous nitrification-denitrification in the aerobic reactor being the predominant contributor. This is discussed further in Section 5.5 below. Unfortunately, before a definitive conclusion about this could be made, the aeration system of the full-scale plants failed and the investigation had to be terminated.

5.3 Phosphorus Removal Performance

5.3.1 Unfiltered & Filtered Influent and Effluent Phosphorus Concentrations

The averaged unfiltered & filtered influent and effluent Total P & Ortho P concentrations for Modules A and B are listed in Tables 4.9 and 4.12 respectively, and are shown plotted in Figures 5.23 & 5.25 and 5.24 for the "site" and "CMC" data respectively. From Figures 5.23 and 5.24 it can be seen that for the eight steady state periods of the investigation, a reasonable correlation for the unfiltered Total P and filtered Ortho P concentrations is achieved for the "site" and "CMC" data. For the "site" data, it can be seen that the unfiltered influent Total P concentration varied between 12 and 13 mgP/ℓ and the filtered influent Total P between 10 and 11 mgP/ℓ. This yielded an average influent P/COD ratio of about 0.021 mgP/mgCOD, which is not high. Detailed characterisation of the influent Total P is given in Appendix A. The unfiltered effluent Total P concentration varied substantially between 0.5 and 8.5 mgP/ℓ. Similarly, the filtered effluent Total P & Ortho P concentrations varied between 0.4 and 8.0 mgP/ℓ & 0.4 and 7.5 mgP/ℓ respectively. For most steady state periods, the effluent Ortho P was > 2 mgP/ℓ so that P removal was not limited by P availability, but rather by biological capability.

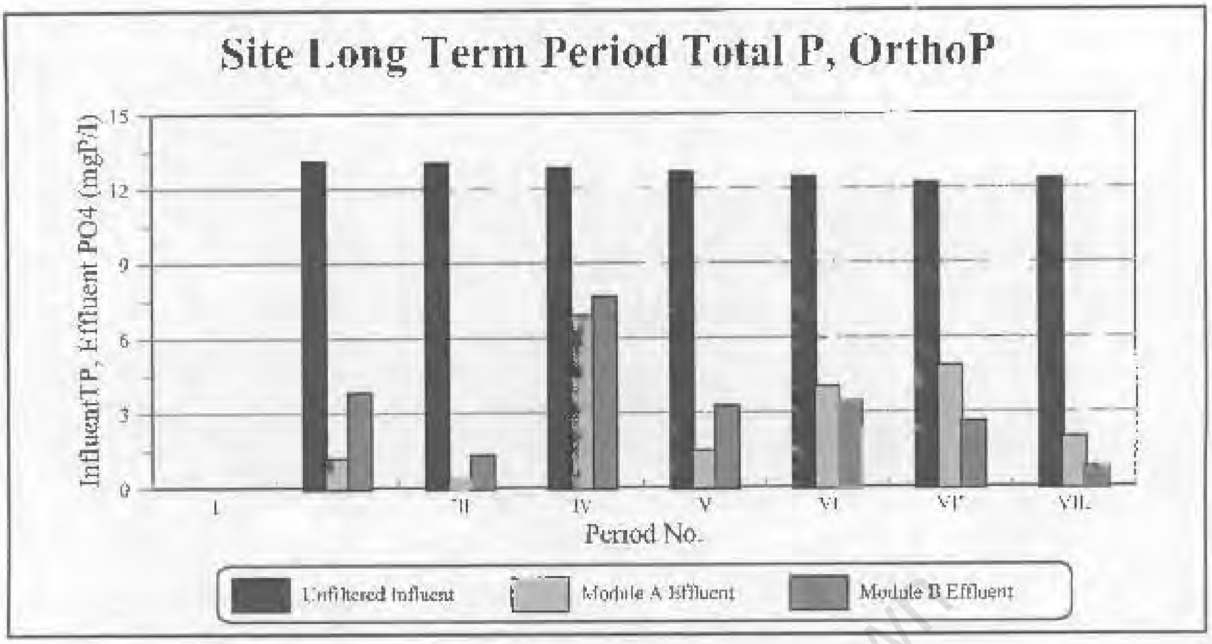


Figure 5.23 : Averaged unfiltered influent Total P and effluent Ortho P concentrations for steady state periods; "site" averages do not include Period I.

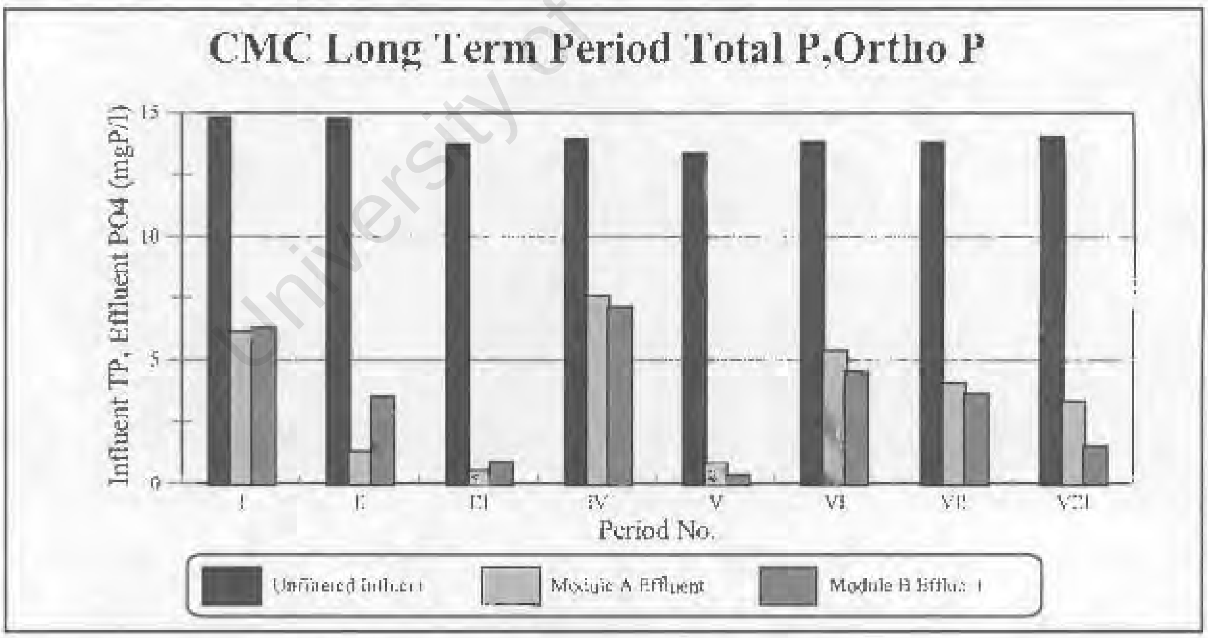


Figure 5.24 : Averaged unfiltered influent Total P and effluent Ortho P concentrations for steady state periods; averages are for "CMC" data.

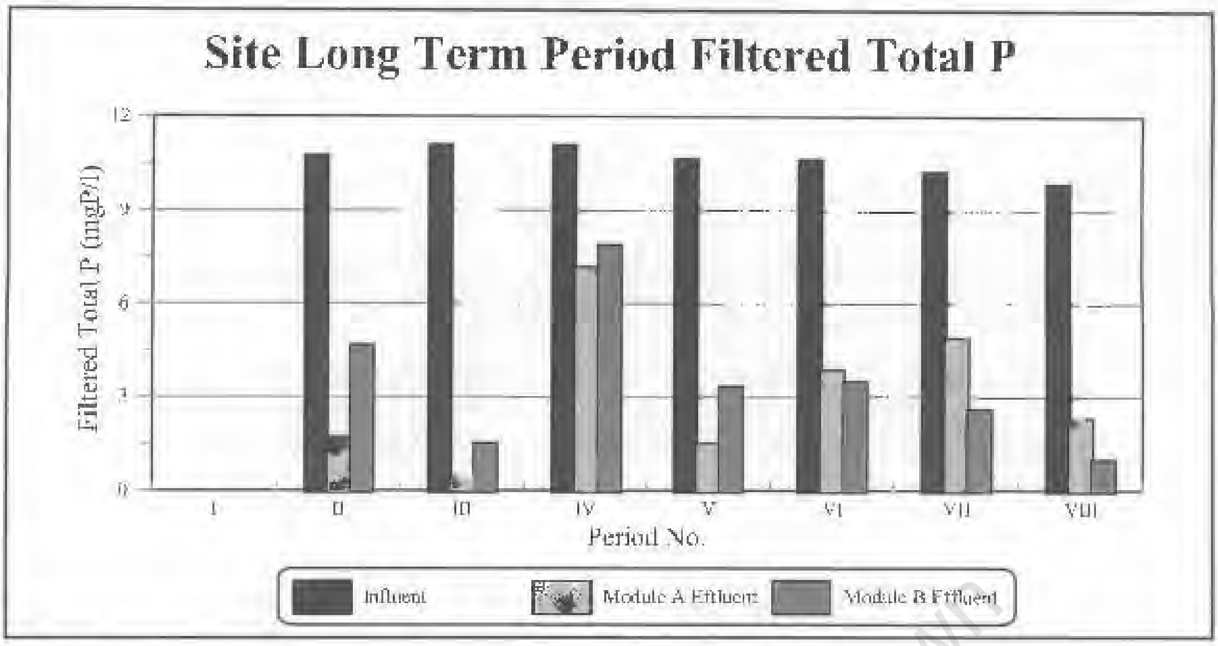


Figure 5.25 : Averaged filtered influent and effluent Total P concentrations for steady state periods; "site" averages do not include Period I.

Table 5.7 : Average effluent P concentrations of Modules A and B for steady state periods; averages are for "site" data which excludes Period I.

Long Term Period No.	Unfiltered Total P (mgP/ℓ)		Filtered Total P (mgP/ℓ)		Filtered Ortho P (mgP/ℓ)		*Soluble Organic P (mgP/ℓ)		Total P of effluent SS (mgP/ℓ)		#TP/VSS of effluent SS (mgP/ℓ)	
	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B	Mod A	Mod B
I	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
II	1.8	5.1	1.7	4.7	1.2	3.8	0.5	0.8	0.1	0.4	0.02	0.08
III	0.5	1.9	0.5	1.5	0.4	1.3	0.1	0.2	0.1	0.3	0.03	0.07
IV	8.5	8.4	7.2	7.9	6.9	7.5	0.3	0.2	1.3	0.5	0.01	0.11
V	1.7	3.8	1.5	3.3	1.5	3.3	0.1	0.1	0.2	0.5	0.03	0.06
VI	4.1	3.7	3.9	3.5	3.9	3.4	0.0	0.1	0.3	0.2	0.12	0.10
VII	5.2	3.4	4.9	2.6	4.9	2.0	0.1	0.0	0.3	0.8	0.07	0.05
VIII	2.5	2.5	2.3	1.0	2.0	0.8	0.3	0.2	0.2	1.5	0.06	0.08
Ave.	2.9	4.0	2.7	3.4	2.4	3.0	0.2	0.3	0.2	0.6	0.04	0.08

* This soluble Total P is soluble unbiodegradable organic P, P_{ousi}. # Calculated from effluent VSS concentration from Table 5.2.

From Table 5.7 above, which gives the effluent P concentrations for Modules A and B for the eight long term periods, it can be seen that:

- The filtered Total P and Ortho P concentrations were similar in Modules A & B *i.e.* 2.9 and 4.0 mgP/ℓ and 2.7 and 3.4 mgP/ℓ respectively.
- The soluble unbiodegradable organic P (P_{ous}) for Modules A and B were similar throughout the investigation, *i.e.* 0.2 and 0.3 mgP/ℓ.
- With the exception of Module A Period IV and Module B Period VIII, the effluent TP of the effluent VSS of Modules A and B varied quite widely from 0.04 to 0.10 mgP/mgVSS mainly due to the significant variation in unfiltered effluent COD concentration.

5.3.2 Phosphorus Removal

P removal is effected by the sequence of P release and P uptake with P removal being the difference between P uptake and P release.

5.3.2.1 P release and P uptake

The P release and uptake of the two modules were examined by measuring the filtered Total P concentrations (soluble Total P) of the influent, anaerobic, anoxic and aerobic zone supernatant and the effluent. Orthophosphate released to the bulk solution by the PAOs increases the soluble P concentration in the anaerobic zone, which results in elevated values in the anaerobic zone. In the subsequent anoxic and/or aerobic reactor, the PAOs take up P from the bulk solution for restoring their PolyP chains and synthesis of new cell mass. The uptake of P to make PolyP chains in the *new* PAO cells generated results in more P being taken up in the anoxic and/or aerobic reactor than is released in the anaerobic reactor, giving a net removal of P from the wastewater in the BNRAS system (Wentzel, 1990).

The average filtered TP concentrations of each module for the steady state periods were given in Table 4.11. The overall average anaerobic, anoxic, aerobic and effluent filtered Total P concentrations were 24.0 & 26.3, 9.0 & 12.1, 2.9 & 3.4 and 2.7 & 3.4 mgP/ℓ influent for Modules A & B respectively. These averaged values appear similar in the two modules indicating that the overall P removal behaviour should be similar but on first sight this appears not to be the case. From the averages of the influent, reactor and effluent concentrations for the long term periods, the magnitude of the net P release or P uptake was calculated by conducting filtered Total P mass balances across all the reactors and SSTs of the modules.

5.3.2.2 Soluble P mass balances across reactors and SST

To demonstrate P release and uptake behaviour, soluble P mass balances were calculated around each reactor and the SST. Taking due consideration of the flows entering and exiting each reactor and the SST, the change in concentration per litre influent in the reactor/SST was calculated. Table 5.8 and Figures 5.26 to 5.32 below, give the mass balances for the steady state "site" data periods (which excludes Period I) where +ve values indicate P release, and -ve P uptake. From Table 5.8 and Figures 5.26 to 5.32 it can be seen that with the exception of Module A Period IV, negligible P release or uptake occurred in the SST indicating that the sludge retention in the SST was low. For Module A Period IV, about 12 mgP/ℓ influent P release took place in the SST. As noted in Section 5.1.1 the RAS failed during this period and sludge accumulated in the SST over a number of days. Thus the anaerobic conditions at the bottom of the SST during this period stimulated P release. The average anaerobic reactor P release is similar in both modules at 25.9 and 29.4 mgP/ℓ influent for Modules A and B respectively. For Module A Period IV, the anaerobic P release was very low at 6 mgP/ℓ influent for reasons mentioned above. The average aerobic reactor P uptake in Module B is significantly higher than in Module A at 44.8 compared with 18.9 mgP/ℓ influent respectively, apparently indicating differing P removal behaviour.

Table 5.8 : Average P release (+ve) or P uptake (-ve) in each reactor and SST as well as net soluble P removal for steady state periods.

Long Term Period No.	ΔP_s in Anaerobic (mgP/ℓ_{inf})		ΔP_s in Anoxic (mgP/ℓ_{inf})		ΔP_s in Aerobic (mgP/ℓ_{inf})		ΔP_s in SST (mgP/ℓ_{inf})		Sol. P removal (mgP/ℓ_{inf})	
	A	B	A	B	A	B	A	B	A	B
I	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
II	22.1	25.1	-13.5	0.0	-19.7	-35.0	0.0	1.7	-11.1	-8.4
III	36.3	36.3	-25.3	10.6	-22.6	-57.6	-0.1	0.7	-11.7	-10.0
IV	6.6	31.8	-5.1	3.4	-21.0	-41.1	12.3	0.9	-7.2	-4.9
V	47.6	37.2	-16.6	8.0	-41.6	-57.2	1.7	1.6	-8.9	-10.4
VI	26.2	37.7	-15.7	8.2	-18.8	-54.1	0.5	0.1	-7.8	-8.2
VII	21.4	14.5	-19.6	12.1	-7.7	-36.2	2.1	0.1	-3.7	-9.5
VIII	27.4	35.0	-26.7	4.3	-11.9	-48.3	1.3	-0.3	-10.0	-9.4
Average	25.9	29.4	-17.6	5.8	-18.9	-44.8	1.5	0.8	-9.1	-8.8

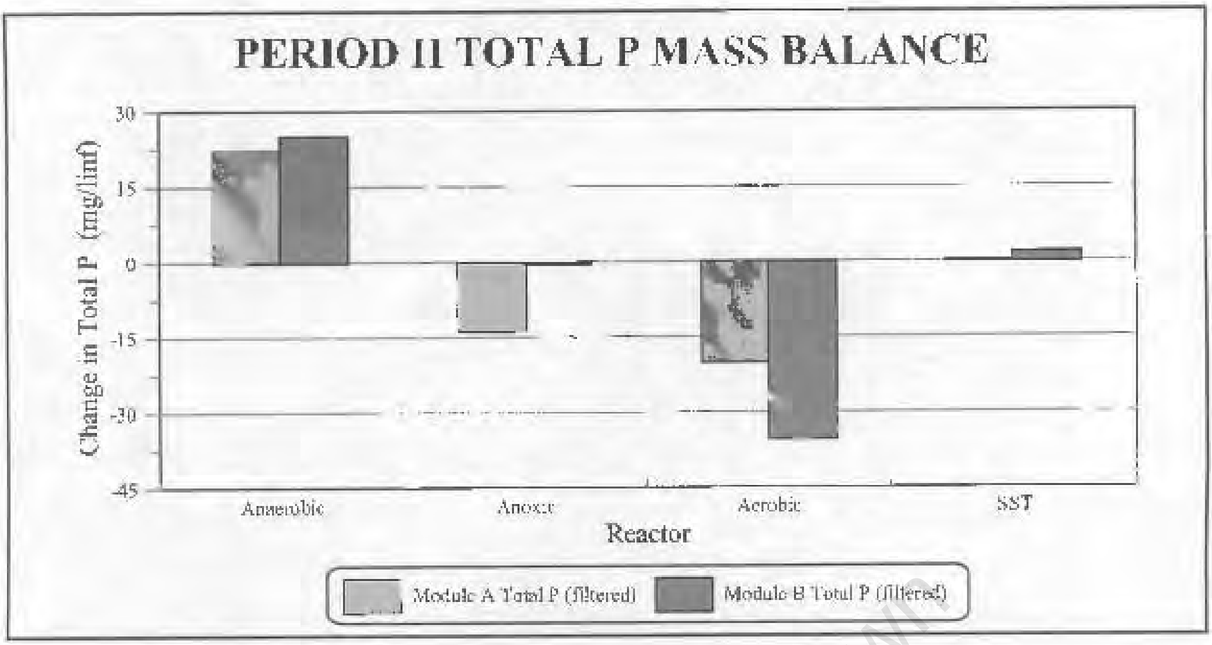


Figure 5.26 : Mass changes in soluble P across the various reactors and SST for Modules A and B, Period II.

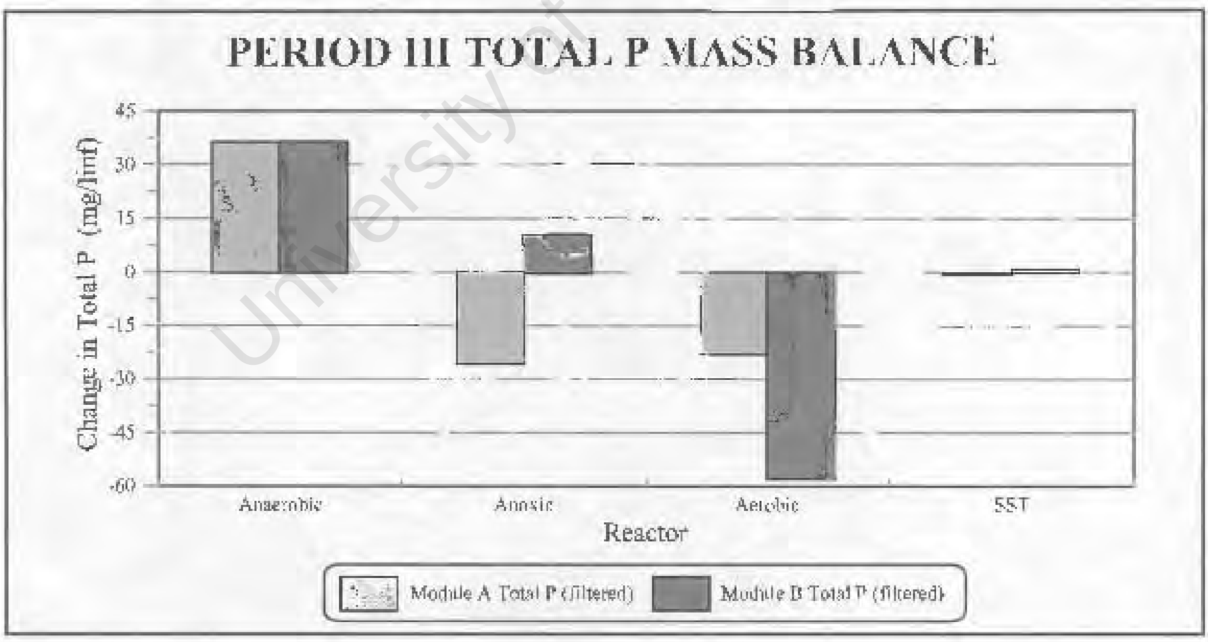


Figure 5.27 : Mass changes in soluble P across the various reactors and SST for Modules A and B, Period III.

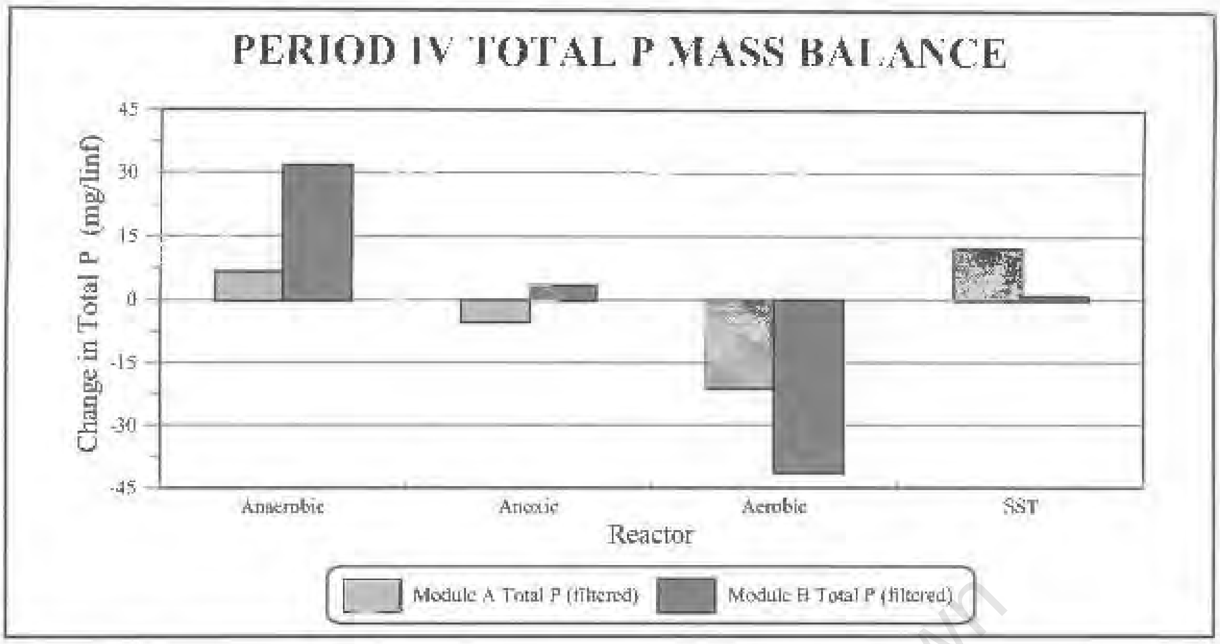


Figure 5.28 : Mass changes in soluble P across the various reactors and SST for Modules A and B, Period IV.

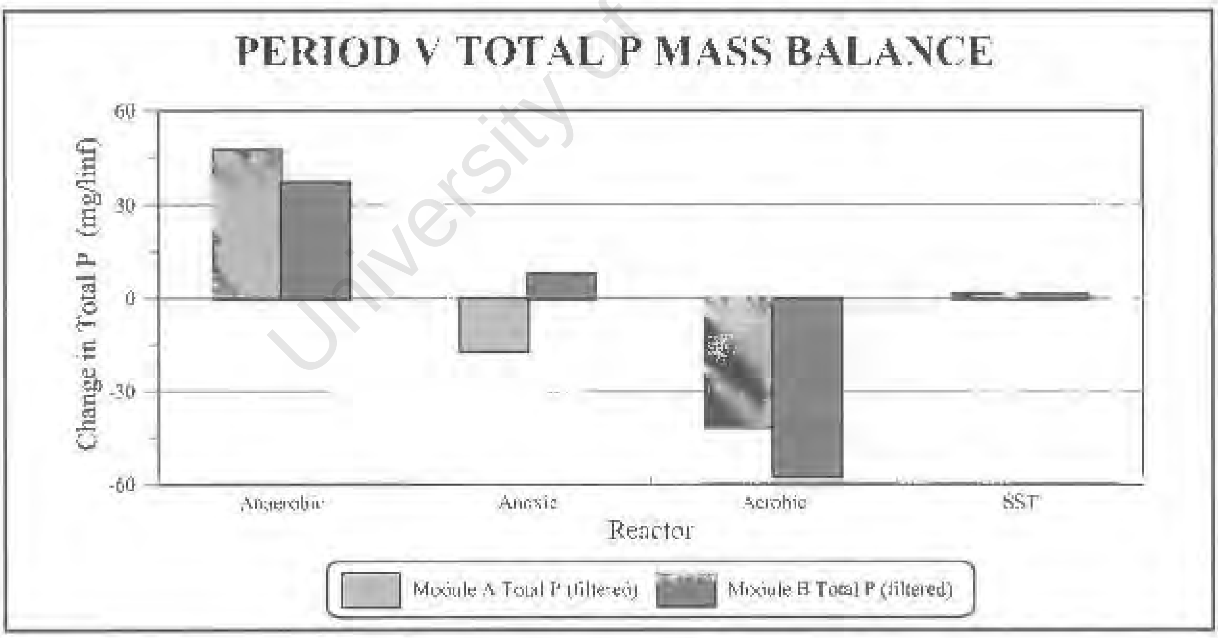


Figure 5.29 : Mass changes in soluble P across the various reactors and SST for Modules A and B, Period V.

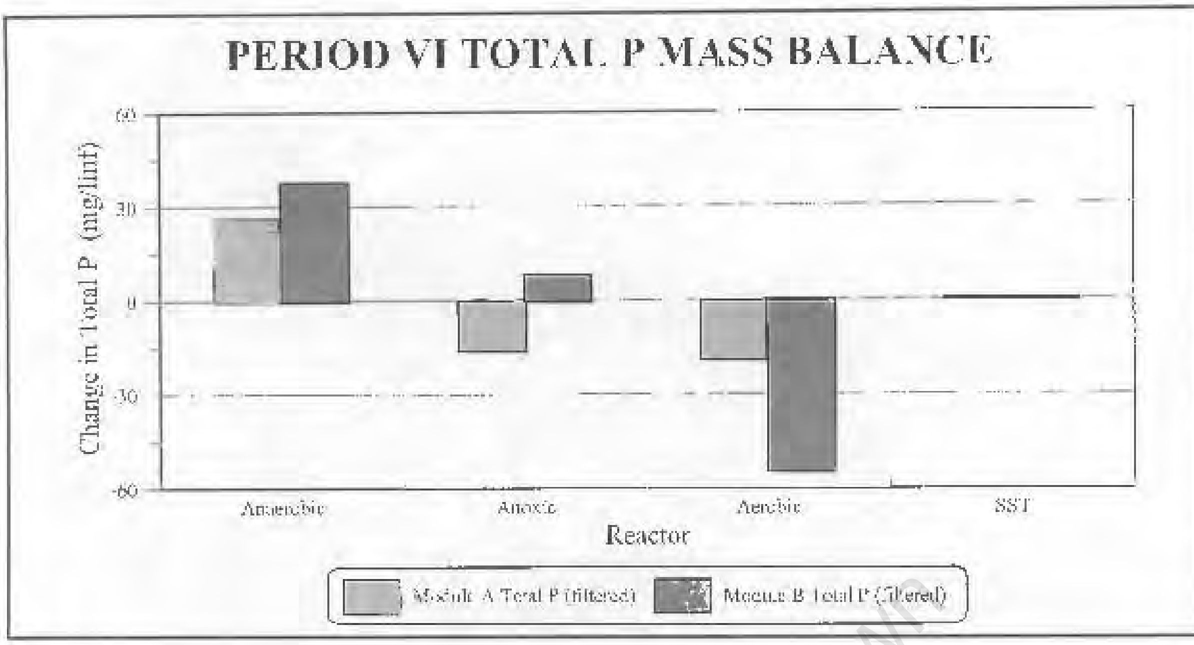


Figure 5.30 : Mass changes in soluble P across the various reactors and SST for Modules A and B, Period VI.

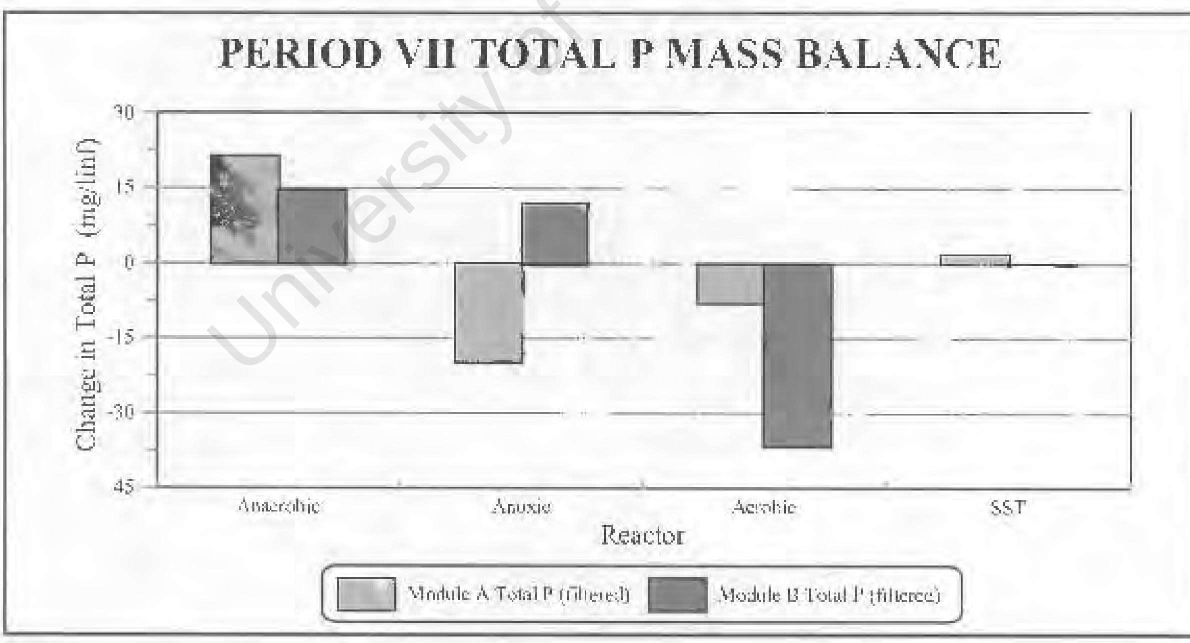


Figure 5.31 : Mass changes in soluble P across the various reactors and SST for Modules A and B, Period VII.

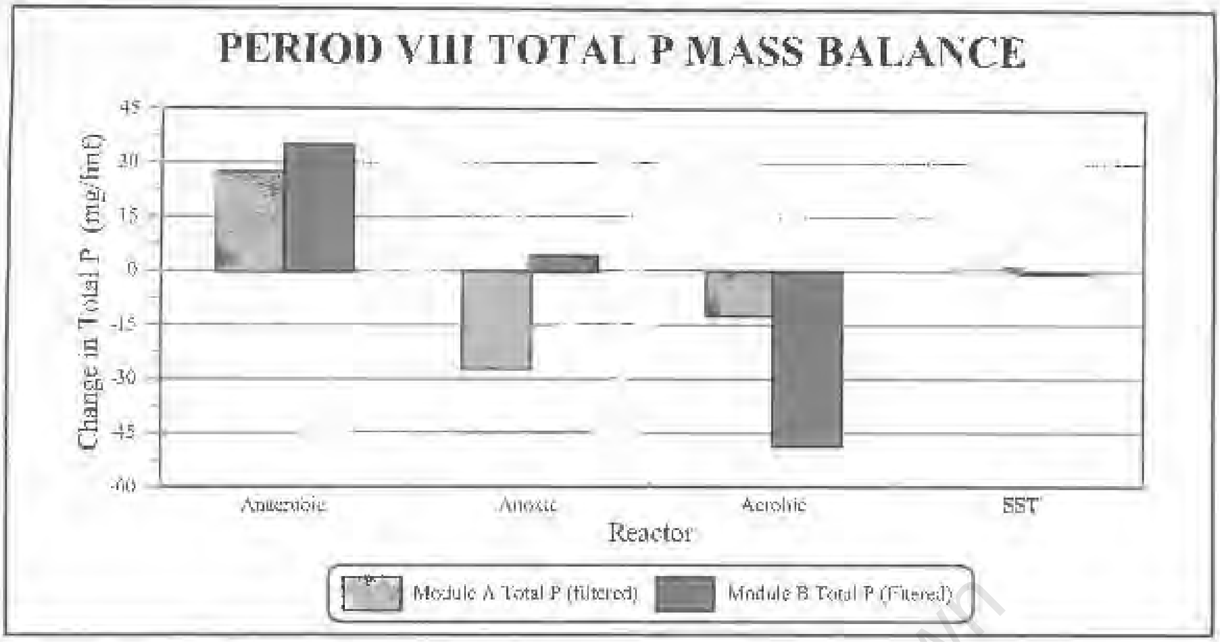


Figure 5.32 : Mass changes in soluble P across the various reactors and SST for Modules A and B, Period VIII.

In the anoxic reactors, the two modules appear to exhibit differing BEPR behaviour. Throughout the investigation anoxic P uptake occurred in Module A, an average of 17.6 mgP/ℓ which is 48 % of the total P uptake in the anoxic and aerobic reactors. In contrast in Module B anoxic P release occurred, an average of 5.8 mgP/ℓ, which is 16 % of the total P release in the system. Anoxic P uptake has been observed in laboratory-scale and full scale plants (Hu *et al.*, 2001), and it happens for various reasons. Hu *et al.* noted that high anoxic P uptake tends to be stimulated when aerobic mass fractions are small and nitrate availability is not limited in the anoxic reactor. The small aerobic mass fraction prevents aerobic uptake PAOs from completing their P uptake and growth process, and the availability of nitrate in the anoxic reactor allows denitrifying PAOs (DPAOs) access to nitrate without competition by the denitrifying OHOs (DOHOs). If the aerobic mass fraction is large, then the aerobic uptake PAOs will dominate the BEPR and squeeze out the denitrifying PAOs because for the same concentration of P release (*i.e.* equal concentrations of RBCOD taken up) the DPAOs get less energy under anoxic denitrification conditions (lower yield, fewer organisms) than aerobic conditions (higher yield, more organisms). These conditions appeared to exist in the two modules. With Module A under-aerated (evident from significant simultaneous nitrification-denitrification in the aerobic reactor), the aerobic mass fraction would be small and with sufficient nitrate available in the anoxic reactor (evident from the high nitrate concentration in the anoxic reactor, 5.36 mgN/ℓ) would stimulate anoxic P uptake BEPR. In contrast, with a higher air supply to Module B (evident from less simultaneous

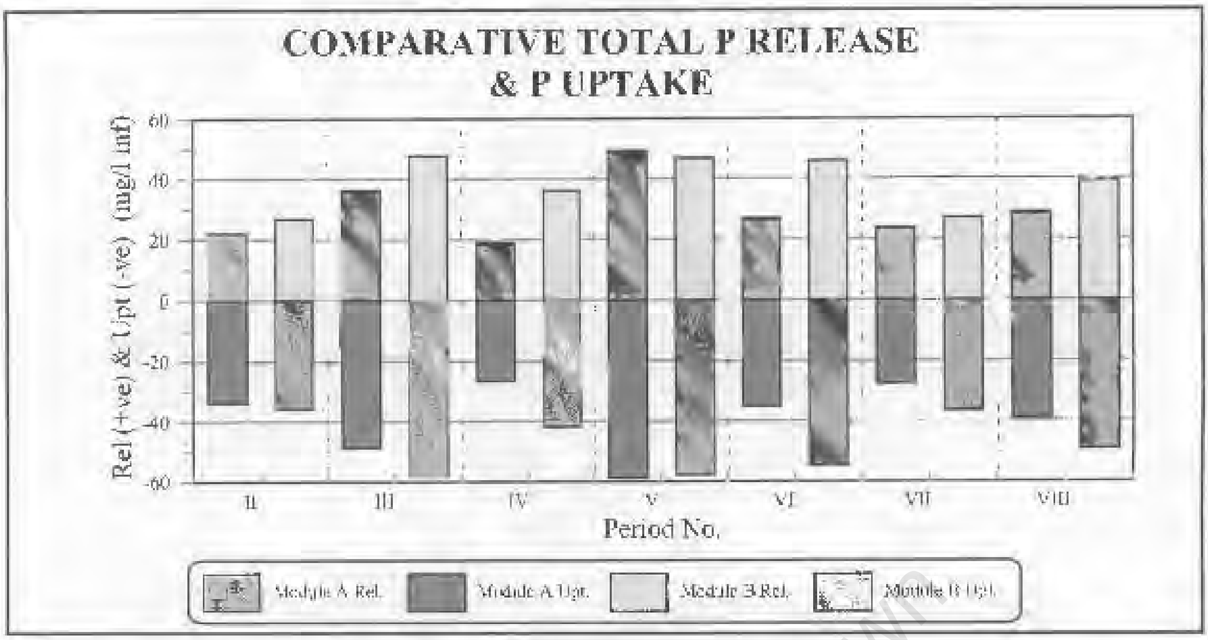


Figure 5.33 : Comparative total P release and total P uptake as measured in Modules A and B, site data does not include Period I.

nitrification-denitrification in the aerobic reactor due to the higher effluent nitrate concentration and lower effluent ammonia concentration than Module A), the aerobic mass fraction is larger and aerobic PAOs are not restricted in their P uptake process and so dominate over the DOHOs, with the result that aerobic P uptake BEPR takes place. However, with anoxic P uptake BEPR a lower P removal is expected than with aerobic uptake BEPR, which was not the case. Both modules achieved closely the same P removal *i.e.* about 10 mgP/ℓ as the difference between the unfiltered influent TP (12.7 mgP/ℓ) and filtered effluent TP.

Figure 5.33 gives a comparison of the total (*i.e.* the sum of each of the reactors and SST) P release and P uptake as measured in Modules A and B; P release is plotted as +ve and P uptake as -ve. From Figure 5.33 it is evident that with the exception of Period V both total P release and total P uptake is smaller in Module A compared to Module B. From Table 5.8 above, the average total P release in Modules A and B was 27 and 36 mgP/ℓ influent respectively; the average total P uptake was 37 and 45 mgP/ℓ influent respectively. Despite the higher P release and uptake in Module B, the P removal was marginally higher in Module A, at 9.1 and 8.8 mgP/ℓ influent for Modules A and B respectively. In UCT and external nitrification BNR systems (Soteman *et al.*, 2000; Vermande *et al.*, 2000), when significant anoxic P uptake was observed, the P release, P uptake and P removal are all lower than with predominantly (>90 %) aerobic P uptake BEPR.

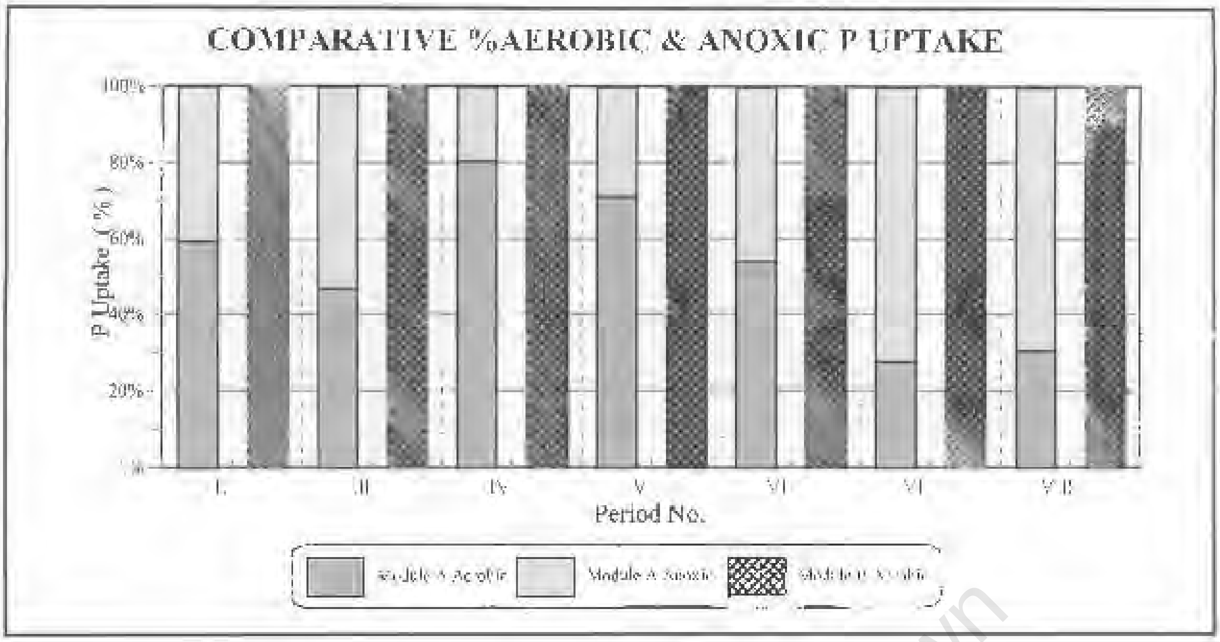


Figure 5.34 : Comparative average % aerobic/anoxic P uptake for steady state periods, site data does not include Period I.

This was not the case for the two modules in which the P removal was virtually the same in each. How this P removal matches up with that expected from BEPR models is discussed below in Section 5.3.4. However, the fact that when (i) aeration to Module A was increased (at the expense of the air supply to Module B), some nitrification took place in the anoxic reactor and (ii) the P removal was the same in both modules, suggests that the P uptake in the anoxic reactor was not anoxic P uptake BEPR, but aerobic P uptake BEPR because this reactor was sufficiently aerobic for this, with the result that the whole of the anoxic and aerobic reactors of Module A were a continuous single quasi anoxic quasi aerobic reactor. While it can be concluded that these were the conditions in the anoxic and aerobic reactors of Module A, the fact that the observed BEPR matched closely that theoretically calculated with the aerobic uptake BEPR model of Wentzel *et al.* (1990) (see Section 5.3.4 below), indicated that the BEPR was predominantly aerobic in the full-scale plants.

Figure 5.34 shows the comparative percentage aerobic/anoxic P uptake for Modules A and B over the long term periods of the investigation. For Module B, only aerobic P uptake was observed; 100 % P uptake occurred in the aerobic reactor. For Module A, both aerobic and anoxic P uptake was observed. In Figure 5.34 the anoxic P uptake as a percentage of the total anoxic – aerobic P uptake can be seen for the various long term periods. For Module A, over the investigation 48 % of the P uptake occurred in the anoxic reactor. The reasons for the P uptake in the anoxic reactor of Module A were, as noted above, not apparent during the investigation. However, circumstantial evidence suggested that a possible explanation for the observed behaviour was that the DO ingress into the anoxic reactor of Module A was underestimated. At the termination of the investigation, when the two modules were drained, significant holes in the aeration pipework near the drainage area at the bottom of the aerobic-anoxic transition baffle of Module A were found and this possibly resulted in significant leakage of air into the anoxic reactor leading to the observed poor denitrification (3 mgN/ℓ). The likelihood that the BEPR was predominantly aerobic is supported by the fact that when the aeration to Module A was increased during Period VI onward (at the expense of the air supply to Module B) in order to improve nitrification (as noted in Section 5.2.2), the anoxic denitrification concomitantly decreased to the extent that net nitrification occurred in the anoxic reactor during Periods VII and VIII and the percentage P uptake in the anoxic reactor <u>increased</u> substantially to 72 and 69 % of the total (aerobic + anoxic) P uptake for Periods VII and VIII respectively. The expectation with greater air supply is for anoxic P uptake to decrease. Thus increased aeration led to increased leakage of DO into the Module A anoxic reactor in addition to that entrained in the recycles to the anoxic reactor. The magnitude of this was not realised during the investigation so a detailed and thorough investigation of the 3-D DO profile in the anoxic zone of Module A was not carried out. However, random inspections of the surface anoxic zone DO concentration with a portable DO meter revealed (i) a maximum reading of only 0.3 mgO/ℓ and (ii) that the DO recorder on each module's aerobic reactor gave inaccurate readings.

5.3.2.3 P Removal

Accepting a 100 % P balance in the system for the eight steady state periods (*i.e.* P not in the effluent exited the system in the waste sludge stream), the P removals for Modules A and B are shown plotted together with the effluent P in Figures 5.35 and 5.36 respectively, where the total height of the stacked bar represents the unfiltered influent TP concentration. Table 5.9 below lists, for each steady state period, the percentage P removal of the systems. From Table 5.9 and Figures 5.35 and 5.36 it is evident that, with the exception of Module A Period III, the unfiltered effluent TP concentration > 1.5 mgP/ℓ indicating that the P removal was not limited by the influent TP concentration. The overall average effluent TP concentrations of the two modules were similar, therefore the overall average P removals (influent-effluent) and percentage P removal of the two systems were similar, at 9.4 and 8.6 mgP/ℓ influent and 69 and 64 % for Modules A and B respectively. A comparison of the observed P removal with that theoretically predicted for the two modules to make a judgement on the P removal performance is given in Section 5.3.4 below. The reasons for the low biological P removal during some of the long term periods is difficult to explain. However, it can be generally accepted that the P removal would be higher with a lower nitrate concentration recycled to the anaerobic reactor. On average over the investigation the nitrate recycled to the anaerobic reactor via the 'r-recycles' were high, at 5.6 and 5.0 mgN/ℓ for Modules A and B respectively. As nitrate recycled to the anaerobic reactor is utilised as electron acceptor by the OHOs, 5 mgN/ℓ x 8.6 mgCOD/mgNO_3-N = 43 mgRBCOD/ℓ entering the anaerobic reactor in the influent would be metabolised directly by the OHOs until the nitrate is depleted. Also the high TP/COD ratio of the settled wastewater affects the percentage P removal achieved by the BEPR system. At TP/COD ratios greater than 0.02 mgP/mgCOD, which is the value for the settled wastewater fed to the pilot plants, Pitman (1991) states that simultaneous chemical phosphorus precipitation will be necessary. On average over the investigation the TP/COD ratio of the settled wastewater (influent) was 0.022 mgP/mgCOD indicating that from a practical point of view (*i.e.* Pitman's) achieving < 1 mgP/ℓ in the effluent would be difficult with the well settled wastewater fed to the pilot plants.

Table 5.9 : Average percentage P removal (based on unfiltered TP) for steady state periods, averages are for "site" data except Period I which is based on "CMC" data.

Long Term Period No.	Influent TP (mgP/ℓ)	Effluent TP (mgP/ℓ)		P Removal (%)	
	Modules A and B	Module A	Module B	Module A	Module B
I	14.8	6.1	6.3	59	57
II	13.1	1.8	5.1	86	61
III	13.0	0.5	1.9	96	85
IV	12.8	8.5	8.4	34	34
V	12.7	1.7	3.8	87	70
VI	12.4	4.1	3.7	67	70
VII	12.2	5.2	3.4	57	72
VIII	12.3	2.5	2.5	80	80
Average	13.5	4.1	4.9	69	64

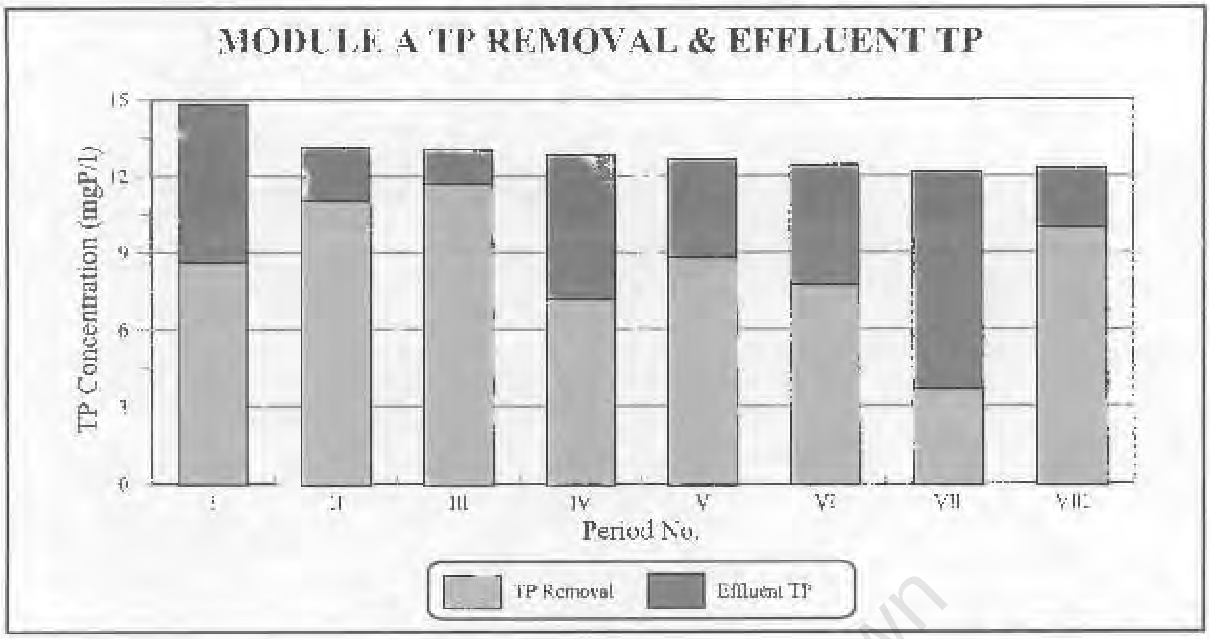


Figure 5.35 : Module A average P removal and effluent P for steady state periods, averages are for "site" data, except Period I which is for "CMC" data.

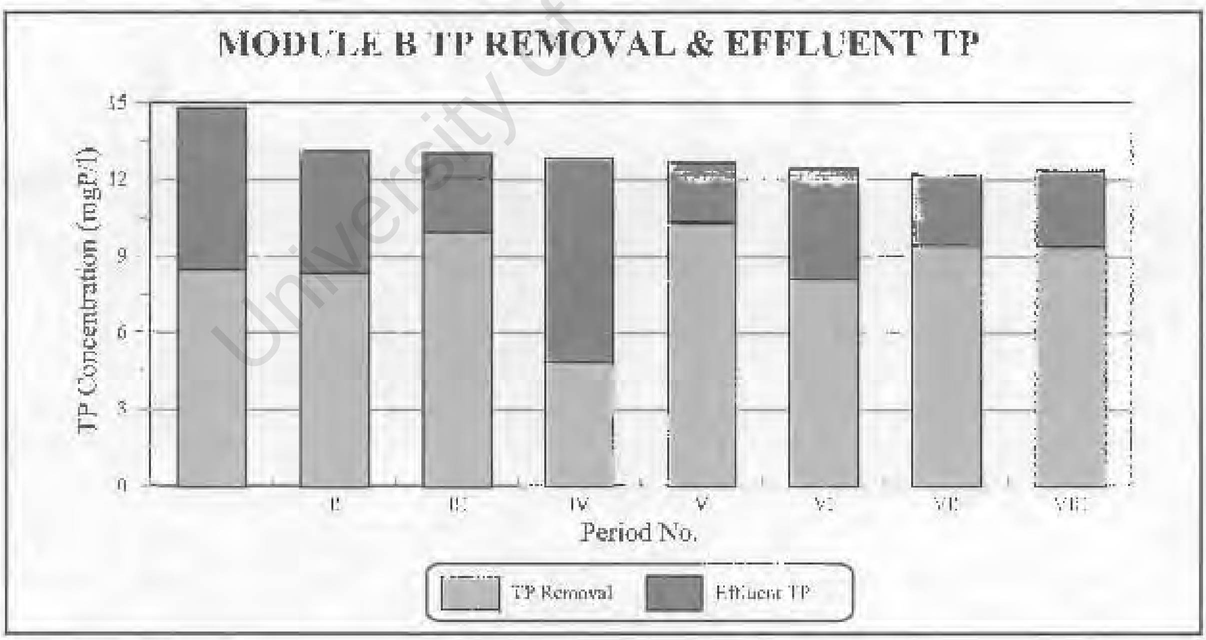


Figure 5.36 : Module B average P removal and effluent P for steady state periods, averages are for site data, except Period I which is for "CMC" data.

5.3.3 Phosphorus Mass Balance

To assess the accuracy of the phosphorus data, P mass balances were calculated for the steady state periods. For the P mass balance, the P exiting the system - (i) with the effluent TP (available from direct measurement), and (ii) with the waste sludge, as P bound in the sludge mass (the waste sludge TP concentration and waste flow rate were available from direct measurement) was reconciled with the P entering the system as influent TP (available from direct measurement).

As for the N mass balances, the P mass balances are used to check the reliability of the data and the operation of the system. A table of the bi-daily ("site") P mass balances is given in Appendix E. P mass balances for the different periods are listed in Table 5.10 and shown in Figure 5.37 below. From Table 5.10 and Figure 5.37, it is evident that the P mass balances, although variable for the different long term periods, gave overall average mass balances for Modules A and B of 103 and 97 % respectively. The variability for the individual periods is not unexpected, due to the fact that the P that enters the system with the influent is incorporated into the sludge mass which is resident in the system for the sludge age. Thus, changes in influent and effluent P concentrations are relative to the hydraulic residence time (1 day), whereas changes in sludge P concentration are relative to solids retention time (15 days). This causes a lag between changes in the P removal and P concentration in the sludge.

Table 5.10 : Average phosphorus mass balance data for steady state periods; averages are for "site" data which does not include Period I.

Long Term Period No.	Total mass P in (kgP/d)		Total mass P out (kgP/d)		P Recovery (%)	
	Module A	Module B	Module A	Module B	Module A	Module B
I	N/A	N/A	N/A	N/A	N/A	N/A
II	19.2	30.2	21.9	32.5	117	109
III	20.7	27.9	15.8	30.9	77	111
IV	14.3	28.2	13.5	46.4	102	166
V	20.4	28.3	24.1	19.4	134	68
VI	24.0	28.4	22.0	32.5	90	114
VII	20.7	26.9	24.9	17.2	123	64
VIII	23.5	28.3	18.9	24.8	82	88
Average	20.8	28.2	20.6	27.3	103	97

The good overall averages indicate that (i) the data relating to P are reliable and (ii) the water flows into and out of the modules were accurately measured.

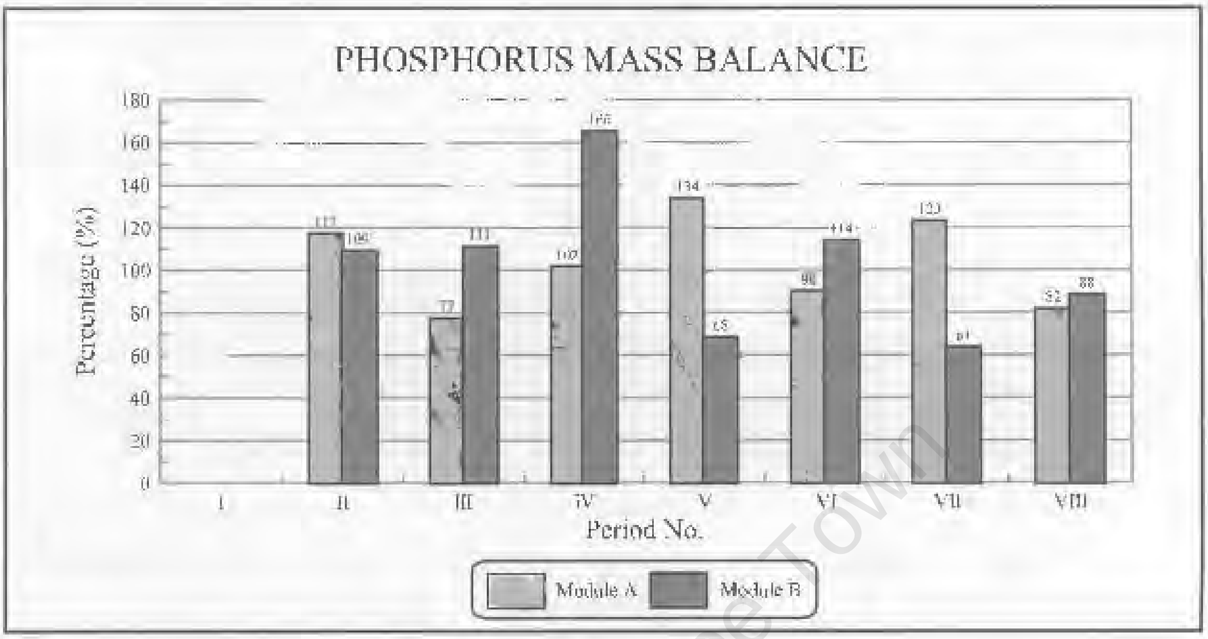


Figure 5.37 : Average phosphorus mass balance for steady state periods; averages are for "site" data.

5.3.4 Comparison of Measured and Calculated P Removal

The BEPR performance of the UCT configured full-scale plants was assessed by comparing the measured P removal with the theoretical P removal calculated by the steady state model of Wentzel *et al.* (1990) which is essentially a simplified subset of the UCTPHO (Wentzel *et al.*, 1992) and IAWQ ASM N° 2 (Henze *et al.*, 1995) dynamic simulation models including 100 % aerobic uptake BEPR. In order to evaluate the theoretically predicted BEPR by the Wentzel *et al.* (1990) BEPR model, the VSS mass needs to be fractionated into its hypothetical constitutive components *viz.* OHOs, PAOs, endogenous residue of OHOs and PAOs and the unbiodegradable particulate VSS (X_i). In doing this procedure, the unbiodegradable particulate COD fraction ($f_{S,up}$) and the two active heterotrophic organism fractions of the VSS are determined (*i.e.* PAOs, $f_{av,PAO}$ and OHOs, $f_{av,OHO}$). The procedure for fractionating the measured VSS concentration and comparing the calculated and measured P removal is summarised below.

5.3.4.1 <u>Determination of $f_{S,up}$, $f_{av,PAO}$, $f_{av,OHO}$ and $f_{XBG,P}$</u>

To determine the unbiodegradable particulate COD fraction ($f_{S,up}$) of the sewage fed to the full-scale plants, the appropriate $f_{S,up}$ value was selected so that the system VSS mass calculated with the BEPR model of Wentzel *et al.* (1990) was equal to the measured VSS mass. The BEPR steady state model is structured such that the heterotrophic organism mass is divided into two groups, the OHOs and PAOs. Using the <u>measured</u> readily biodegradable COD (RBCOD) concentration (appropriately corrected for nitrate inflow to the anaerobic reactor) and the influent characteristics of the sewage (*i.e.* fraction of unbiodegradable soluble COD/total influent COD, $f_{S,us}$ and total influent COD, S_{ti}) and the known system parameters (anaerobic mass fraction and sludge age) as input, an estimate of $f_{S,up}$ is made. By means of an iterative process the biodegradable COD calculated by difference is split between the OHOs and PAOs. From these the masses of the active and endogenous VSS generated by these two groups are calculated. Also from the initial estimate of $f_{S,up}$, the unbiodegradable particulate (inert) VSS mass is calculated. The total VSS mass of the system is the sum of the five constituent components of the VSS mass. The appropriate $f_{S,up}$ value is that value which sets the calculated VSS mass equal to the measured VSS mass. The OHO and PAO active VSS mass fractions are then determined from the ratio of the masses of OHO and PAO VSS to the total VSS. <u>This procedure assumes a 100 % COD mass balance in the systems</u> and that the heterotrophic yield coefficients for anoxic and aerobic conditions are equal. After reconciling the calculated VSS mass in the two systems with that measured, the P content of the PAOs ($f_{XBG,P}$) is estimated so that the calculated sum of the P contents of the five constituent components of the VSS equals the measured P removal. The appropriate value of $f_{XBG,P}$ is that value for which the calculated P removal is equal to the measured P removal.

The calculated P removal of the two systems for the standard (*i.e.* based on aerobic P uptake) PAO P content ($f_{XBG,P}$ = 0.38 mgP/mgPAOAVSS) is compared with the measured P removal for each long term period in Table 5.11 below. A detailed spreadsheet and graphs of the bi-daily ("site") results are given in Appendix F. From Table 5.11 it can be seen that the overall average calculated P removal is higher than the measured value for both modules (at about 13.5 versus 9.0 mgP/ℓ). In order to decrease the calculated P removal, the P content of the PAOs, $f_{XBG,P}$ is decreased. An average $f_{XBG,P}$ value of 0.322 matches the calculated and measured P removal (see Table 5.12 below).

Table 5.11 : Calculated versus measured P removal for steady state periods.

Long Term Period No.	Module A P Removal ($mgP/\ell_{influent}$)		Module B P Removal ($mgP/\ell_{influent}$)	
	Calculated	**Measured**	**Calculated**	**Measured**
I	N/A	N/A	N/A	N/A
II	13.62	11.30	13.63	8.00
III	14.27	12.50	13.22	11.10
IV	18.92	4.30	15.93	4.40
V	25.16	11.00	24.27	8.90
VI	15.28	8.30	15.21	8.70
VII	9.18	7.00	10.43	8.80
VIII	9.26	9.80	10.10	9.80
Average	13.83	9.40	13.70	8.60

As noted above, the procedure to determine $f_{S,up}$ assumes a 100 % COD mass balance. It was realised that poor (much greater than 100 %) COD balances would be obtained from the sporadic sludge ingress with the result that the OUR was not measured on the pilot plants except during the two 24h tests (see Section 5.6 below). Due to significant effort this requires, this was reserved for a time when there was greater certainty about getting good COD balances. Unfortunately, the aeration system on the full-scale plants failed irreparably before the sludge ingress problem could be definitively resolved terminating operation of the full-scale plants. This resulted in the secondary objective of the investigation - does significant anaerobic reactor COD loss take place in large scale BNR plants - not being achieved.

Table 5.12 : Calculated $f_{S,up}$, $f_{av,OHO}$, $f_{av,PAO}$ and $f_{XBG,P}$ fractions for steady state periods using BEPR model of Wentzel *et al.* (1990).

Long Term Period No.	S_{bsi} (mgCOD/ℓ)	$f_{S,us}$	$f_{S,up}$	$f_{av,OHO}$	$f_{av,PAO}$	$f_{XBG,P}$
I	N/A	N/A	N/A	N/A	N/A	N/A
II	221.4	0.060	0.319	0.154	0.121	0.350
III	222.8	0.070	0.210	0.215	0.144	0.364
IV	238.0	0.100	0.428	0.131	0.140	0.172
V	364.0	0.090	0.239	0.148	0.282	0.112
VI	238.7	0.080	0.152	0.245	0.183	0.207
VII	157.7	0.120	0.171	0.286	0.103	0.354
VIII	162.9	0.120	0.147	0.283	0.108	0.465
Average	217.3	0.086	0.239	0.210	0.140	0.322

Note : The values for the two modules were virtually identical.

After reconciling the calculated VSS mass with that measured, an overall average $f_{XBG,P}$ value of 0.322 mgP/mgPAOAVSS with sample standard deviation of 0.202 mgP/mgPAOAVSS was estimated which sets the calculated P removal equal to that measured in the systems. The calculated $f_{S,up}$, $f_{av,OHO}$, $f_{av,PAO}$ and $f_{XBG,P}$ fractions for each long term period is listed in Table 5.12. The BEPR steady state model links the measured influent RBCOD concentration (S_{bsi}) to the PAO mass which for a constant P content of PAOs ($f_{XBG,P}$) gives a fixed P removal. In contrast from Table 5.12, the $f_{XBG,P}$ fraction appears to be inversely proportional to S_{bsi} in that high S_{bsi} concentrations lead to low $f_{XBG,P}$ fractions and *visa versa*. As with the P mass balance over the different steady state periods, this is mainly because the changes in influent P and RBCOD concentrations are relative to the hydraulic residence time, whereas changes in sludge P concentration are relative to solids retention time (sludge age). The calculated PAO P content ($f_{XBG,P}$) of 0.332 mgP/mgPAOAVSS is below the standard value of 0.38 mgP/mgPAOAVSS based on aerobic P uptake and those found in earlier investigations in which no anoxic P uptake was observed *e.g.* Clayton *et al.* (1991) and Sneyders *et al.* (1998) who found the $f_{XBG,P}$ fraction to be 0.388 and 0.428 mgP/mgPAOAVSS respectively. As mentioned above, a lower $f_{S,up}$ value will result in a lower calculated P removal. To compensate for this lower calculated P removal the $f_{XBG,P}$ value will increase. Overall average $f_{av,OHO}$ and $f_{av,PAO}$ values of 0.210 and 0.140 with sample standard deviations of 0.129 and 0.092 respectively were determined. High $f_{S,up}$ values lead to low $f_{av,OHO}$ and $f_{av,PAO}$ values. The sludge ingress problem is the main reason for the high $f_{S,up}$ fractions and low $f_{av,OHO}$ and $f_{av,PAO}$ fractions given in Table 5.12.

In examining the $f_{S,up}$ values obtained for the various long term periods in Table 5.12, unusually large values for Periods II to V are noted due to the sludge ingress from the main plant. The overall average $f_{S,up}$ value of 0.239 (with sample standard deviation of 0.173) does not fall within the expected range for typical municipal settled wastewaters (*i.e.* 0.00 - 0.10), which can be attributed to the poor sludge wasting regime at the Mitchell's Plain WWTP (sludge back flow from the main plant into the two modules). The value of $f_{S,up}$ is high because essentially the model needs to create a high sludge production from the measured influent COD mass to account for the back flow of sludge from the main plant. Without this back flow sludge, which does not form from the influent COD mass, the $f_{S,up}$ will be significantly lower, with the result that the calculated P removal will be lower. Accepting an $f_{S,up}$ of 0.05 for the settled wastewater changes the average $f_{XBG,P}$ to 0.396 to match the calculated and measured P removal which is virtually the same as the standard value of 0.38 in the BEPR model of Wentzel *et al.* (1990). In Section 5.5.5 below, which compares the measured with the calculated P removal for the lab-scale system, a $f_{S,up}$ value of 0.03 was determined which is a more appropriate value than that calculated for the full-scale plants as the lab-scale system had no sludge back flow problems.

Comparing the values for $f_{av,OHO}$, $f_{av,PAO}$ and $f_{XBG,P}$ obtained in Table 5.13 below ($f_{S,up}$ fixed at 0.05) with those in Table 5.12 (overall average $f_{S,up}$ of 0.239 for the full-scale plants), it can be seen that the $f_{av,OHO}$, $f_{av,PAO}$ and $f_{XBG,P}$ values are higher for the lower $f_{S,up}$ of 0.05. The overall average $f_{XBG,P}$ fraction of 0.396 mgP/mgPAOAVSS is close to the model 0.38 mgP/mgPAOAVSS indicating aerobic P uptake BEPR. The P removal performance of the full-scale plants can therefore be deemed very good and at the maximum possible achievable for the wastewater (*i.e.* influent P and RBCOD, and nitrate recycled). If the nitrate concentration in the recycle were zero (instead of ~ 5 mgN/ℓ) then (theoretically) about 3 to 4 mgP/ℓ additional P removal could be achieved *i.e.* a total of about 12.5 mgP/ℓ.

Table 5.13 : Calculated $f_{av,OHO}$, $f_{av,PAO}$ and $f_{XBG,P}$ fractions for steady state periods using a fixed $f_{S,up}$ of 0.05 in the BEPR model of Wentzel *et al.* (1990).

Long Term Period No.	S_{bsi} (mgCOD/ℓ)	$f_{S,us}$	$f_{S,up}$	$f_{av,OHO}$	$f_{av,PAO}$	$f_{XBG,P}$
I	N/A	N/A	N/A	N/A	N/A	N/A
II	221.4	0.060	0.05	0.363	0.182	0.488
III	222.8	0.070	0.05	0.353	0.197	0.426
IV	238.0	0.100	0.05	0.349	0.196	0.213
V	364.0	0.090	0.05	0.259	0.348	0.141
VI	238.7	0.080	0.05	0.345	0.212	0.217
VII	157.7	0.120	0.05	0.391	0.128	0.419
VIII	162.9	0.120	0.05	0.389	0.131	0.530
Average	217.3	0.086	0.05	0.359	0.185	0.396

5.4 Filamentous Organisms and Sludge Settleability

The prolific growth of filamentous organisms (bulking) which inhibit the rate of sludge settling in the clarifier and reduces operating capacity, has been plaguing nutrient removal activated sludge systems treating municipal sewage. The principal filaments causing the bulking problems are the so-called low F/M ones *viz.* type 0092, 0041, *Microthrix Parvicella*, type 1851, 0675 and 0914 (Blackbeard *et al.*, 1988). In experiments with real and synthetic sewage, Gabb *et al.* (1989) and Casey *et al.* (1990,1991) found that the low F/M filaments did not proliferate in fully aerobic or fully anoxic low F/M systems, but appear to proliferate in systems that expose the sludge mass to alternate periods of aerobic and anoxic conditions as in anaerobic-anoxic-aerobic multi-reactor N & P removal systems and completely mixed intermittently aerated N removal systems (ditch type plants). Because the low F/M condition did not appear to influence the bulking significantly in experiments on the above systems, whereas alternating anoxic-aerobic conditions did, the filamentous organisms responsible were renamed anoxic-aerobic (AA) filaments (Casey *et al.*, 1994).

The following hypothesis for the proliferation of AA filaments in N and N & P removal plants was proposed by Casey *et al.*, 1994 :

> "In nitrification-denitrification (ND) and nitrification-denitrification biological excess phosphorus removal (NDBEPR) systems, the majority of heterotrophic organisms can be classified by their morphological characteristics as either filamentous or floc-forming organisms. The floc-forming organisms are aerobic-facultative; under aerobic conditions they utilise oxygen and under anoxic conditions they denitrify NO_3^- or NO_2^- to N_2 as described by the denitrification pathway (*i.e.* NO_3^- ® NO_2^- ® NO(g) ® N_2O(g) ® N_2(g)). The filamentous organisms are also aerobic-facultative but are nitrate reducers only; under anoxic conditions they reduce NO_3^- to NO_2^- only.
>
> When sludge is exposed to alternating periods of anoxic-aerobic conditions in which NO_3^- and/or NO_2^- are present throughout the anoxic period, floc-formers denitrify NO_3^- and NO_2^- through each of the denitrification intermediates to the end-product N_2 in which process some level of intracellular NO is produced. When floc-formers with intracellular NO are subjected to aerobic conditions, the NO inhibits the utilisation of oxygen (and concomitantly the utilisation of substrate). Furthermore, while NO is present under aerobic conditions, the floc-formers continue to respire with NO_3^- or NO_2^- (*i.e.* aerobic denitrification) due to the intracellular inhibition by NO of the enzymes mediating the transfer of electrons to oxygen, albeit at a much reduced rate to that under anoxic conditions. For filamentous organisms, under anoxic conditions NO is not an intermediate hence does not accumulate intracellular; these organisms are therefore not inhibited in their substrate utilisation under subsequent aerobic conditions. When sludge is exposed to alternating anoxic-aerobic conditions in which NO_3^- and/or NO_2^- are not present at the end of the anoxic period, no intracellular NO is present in the floc-formers and under subsequent aerobic conditions substrate utilisation is not inhibited.
>
> With intracellular NO present, and inhibition induced, floc-formers are disadvantaged with respect to the filaments in competition for substrate under aerobic conditions. Consequently, the filamentous organisms utilise a greater proportion of the substrate under aerobic conditions than they would if the floc-formers were not inhibited. With floc-forming organisms inhibited, the filamentous organisms increase their relative mass in the sludge with each exposure to aerobic conditions, leading to the condition referred to as a bulking sludge."

The following strategy for the control of AA filaments in N and N & P removal plants was proposed by Casey *et al.*, 1994 :

> "In the design and operation of ND and NDBEPR activated sludge systems, it is essential that the denitrification capacity of the anoxic zone is not exceeded so that nitrite is not present in excess to cause accumulation of nitric oxide and inhibition of floc-former substrate utilization under subsequent aerobic conditions. This can be accomplished by manipulation of the 'a-recycle' (aerobic-anoxic recycle) to ensure that the nitrate load to the anoxic zone immediately prior to the aerobic zone never exceeds the denitrification potential of that zone."

5.4.1 Filamentous Organisms

Approximately once monthly mixed liquor single grab samples were taken from the end of the aerobic reactors of Modules A and B and the UCT laboratory scale system for microscopic analysis and filamentous organism identification in accordance with the methods outlined by Jenkins *et al.* (1984) (see Appendix H for details). This was done to determine the relative type and abundance of AA (low F/M) filaments in the two full scale systems and the laboratory scale system. During the investigation, the filament identifications were done 17 and 16 times on Module A and B respectively. For the identifications on each system, the percentage frequency of occurrence and dominance were determined and are listed in Table 5.14.

From Table 5.14, the filament most frequently dominant in both Module A and B was *M. parvicella* (41 and 44 % respectively). The next most frequently dominant filaments were type 0092 and type 1851. All of these filaments are classified as typical of the low F/M category (Jenkins *et al.*, 1984) later renamed Anoxic-Aerobic(AA) (Casey *et al.*, 1994) and are almost always observed in both full scale (Blackbeard *et al.*, 1986, 1988) and laboratory (Ekama *et al.*, 1996) ND and NDBEPR systems.

The five most frequently occurring filament types in Modules A and B in descending order of frequency were, *M. parvicella* present in 82 and 94 % of samples, type 0092 present in 77 and 69 %, type 1851 in 53 and 63 %, type 1701 in 6 and 13 % and *N. limicola* in 6 and 6 % respectively. *Nocardia* spp. occurred in 6 % of samples analysed for Module B. Jenkins *et al.*

(1984) categorises this filament in systems which exhibit a high degree of foaming which is consistent with the observations of excessive foaming in Module B at that time.

Table 5.14: Frequency of occurrence (observed in sample, rank > 1) and dominance (rank = 1) of filamentous organisms in the UCT configured full-scale plants.

Filamentous micro-organism	Occurrence (%)		Dominance (%)	
	Module A	Module B	Module A	Module B
M. parvicella	82	94	41	44
Type 0092	77	69	29	31
Type 1851	53	63	29	31
Type 1701	6	13	0	0
N. limicola	6	6	0	0
Nocardia spp.	0	6	0	0
H. hydrossis	0	0	0	0

5.4.2 Sludge Settleability

The sludge settleability of the two systems was monitored by means of the Diluted Sludge Volume Index (DSVI). Figures 5.38 and 5.39 below, show the DSVIs for the "site" and "CMC" data respectively. From Figures 5.38 and 5.39 it can be seen that for the various steady state periods, a reasonable correlation for the DSVIs of the two sets of data is achieved (most DSVIs between 90 and 110 mℓ/g).

The principle aim in this research project was to investigate at full-scale the implementation of the proposed strategy to control bulking by AA filaments, namely that by limiting the anoxic nitrate/nitrite concentrations to < 1 mgN/ℓ by controlling the 'a-recycle' ratio, a good settling sludge (DSVI < 100 mℓ/g) could be achieved. In the investigation, it was proposed to run the two modules in parallel, one (Module A) with a low 'a-recycle' ratio to give low anoxic nitrate concentrations and the other (Module B) with a high 'a-recycle' ratio to give high anoxic nitrate concentrations. In terms of the AA filament bulking hypothesis and the control strategy derived

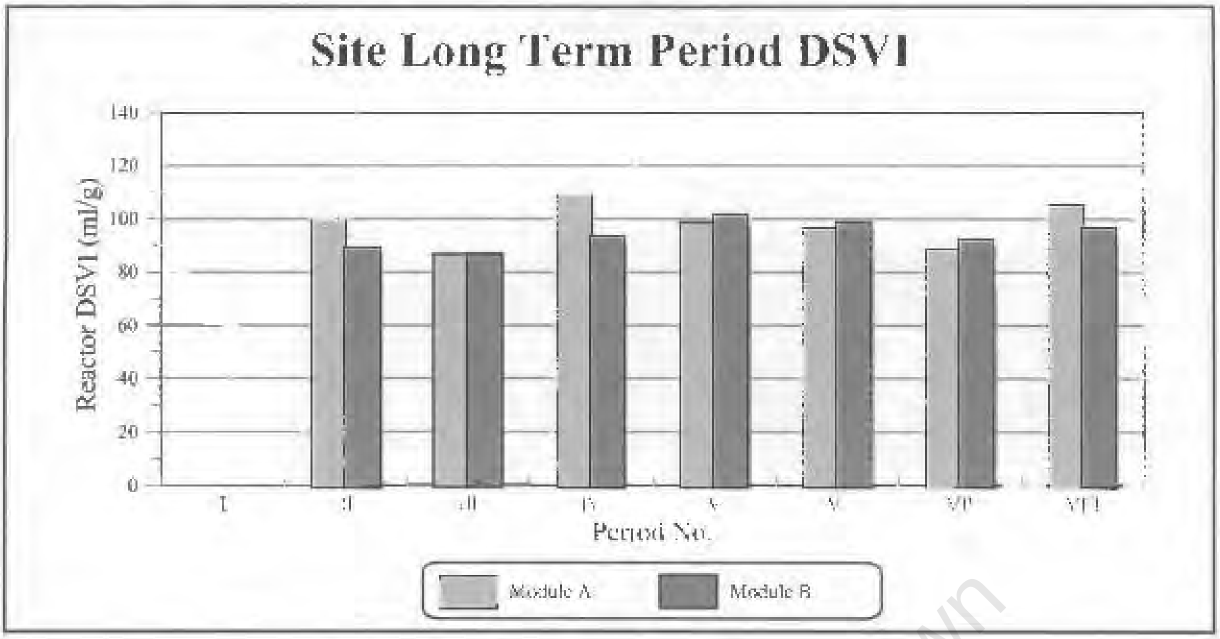


Figure 5.38 : Averaged mixed liquor DSVI for steady state periods; "site" averages do not include Period I.

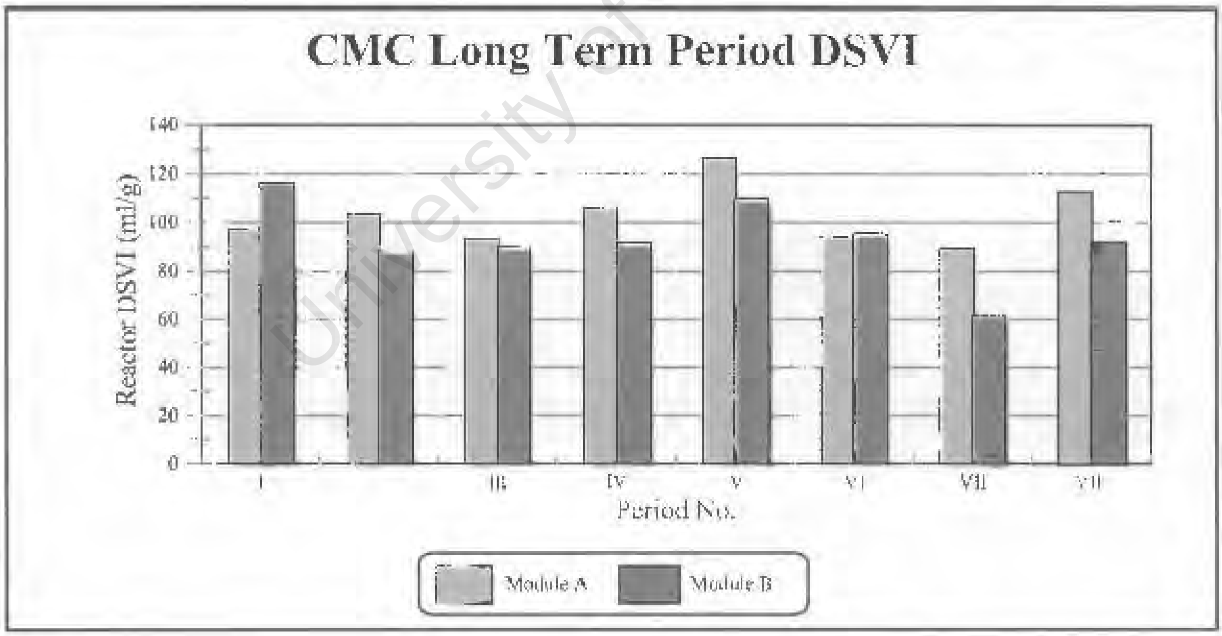


Figure 5.39 : Averaged mixed liquor DSVI for steady state periods; averages are for "CMC" data.

from it, this should cause the module with high anoxic nitrate concentrations to bulk due to AA filaments (Module B) and the module with low anoxic nitrate concentrations (Module A) not to bulk. To assess whether this aim had been achieved, for the different periods the averaged anoxic nitrate and nitrite concentrations and DSVIs are listed in Table 5.15 below. Also, the daily nitrate and nitrite concentrations leaving the anoxic reactor and DSVIs are shown plotted in Figures 5.40 and 5.41 for Modules A and B respectively. From Table 5.15 and Figures 5.40 and 5.41 below, it is evident that in both modules the anoxic nitrite concentrations were low throughout the investigation with an overall average of 0.17 and 0.25 mgN/ℓ for Modules A and B respectively. In both modules, anoxic nitrate concentrations were high except for Module A Periods IV and V where nitrification failed with an overall average of 5.36 and 5.17 mgN/ℓ for Modules A and B respectively. The objective of achieving high anoxic nitrate concentrations in Module B was achieved, but that of achieving low nitrate concentrations in Module A clearly was not, despite implementing a 0:1 'a-recycle' ratio for this module from Period III onward (see Table 4.2). The inability to achieve low anoxic nitrate concentrations in Module A was due to its poor anoxic denitrification performance from the significant back mixing and oxygen ingress from the aerobic reactor and aeration system. This led to anoxic and aerobic reactors being a continuous quasi anoxic quasi aerobic reactor without clear separation of anoxic and aerobic conditions in the anoxic and aerobic reactors respectively. While significant simultaneous nitrification and denitrification took place in the aerobic reactor of Module B, in this module there was better separation of anoxic and aerobic conditions between the anoxic and aerobic reactors (Section 5.2.2). In terms of the hypothesis and the bulking control strategy, since both modules have high anoxic nitrate concentrations both should produce a bulking sludge due to AA filament proliferation. Clearly this did not happen - for all the long term periods of the investigation both systems produced good settling sludges with low average DSVIs, < 110 mℓ/gTSS with overall averages of 97 and 102 mℓ/gTSS. This is well below that which can be considered a bulking sludge (*i.e.* 150 mℓ/gTSS). From the above, the observations do not support the AA filament bulking hypothesis. Curiously, the quasi anoxic-aerobic conditions that stimulate simultaneous nitrification-denitrification as in Carousel or Orbal ND plants have been observed frequently to lead to AA filament bulking sludges, but this did not happen in the full-scale plants. It is possible that the oxygen supply rate was sufficiently high to avoid this.

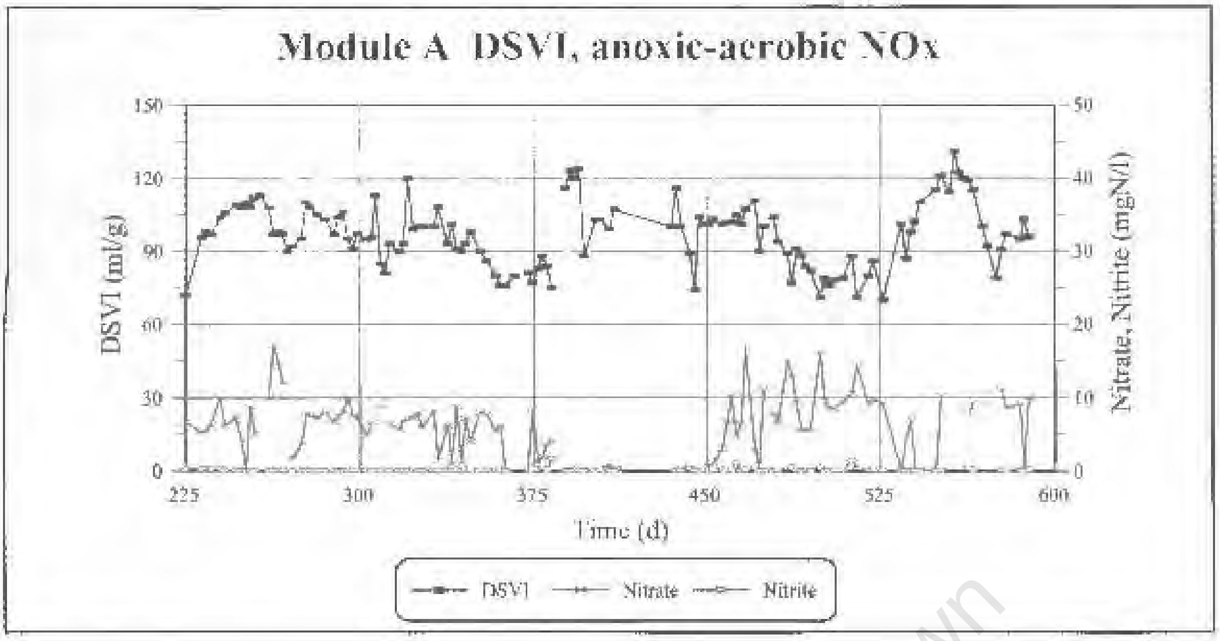


Figure 5.40 : Module A DSVI and nitrate & nitrite concentration at end of anoxic reactor.

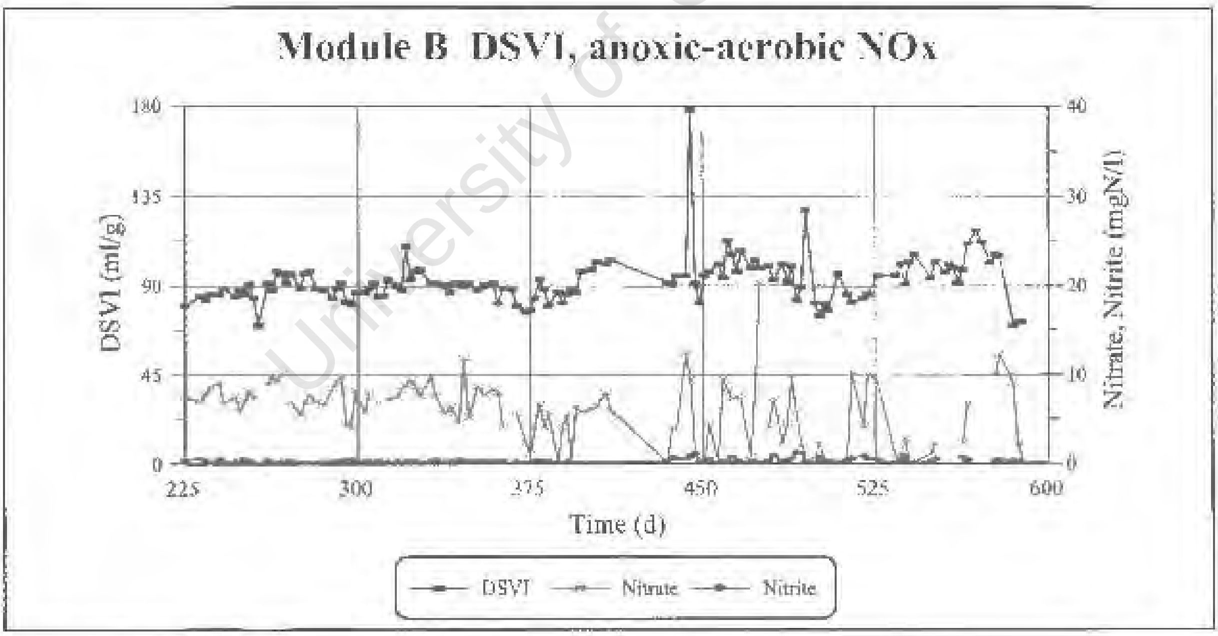


Figure 5.41 : Module B DSVI and nitrate & nitrite concentration at end of anoxic reactor.

Table 5.15: Average anoxic nitrate and nitrite concentrations and DSVIs for "steady state" periods.

Long Term Period No.	Module A			Module B		
	Anoxic		DSVI (mℓ/gTSS)	Anoxic		DSVI (mℓ/gTSS)
	Nitrate (mgN/ℓ)	Nitrite (mgN/ℓ)		Nitrate (mgN/ℓ)	Nitrite (mgN/ℓ)	
I	N/A	N/A	97.4	N/A	N/A	116.1
II	7.22	0.13	99.8	8.01	0.20	89.2
III	3.39	0.25	86.8	5.17	0.21	87.0
IV	0.07	0.03	109.2	5.01	0.07	93.7
V	0.13	0.04	98.7	3.29	0.46	101.7
VI	6.94	0.28	96.6	5.34	0.42	98.6
VII	6.73	0.20	88.6	1.67	0.18	92.4
VIII	8.32	0.22	105.3	4.44	0.24	96.8
Average	5.36	0.17	97.2	5.17	0.25	101.5

Note : For the anoxic nitrate & nitrite concentrations no "site" or "CMC" data is available for Period I.

5.5 Comparison between Full-Scale (Module A) and Lab-Scale System

Operating conditions, monitoring and data collection and analysis of the UCT laboratory scale system was given in Section 4.4.1.

5.5.1 Comparison of Influent, Reactor and Effluent Concentrations

5.5.1.1 <u>Influent concentrations and COD balance</u>

Figure 5.42 below gives a comparison of the overall average influent concentrations to Module A and the lab-scale system. From Figure 5.42 it can be seen that the influent ammonia and Total P concentrations were very similar, however the COD and TKN concentrations were considerably higher for Module A. This is because (i) the investigation periods of the two systems were not identical, (ii) COD loss in the sewage feed to the lab-scale system due to maceration and straining (through 1 mm mesh) - these were done to avoid blockages in the lab unit and (iii) the likelihood of COD loss in transport and storage in the laboratory.

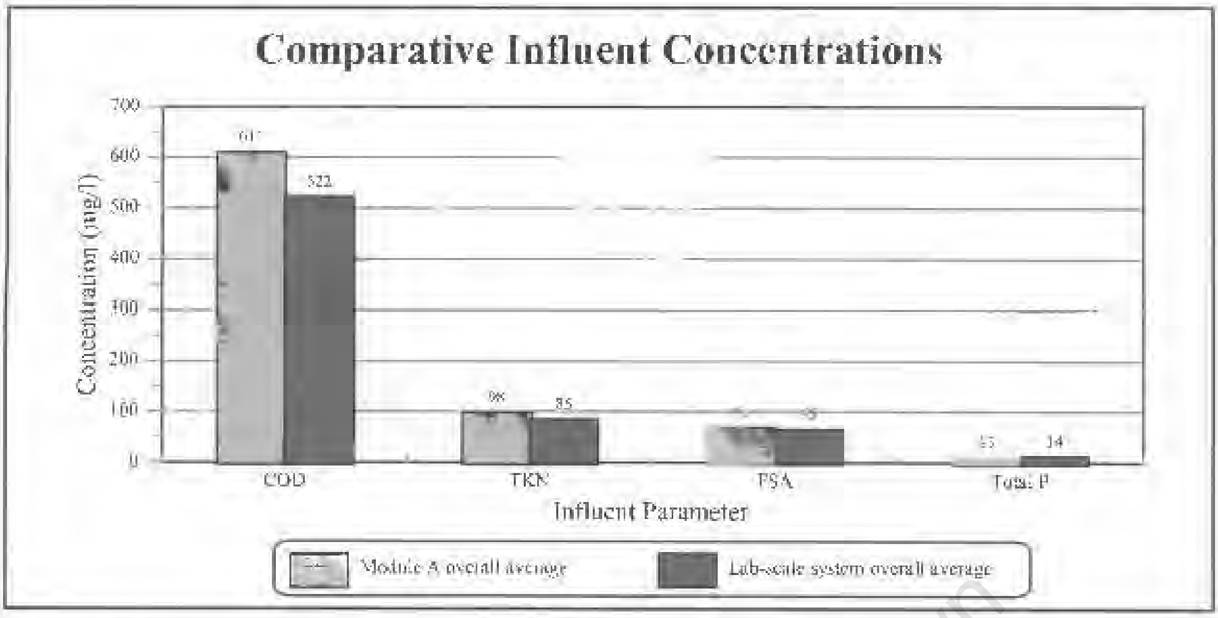


Figure 5.42 : Comparison between overall average influent concentrations for Module A and lab-scale system.

Table 5.16 gives the average COD mass balance of the lab-scale system for each sewage batch. From Table 5.16 it can be seen that the COD mass balance ranged between 76 and 92 % with an overall average of about 81 %. The low COD mass balances arise from low OUR (Batch 3) and VSS (Batch 4) measurements. Although considerably lower than 100 %, the overall average mass balance obtained is not far below those achieved in earlier laboratory scale investigations on N & P removal systems (85 - 95 %).

Table 5.16 : Averaged COD mass balance for sewage batches; averages are for "UCT" data.

Sewage Batch No.	Day No.	Mass COD in influent (mgCOD/d)	Mass COD in waste (mgCOD/d)	Oxygen Demand (mgO/d)	Mass COD in effluent (mgCOD/d)	COD Recovery (%)
1	470-497	12560.3	3570.1	6473.3	1174.0	89.31
2	498-528	12980.4	3874.8	6984.8	1129.6	92.36
3	529-574	12320.3	3426.0	2762.3	1390.0	61.51
4	575-632	12487.3	2944.8	5218.9	1336.6	76.08
Ave.	470-632	12536.3	3361.3	5477.4	1282.2	80.73

5.5.1.2 Filament identification, DSVI and reactor mixed liquor concentrations

Mixed liquor samples were taken from the aerobic reactor of the UCT lab-scale system at the same time as the full-scale plants for microscopic analysis and filament identification. During the investigations, 17 and 11 filament identifications were done on Module A and the lab-scale system respectively. For the identifications on each system, the percentage frequency of occurrence and dominance were determined and are listed in Table 5.17.

From Table 5.17, the filaments most frequently dominant in both Module A and the lab-scale system were, in descending order, *M. parvicella* and type 0092. *M. parvicella* was dominant in 100 % of samples from the lab-scale system compared to 41 % of samples from Module A. Type 1851 occurred in both systems but was never dominant in the lab-scale system. All of these filaments are classified as low F/M (AA) types. *H. hydrossis* occurred in 9 % of samples analysed for the UCT lab-scale system but was never dominant.

Table 5.17: Frequency of occurrence and dominance of filamentous organisms in Module A (full-scale UCT system) and lab-scale UCT system.

Filamentous micro-organism	Occurrence (%)		Dominance (%)	
	Module A	Lab-scale	Module A	Lab-scale
M. parvicella	82	100	41	100
Type 0092	77	36	29	0
Type 1851	53	27	29	0
Type 1701	6	0	0	0
N. limicola	6	0	0	0
Nocardia spp.	0	0	0	0
H. hydrossis	0	9	0	0

Table 5.18 below gives a comparison of the overall average reactor parameters of Module A and the lab-scale system. From Table 5.18, in both systems anoxic nitrate+nitrite (NO_x) concentrations were high (> 1 mg/ℓ). Thus, the objective of achieving low anoxic NO_x concentrations in both Module A and the lab-scale system (both with 0:1 mixed liquor 'a-recycle') could not be achieved. Therefore, in terms of the AA filament bulking hypothesis both

systems should produce a bulking sludge. From Table 5.18 we see that this was not true for Module A, but that the lab-scale system produced a bulking sludge (DSVI > 150 mℓ/g). Further, as noted in Section 4.4.3.2, for the lab-scale system the anoxic NO_x concentration and DSVI appeared to be linked, both increasing concomitantly. The lab system had none of the operational problems that Module A had - insufficient oxygen supply in the aerobic reactor and too much oxygen ingress in the anoxic reactor - and the anoxic and aerobic reactors indeed had good anoxic and aerobic conditions. As a consequence, in the lab system nitrification was much better (effluent FSA = 2 mgN/ℓ compared with 12 mgN/ℓ, see Figure 5.43) and the effluent nitrate concentration much higher (38 $mgNO_3$-N/ℓ compared to 10 $mgNO_3$-N/ℓ) due to the absence of denitrification in the aerobic reactor. The difference in bulking behaviour must have its causes somewhere in these differences. One notable difference is the generally low DO concentration in the Module A aerobic reactor compared to the higher DO concentration in the aerobic reactor of the lab-scale system. Casey *et al.* (1994) notes that for intermittent aeration conditions, the higher the DO concentration during the aerobic period the higher the DSVI. Additionally, for systems with low continuous DO conditions, sludges with low DSVI develop. Thus, the quasi-aerobic conditions that developed in Module A (and Module B to a lesser degree) are similar to the conditions described by Casey *et al.* (1994).

Table 5.18: Comparison of overall average reactor mixed liquor concentrations.

System	MLVSS (mgVSS/ℓ)	MLSS (mgTSS/ℓ)	Anoxic NO_x (mgN/ℓ)	DSVI (mℓ/gTSS)
Module A Overall Average	2818	3755	5.53	97
Lab-scale System Overall Average	1817	2111	2.14	234

The MLSS and MLVSS concentrations in the two modules are around 60 % higher than in the lab-scale system. Because the COD balance (81 % - see Section 5.5.1.1) in the lab system was not unreasonable (previous investigations on UCT type systems yielded 80 - 92 % COD balances, Pilson *et al.*, 1994, Mellin *et al.*, 1997 and Sneyders *et al.*, 1998) and the VSS concentration so much lower than in the two modules, it can be concluded that sludge ingress from the main plant clearly was substantial and makes drawing definitive conclusions from the results difficult. The significant sludge ingress added a substantial additional nitrifier organism mass. Under the limited aeration conditions in the two modules it is possible that nitrification may not have been sustainable if this depended only on the nitrifiers that grew in the full-scale plants themselves.

5.5.1.3 Effluent concentrations

Figure 5.43 below gives a comparison of the overall average effluent concentrations of Module A and the lab-scale system. It can be seen that the effluent COD, TKN and FSA concentrations were all higher for Module A. This is expected as Module A had inadequate aeration during most of the investigation as noted in Section 5.2.2.1. The Module A effluent NO_x was, as expected, lower than the lab-scale system, because of simultaneous denitrification in the aerobic reactor. Figure 5.43 shows that the effluent soluble P concentration is significantly higher in the lab-scale system (8 mgP/ℓ compared with 3 mgP/ℓ). This is unexpected as the anoxic nitrate concentration is lower in the lab-scale system leading to a lower nitrate recycle to the anaerobic reactor. This should have led to higher biological P removal in the lab system resulting in lower effluent P concentrations than Module A. This is examined further in Sections 5.5.4 and 5.5.5 below.

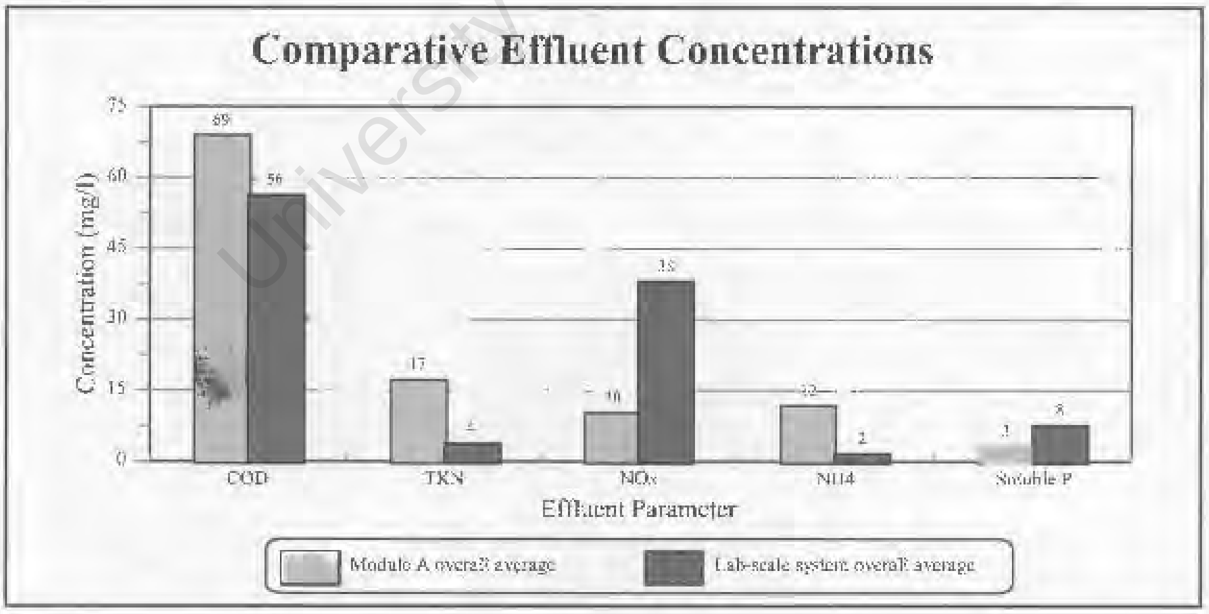


Figure 5.43 : Comparison between overall average effluent concentrations for Module A and lab-scale system.

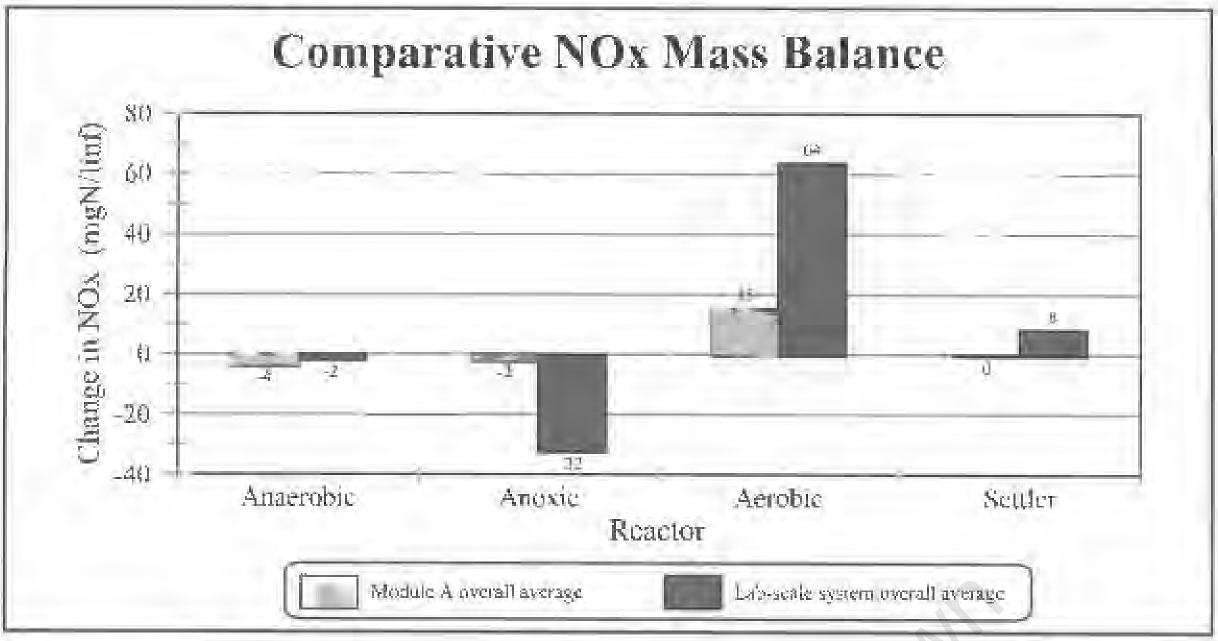


Figure 5.44 : Comparison between overall average NO_x mass balances accross various reactors and SST for Module A and lab-scale system.

5.5.2 Comparison of N Mass Balance

One of the principal aims of operating the parallel lab-scale UCT system was to determine the reasons for the poor N mass balances in the full-scale plants (Modules A and B).

5.5.2.1 <u>NO_x mass balance around reactors</u>

To determine the overall average net nitrification and denitrification, NO_x mass balances were calculated around each reactor and SST of the lab-scale system. Figure 5.44 shows the mass balances for Module A and the lab-scale system; +ve values indicate nitrification and -ve values denitrification. It can be seen that on average small amounts of denitrification occurred in the anaerobic reactors indicating some nitrate recycling via the 'r-recycles'. As expected in the lab-scale system most of the denitrification occurred in the anoxic reactor and most of the nitrification in the aerobic reactor of the lab-scale system. Significant nitrification also occurred in the SST. On average over the 163 day investigation the net nitrification in the lab-scale SST accounted for 11 % of the total system nitrification. However, for Module A the net anoxic denitrification was very small due to excessive DO ingress (as noted in Section 5.3.2.2) and "nitrification" low in the aerobic reactor due to inadequate aeration and simultaneous denitrification. From Figure 5.44 it can be seen that the overall average total denitrifcation (sum of -ve values) for Module A was a mere 6 mgN/ℓ influent compared to the lab-scale system's 34 mgN/ℓ influent.

5.5.2.2 N mass balance

Table 5.19 gives a comparison between the Module A and lab-scale system N mass balance. From Table 5.19 it is evident that very good N mass balance was achieved in the lab-scale system (99 %). In contrast the Module A N mass balance was very poor for reasons already discussed. It can be seen that in the investigation overall for both systems, the largest contribution to the N mass balance is the N in the final effluent. However, the lab-scale system's contribution was significantly higher due to the higher effluent NO_x measured (see Section 5.5.1.3). Thus it is expected that the total NO_x denitrified should be significantly lower in the lab-scale system. However, from Table 5.19 it can be seen that the opposite was observed. The lab-scale system's contribution to the N mass balance as NO_x denitrified was more than 26 % higher than Module A. To examine this further the N removal and effluent N is compared below.

Table 5.19: Comparison of overall average N mass balance.

System Overall Average	N in Influent	N in Waste	N in Effluent	Total NO_x Denitrified	% N Recovery
Module A (kg/d)	157.7	27.1	41.8	21.0	57.0
Module A component (%)	100.0	17.2	26.5	13.3	57.0
Lab system (mg/d)	2050.8	274.2	952.0	811.4	99.4
Lab system component (%)	100.0	13.4	46.4	39.6	99.4

" Total refers to the sum of the denitrification in all the reactors and SST.

5.5.3 Comparison of N Removal and Effluent N

In Section 5.2.3 two possibilities were identified as the causes of the low N mass balances for the full-scale plants *viz.*

(1) Simultaneous nitrification/denitrification

(2) Error in nitrate analysis

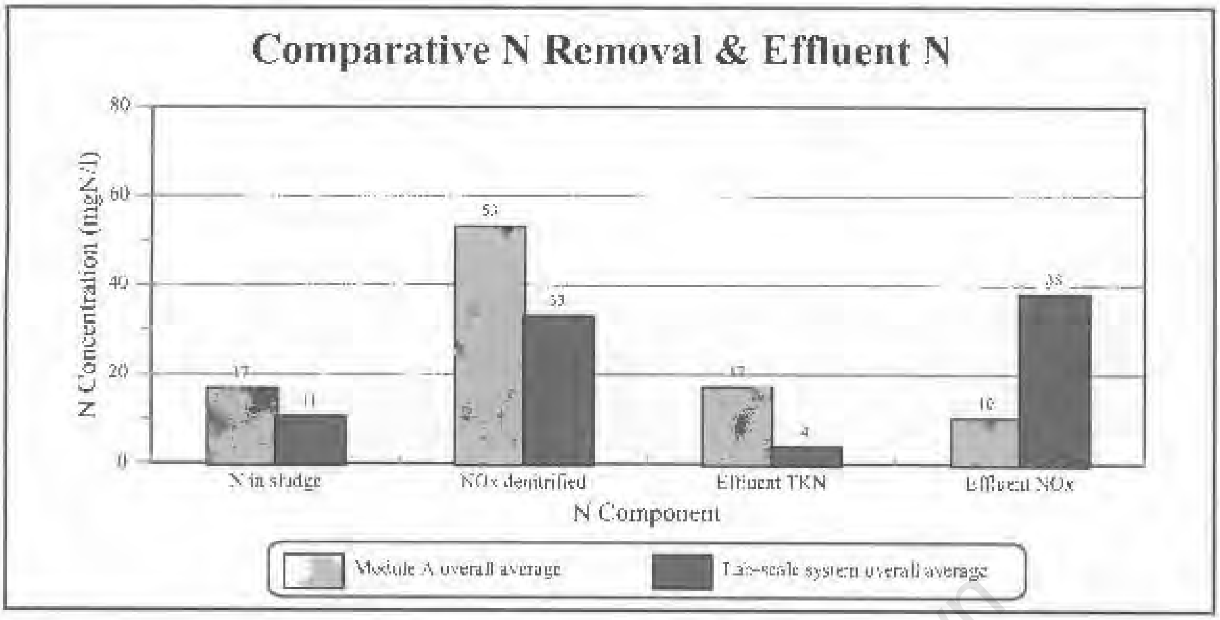


Figure 5.45 : Comparison between overall average N removal and effluent N as concentrations for Module A and lab-scale system.

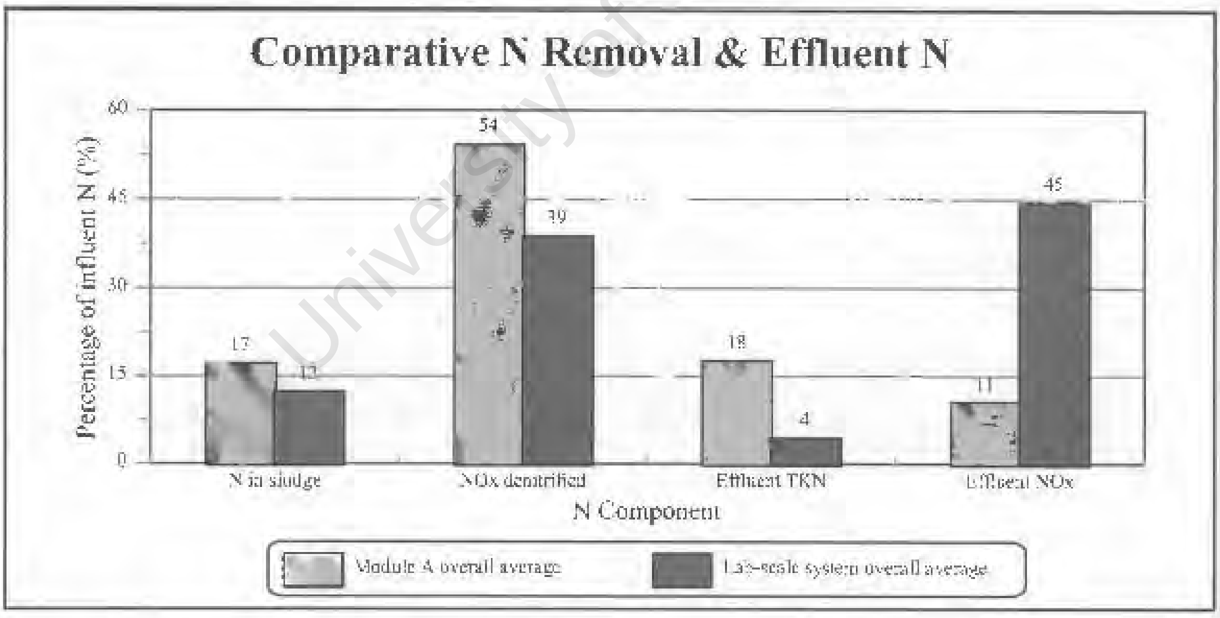


Figure 5.46 : Comparison between overall average N removal and effluent N as percentage of influent N for Module A and lab-scale system.

In order to determine which of the two possibilities was the most likely cause of the poor N mass balances in the full-scale plants, the N removal and effluent N of Module A and the lab-scale system are compared. Accepting a 100% N mass balance in both systems, the components of the overall average N removal and effluent N as concentrations and percentages of the influent are shown plotted above in Figures 5.45 and 5.46 respectively. From these figures it can be seen that the N in the sludge is slightly higher in Module A. The high TKN in the effluent of Module A is as a result of the poor nitrification performance caused by inadequate aeration. As expected the effluent NO_x is lower in Module A than the lab-scale system. However, as mentioned above, the magnitude of the difference (38 - 10 = 28 mgN/ℓ) is exceptionally large; for Module A the effluent NO_x component is 11 % of the influent N whereas for the lab-scale system the effluent NO_x component is significantly higher at 45 % of the influent N. From Figure 5.46 it can be seen that for the total NO_x denitrified (calculated by difference of the sum of the effluent components and the N in the sludge from the influent N), the NO_x denitrified for Module A was 54 % of the influent N whereas for the lab-scale system it was only 39 % of the influent N. Setting the NO_x denitrified for Module A the same as the lab-scale system (at 39 % of the influent N), the effluent NO_x as a percentage of the influent N for Module A is increased from 11 to 26 %.

5.5.4 Comparison of Soluble P Mass Balance around Reactors and SST

Figure 5.47 below shows the difference in P release/uptake between Module A and the lab-scale system. It can be seen that the P release in the anaerobic reactor of Module A was significantly higher than the lab-scale system (26 vs 11 mgP/ℓ influent). In the SSTs divergent behaviour was observed. A small amount of P release was observed in Module A and a small amount of P uptake in the lab-scale system. The anoxic P uptake was seemingly higher in Module A than the lab-scale system (18 vs 4 mgP/ℓ influent). However, as noted in Section 5.3.2.2 the apparent occurrence of anoxic P uptake could best be explained as a result of excessive DO ingress into the Module A anoxic reactor. Thus for Module A the circumstantial (and experimental) evidence suggest P uptake by PAOs under <u>aerobic</u> conditions rather than under <u>anoxic</u> conditions. The P uptake in the aerobic reactor was significantly larger in Module A than the lab-scale system (19 vs 10 mgP/ℓ influent).

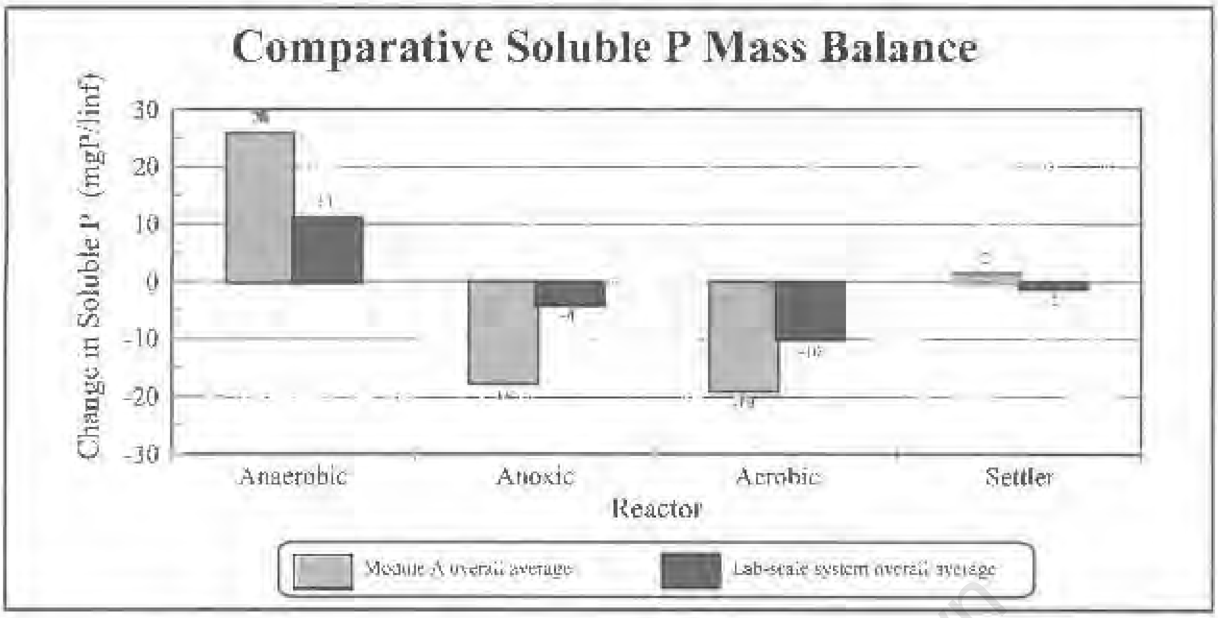


Figure 5.47 : Comparison between overall average soluble P mass balance across reactors and SST of Module A and lab-scale system.

The average anoxic nitrate + nitrite concentration of the lab-scale system was much lower than Module A (2.1 vs 5.53 mgN/ℓ). With this larger mass of nitrate recycled to the anaerobic reactor of Module A via the 'r-recycle', in addition to the generally poor Module A aeration which negatively affected P uptake , it is expected that the measured P removal of Module A would be considerably smaller than the lab-scale system. In contrast, the measured P removal was greater in Module A than in the lab-scale system (10.0 vs 3.8 mgP/ℓ influent).

5.5.5 Comparison of Calculated versus Measured P Removal

In Section 5.5.1.3 above, it was noted that the effluent soluble P concentration was significantly higher in the lab-scale system compared with Module A (*i.e.* 8 mgP/ℓ compared with 3 mgP/ℓ). Another reason for operating the parallel lab-scale UCT system was to determine the differences in BEPR behaviour between the lab system and the full-scale plants that led to this big difference in effluent P concentrations. Table 5.20 below gives the comparison between the calculated P removal (using the BEPR model of Wentzel *et al.*, 1990) of the lab-scale system and Module A. A spreadsheet of the daily "UCT" calculated vs measured P removal is given in Appendix G.

Table 5.20: Comparison of overall average calculated P removal.

System Overall Average	S_{bsi} (mgCOD/ℓ)	$f_{S,us}$	$f_{S,up}$	**P Removal** (mgP/ℓ infl)	$f_{av,OHO}$	$f_{av,PAO}$	$f_{XBG,P}$
Lab System	#148.6	0.086	0.03	8.32	0.419	0.163	0.231
Module A	217.3	0.086	*0.05	13.83	0.359	0.185	0.396

* The more reasonable value of 0.05 is used instead of the calculated value of 0.239. This value is also appropriately larger than the lab-scale system's 0.03 because of the lower influent COD fed to the lab system due to maceration and straining to avoid blockages in the lab system. # When calculating the theoretical BEPR, the influent RBCOD was reduced proportionately to the total influent COD concentrations.

From Table 5.20, it can be seen that $f_{av,OHO}$ and $f_{av,PAO}$ fractions are greater and smaller respectively in the lab-scale system than Module A. It can be seen that the calculated P removal and the $f_{XBG,P}$ fraction are significantly lower in the lab-scale system than Module A. In Section 5.5.4 above, it was noted that P release in the anaerobic reactor, P uptake in both the aerobic and anoxic reactors and the measured P removal were significantly smaller in the lab-scale system than Module A. Also, the total P uptake (sum of the P uptake in the anoxic and aerobic reactors) in Module A was considered aerobic uptake BEPR. In contrast, the lab-scale system exhibited anoxic uptake BEPR (29 % of P uptake took place in the anoxic reactor). The differing P release, uptake and removal of the two systems is consistent with the observation that when significant anoxic P uptake is observed, the P release, P uptake and P removal are all lower than with predominantly aerobic P uptake BEPR. In earlier lab-scale investigations in which significant anoxic P uptake was observed, Musvoto *et al.* (1992), Mellin *et al.* (1995) and Pilson *et al.*(1995) found the $f_{XBG,P}$ fraction to be 0.144, 0.280 and 0.136 respectively. Comparing the overall average $f_{XBG,P}$ value of 0.231 mgP/mgPAOAVSS found for the lab-scale system with that obtained for the full-scale plants (0.396 mgP/mgPAOAVSS) and in earlier lab-scale investigations, it can be seen that $f_{XBG,P}$ is lower when anoxic P uptake is observed than when aerobic P uptake is observed.

Also, the lower COD concentration in the influent to the lab-scale system resulting in a higher influent TP/COD ratio than that of the full-scale plants (0.026 versus 0.022 mgP/mgCOD) which affects the percentage P removal achieved by the BEPR system, contributed somewhat to the lower P removal obtained for the lab system, but the greatest contributing factor was the anoxic

P uptake BEPR behaviour in the lab system. It should be noted that the poor sludge settleability is not likely to be associated with the anoxic uptake BEPR compared with the aerobic uptake BEPR in the full-scale plants because poor sludge settleability (DSVI > 250 mℓ/g) due to AA filaments like *M. parvicella*, has been often observed in lab systems with predominantly aerobic P uptake BEPR (*e.g.* Clayton *et al.*, 1989) and good sludge settleability (DSVI < 60 mℓ/g) in systems with high anoxic P uptake BEPR (*e.g.* Hu *et al.*, 2001).

5.6 24 HOUR TESTS ON THE FULL-SCALE PLANTS

On days 326 to 327 and 344 to 345 of the investigation, Modipa and Diale (2000) did two separate 24 hr tests on influent, reactor and effluent samples of the full-scale plants (Modules A and B). The main objectives of these tests were (i) to measure oxygen utilisation rates (OUR) in order to calculate COD mass balances and (ii) to determine the variations in the influent, reactor and effluent concentrations over a day (24 hr period) for the full-scale plants. A summary of their more important results is given in Table 5.21 below. It can be seen that the average (Modules A & B) COD mass balances were very poor on both occasions (varying between very high- 150 % and very low- 44 % for the first and second tests respectively) mainly due to uncertainty in the OUR measurements and the extent of sludge ingress from the main treatment plant. Clearly the OUR of the first 24h test is much too low to be realistic, and therefore the sludge ingress must have been high at this time to make the COD balance > 140 %. Then when the OUR is high, the COD balance is low. The mass balance calculations are based on the unaerated and aerated reactors receiving zero and sufficient oxygen. The fact that this was not the case in the full-scale plants also distorts the COD mass results. It can also be seen that the average estimated $f_{S,up}$ value on both occasions were very high (0.384 and 0.771) due to the substantial sludge back flow problems already mentioned. The average N mass balances (83 and 74 %) were also low due to the simultaneous nitrification-denitrification in the aerobic reactors of the full-scale plants.

The most important outcome of the 24h tests is that the Module A and B influent, reactor and effluent concentrations were fairly constant over the 24 hr periods indicating that the single grab samples taken from the reactors in the "site" data set (see Table 4.4) can be considered representative of the concentrations in the reactors for that day. Graphs showing the profiles of the reactor concentrations over the 24 hr periods are given in Appendix J.

Table 5.21: Summary of OUR and mass balance results for the 2 x 24hr tests.

24 hr Test	Module	OUR (mgO/ℓ/h)	N balance (%)	COD balance (%)	$f_{S,up}$
First Day 326-327	A	13.35	77	159	0.306
	B	8.94	88	140	0.462
Second Day 344-345	A	59.28	97	38	0.735
	B	56.25	51	49	0.806

5.7 SIMULATION OF THE FULL-SCALE PLANTS

Over the past two decades activated sludge (AS) systems have been successfully designed and operated at full-scale, progressively including the biological removal of carbon (C), nitrogen (N) and phosphorus (P). The implementation of these advances has been aided by the development of a number of steady-state models (*e.g.* WRC, 1984; Wentzel *et al.*, 1990; Maurer *et al.*, 1994) and kinetic simulation models (*e.g.* Dold *et al.*, 1980; Van Haandel *et al.*, 1981; Henze *et al.*, 1987; Wentzel *et al.*, 1992; Henze *et al.*, 1995).

All activated sludge models (the equations) which include nitrification-denitrification and BEPR (NDBEPR) have their basis on that Wentzel *et al.* (1992). This model has been coded into a Pascal computer programme called *UCTPHO*. Other models such as ASM N° 2 or 2d (Henze *et al.*, 1995) and that of Barker and Dold (1997) are modifications/additions to the Wentzel *et al.* one. When using a NDBEPR computer programme it is important to know which model has been included in it. In some instances the changes in the models are significant and have a major influence on the simulation results. Differences in the models hinge around two main areas :

(1) The denitrification ability of the PAOs. In the Wentzel *et al.* and IWA N° 2 models, the BEPR is based on 100 % aerobic P uptake, whereas the IWA ASM 2d and Barker and Dold (1997) models include anoxic and aerobic P uptake; the first two models were validated with a substantial data set including enhanced cultures of aerobic uptake PAOs; however, the validation of ASM 2d and Barker & Dold models are uncertain in particular in respect of anoxic uptake BEPR and the heterotrophic denitrification rates in the anoxic reactors.
(2) The fermentation process of RBCOD to volatile fatty acids (VFA) in the anaerobic reactor. In the Wentzel *et al.* and ASM 2 and 2d models (as well as the Dold *et al.*, 1980 and IWA ASM N° 1, Henze *et al.*, 1987 models for ND systems), no COD loss takes place under anaerobic conditions (*i.e.* zero nitrate and DO) in the anaerobic fermentation of RBCOD to VFA, whereas in the Barker & Dold model COD is lost in this process. This loss of COD results in a lower BEPR so to increase the predicted P removal a hydrolysis of slowly biodegradable COD to RBCOD process is included in the model. This process and its magnitude has little experimental support and is primarily based on matching the predicted and observed P removals when allowing loss of RBCOD under anaerobic conditions.

The various models have been coded into computer programmes. As mentioned above, the Wentzel *et al.* model is coded into a programme called *UCTPHO*. Frequently used programmes are ASIM 2.2 (Gujer, 1995) and Aquasim (Reichert, 1998). These two programmes are "shell" packages which allow programming into them, both the model of ones choice or making and system to be simulated. The Barker and Dold model is commercially available as *BIOWIN* (Envirosim & Associates, Canada, 2001). Other activated sludge simulation programmes available are SIMBA (Otterpöhl, Germany) and GPX (Hydromantes, Canada). As mentioned above, it is vitally important to know and understand the details of the model included in the package being used. In this investigation, *UCTPHO* and *BIOWIN* are used and compared as characteristic of COD conservative - 100 % aerobic P uptake - COD loss and anoxic/aerobic P uptake models respectively.

While using *BIOWIN* (latest *BIOWIN32* release, 2001) for the modelling of the full-scale plants for each of the steady state periods (see Table 4.1), it was found that the steady-state solver in *BIOWIN* produced solutions that could not be considered theoretically valid. These spurious results were first noted by De Haas *et al.* (2001) in *BIOWIN* (earlier *BIOWIN32* release, 1998), *viz.* :

- PAO biomass "washed out" (zero PAO biomass in the steady-state solution leading to zero BEPR and no uptake of RBCOD in the anaerobic reactors - the anaerobic S_{bs} concentration equal to influent concentration, after accounting for the dilution effect due to the 'r-recycle').

This problem was solved by running the dynamic simulation with constant influent flow (and therefore load) which produced a "dynamic steady-state" solution that was different from the steady-state solver solution and consistent with that expected from steady state theory - it appears that the "dynamic steady-state" solution is derived mathematically independently of the steady-state solver. Two other aspects also noted by De Haas *et al.* (2001) were mentioned above, but bear repeating:

- Large COD losses (via fermentation in anaerobic reactor), leading to lower VSS production and OUR and a low COD mass balance (80-90%) and,
- High denitrification rates in the anoxic reactor (1998 version).

In this section it was proposed to examine the effect of COD mass loss, by comparing experimental data to simulated performance with *UCTPHO* (no COD loss) and *BIOWIN* (COD loss included).

5.7.1 Comparison of sludge production, OUR and COD loss in the default *BIOWIN* and *UCTPHO*

While using *BIOWIN* and *UCTPHO* for modelling the full-scale plants, it was found that the *BIOWIN* simulations with the default settings for model parameters produced results which were significantly at variance with the *UCTPHO* model results for the identical (or closely similar) design and operating system set-up. De Haas *et al.* (2001) lists the detailed differences in model structure of *BIOWIN* and *UCTPHO*. De Haas *et al.* noted that one of the major differences between *BIOWIN* and *UCTPHO* was the COD mass balance issue. The *UCTPHO* model is based on 100 % COD mass balance whereas the default *BIOWIN* model (when an anaerobic processes are included) includes COD losses (and is therefore based on a lower COD mass balance). This inclusion of COD losses leads to significantly lower predictions of sludge VSS production and oxygen utilisation rates (OUR). Hence, the default *BIOWIN* model parameters were adjusted to eliminate as much as possible this COD loss so as to closely emulate the *UCTPHO* model parameters (see De Haas *et al.*, 2001; Wentzel *et al.*, 2002).

Table 5.22 below gives a comparison of the sludge production, OUR and % COD recovery for the *UCTPHO* and default *BIOWIN* models. In Table 5.22, full-scale plant Long Term Periods VII and VIII were chosen for the illustration, as considerable problems with sludge wasting from the full-scale plants occurred in the earlier stages of the investigation (see Section 4.1). It can be seen that using the default settings, *BIOWIN* predicted on average approximately 14 % less sludge production, relative to *UCTPHO*. The difference in VSS prediction between the models is attributed directly to the inclusion of the COD losses. It can also be seen that the VSS predictions with *UCTPHO* are slightly closer to the measured values than the default *BIOWIN* predictions but it is known that the measured VSS values are too high due to the sludge ingress problems. Table 5.22 shows that the OUR predictions using the default *BIOWIN* were consistently lower than *UCTPHO* predictions. On average the OUR was about 24 % lower for the default *BIOWIN* predictions, relative to *UCTPHO* predictions. Finally, it can be seen that, as expected, 100 % COD mass balances were obtained from the *UCTPHO* model predictions. This was clearly not the case with the default *BIOWIN* predictions which gave COD mass balances of 79 to 93 %, due to the incorporation of COD loss mechanisms explicitly in the model.

Table 5.22 : Comparison of *UCTPHO* and the <u>default</u> *BIOWIN* predictions for the VSS, TSS, OUR and % COD recovery of the full-scale plants (Modules A and B).

Long Term Period	Module A									
	VSS (mgVSS/ℓ)			TSS (mgTSS/ℓ)			*OUR (mgO/ℓ.h)		COD bal. (%)	
	Measured	*UCTPHO*	*BIOWIN* default	*Measured*	*UCTPHO*	*BIOWIN* default	*UCTPHO*	*BIOWIN* default	*UCTPHO*	*BIOWIN* default
VII	2593	2841	2365	3343	3663	3085	56.8	39.0	100	79
VIII	2702	3163	2689	3626	4245	3891	64.7	46.5	100	83
Long Term Period	**Module B**									
	VSS (mgVSS/ℓ)			TSS (mgTSS/ℓ)			*OUR (mgO/ℓ.h)		COD bal. (%)	
	Measured	*UCTPHO*	*BIOWIN* default	*Measured*	*UCTPHO*	*BIOWIN* default	*UCTPHO*	*BIOWIN* default	*UCTPHO*	*BIOWIN* default
VII	2580	2332	2114	3330	3010	2873	47.9	33.7	100	84
VIII	2249	2345	2015	3012	3140	2828	49.1	45.7	100	93

* The OUR in the aerobic reactors of the full-scale plants could not be measured because of the non-steady state conditions.

Examining this COD loss more closely shows that the <u>default</u> *BIOWIN* model settings incorporate two COD loss mechanisms :

(1) In the anaerobic fermentation process, *BIOWIN* includes an empirical factor for COD loss and assumes that only a portion of fermentation products is short chain fatty acids (SCFA), the remainder is lost from the system. The stoichiometric constant regulating this COD loss in *BIOWIN* is Y_{AC} (*i.e.* fermentation yield);
(2) Of the the SCFA sequestered in the anaerobic reactor by the polyphosphate accumulating organisms (PAOs), only a fraction appears as poly-β-hydroxybutyrate (PHB), the balance assumed lost from the system. The stoichiometric constant regulating this COD loss in *BIOWIN* is Y_{PHB} (*i.e.* PHB yield upon sequestration).

De Haas *et al*. noted that in the end these COD loss mechanisms in *BIOWIN* do not significantly affect the PAOs, because an anaerobic hydrolysis process of slowly biodegradable COD to RBCOD compensates for this COD. The model therefore transfers the COD loss onto the ordinary heterotrophic organisms (OHOs). Thus, the net effect of the COD loss in *BIOWIN* is to reduce the slowly biodegradable COD (SBCOD) concentration available for growth of the OHOs. In turn, the reduction in OHO active mass is partly compensated for by a reduced heterotrophic cell yield under anoxic conditions, which increases the specific denitrification rate. Of these changes, the most theoretically and experimentally validated one is the reduced anoxic yield. With regard to the anaerobic COD loss, this has been frequently observed in lab-scale NDBEPR experimental systems, but the electron acceptors for this COD loss have not been found yet after a decade of research. So while COD loss is substantiated, there is no theoretical basis for it yet. To check if this takes place at large scale was one of the objectives of this investigation but unfortunately could not be achieved due to sludge wastage problems at the plant. Because the COD loss is unsubstantiated at large scale and can lead to considerable under-design of reactor tankage and oxygen supply, it is recommended that COD losses not be included in the model until a better understanding of the phenomenon of COD loss in NDBEPR systems emerges. This is the principal reason why COD loss is not included in *UCTPHO*. Therefore, in the adjusted *BIOWIN* model settings, the COD loss mechanisms were eliminated by setting both **Y_{AC} and Y_{PHB} equal to unity**.

5.7.2 Comparison of reactor denitrification rates in the default *BIOWIN* and *UCTPHO*

In earlier versions of *BIOWIN*, the reactor denitrification rates for ordinary heterotrophic organisms (OHOs) in the default case for *BIOWIN* were significantly higher compared with *UCTPHO*. In the latest release of *BIOWIN* (2001, which was used in this investigation to simulate the full-scale plants) the OHO denitrification rates were reduced to more closely conform to the denitrification rates in the *UCTPHO* model. However, as mentioned earlier, *BIOWIN* (based on the Barker & Dold model) includes anoxic P uptake (and associated denitrification by PAOs) whereas *UCTPHO* does not. De Haas *et al*. (2001) noted that *BIOWIN*, under anoxic conditions applied a neta term (η_p) to the aerobic PAO growth expression. The neta term conceptually represents the proportion of PAOs in the system capable of growing under anoxic conditions. De Haas *et al*. and Hu *et al*. (2001) noted that the contribution of the PAOs to denitrification is small (~10 % of the total reactor denitrification rate) even with significant anoxic P uptake and that biological N removal is relatively insensitive to the value for η_p (*i.e.* the fraction of PAOs that denitrify). Nevertheless, in the simulation of the full-scale plants using the adjusted *BIOWIN* the contribution of the PAOs to denitrification was eliminated by "switching off" anoxic P uptake by setting η_p **equal to zero**.

With the above-mentioned changes made, the adjusted *BIOWIN* (used in the simulation of the full-scale plants) therefore very closely emulates the *UCTPHO* model with no significant differences between the two models.

5.7.3 Comparison of measured values with the default and adjusted *BIOWIN* predictions

Tables 5.23 and 5.24 below, give comparisons of the measured effluent values with the default and adjusted *BIOWIN* model results for Modules A and B respectively. Similarly, Tables 5.25 and 5.26 below, give comparisons of the measured sludge production with the default and adjusted *BIOWIN* model results for Modules A and B respectively. A comparison of the default and adjusted *BIOWIN* OUR results is also given in Tables 5.25 and 5.26. From Tables 5.25 and 5.26 with the exception of Long Term Period IV, Module A, lower sludge production in terms of reactor VSS (and TSS) is obtained with the default *BIOWIN* model. For some long term periods, the measured VSS (and TSS) are significantly greater than both sets of predicted values. Again, as mentioned above this can be attributed to the inadequate sludge wasting from the full-scale plants particularly in the earlier stages of the investigation. Also, with the exception of Long Term Period IV, Module A, the oxygen utilisation rates (OUR) are lower with the default *BIOWIN* model.

From Tables 5.23 to 5.26 it can be seen that, in general, the combination of results obtained from the *BIOWIN* simulations using the adjusted model parameters were closer to the measured data than the default *BIOWIN* simulation results. However, a good correlation was never expected and certainly was not obtained due to the sludge wastage and aeration difficulties experienced in the full-scale plants. The simulation results nevertheless have value because (i) it gives an indication of the full-scale plants results under "ideal" conditions (*i.e.* anoxic and aerobic reactors are indeed functioning as such) and (ii) compares the two NDBEPR models with and without COD conservation and anoxic P uptake kinetics.

5.7.4 Comparison of measured effluent and reactor parameters with the adjusted *BIOWIN* and *UCTPHO* predictions.

Figures 5.48 to 5.55 and Tables 5.27 & 5.28 below, show the measured versus predicted (using the adjusted *BIOWIN* and *UCTPHO* models) effluent and reactor parameters for each steady state period (I to VIII). More detailed comparisons between measured and predicted values (*BIOWIN* and *UCTPHO*) are given in Appendix K.

5.7.4.1 Effluent parameters

From Figures 5.48 to 5.55 it can be seen that :

- There is a reasonably good correlation between the measured and predicted S_{us} and FSA concentrations. The S_{us} was achieved by using the calculated $f_{S,us}$ values (see Section 5.1.2) as input to the programmes. The FSA was achieved by inputting the DO (for each long term period) and adjusting the autotroph half-saturation constants ($K_{S,O2}$ in *UCTPHO* set between 0.10 and 2.00 and $K_{DO,AUT}$ in *BIOWIN* set to 0.50) of the oxygen switching functions.
- With the exception of Long Term Period I, for both modules, the predicted effluent NO_3 concentrations were consistently higher than the measured values. This was due to significant aerobic denitrification which occurred in both modules (see Section 5.2.2.4) whereas in the model this did not take place to any significant degree. One can induce it with the switching functions but this was not done.
- For the effluent Ortho P concentrations, a reasonably good correlation between measured and predicted values was obtained for Long Term Periods I to III, V and VIII. The *BIOWIN* model predictions for the effluent Ortho P concentrations (linked to the system P removal) are greatly affected by the accuracy of the predicted NO_3 recycled from the anoxic to the anaerobic reactor (see below).

Table 5.23 : Comparison of measured effluent data with the default and adjusted *BIOWIN* model simulation results for Module A.

Long Term Period	Effluent S_{us} (mgCOD/ℓ)			Effluent FSA (mgN/ℓ)			Effluent NO_3 (mgN/ℓ)			Effluent PO_4 (mgP/ℓ)		
	"Site"	*BioWin* Default	*BioWin* Adjust.	"Site"	*BioWin* Default	*BioWin* Adjust.	"Site"	*BioWin* Default	*BioWin* Adjust.	"Site"	*BioWin* Default	*BioWin* Adjust.
I	40.11	37.02	40.10	0.30	1.59	0.98	13.00	25.88	14.60	5.01	7.20	4.72
II	32.11	40.98	32.87	1.86	4.56	2.10	12.49	29.85	25.40	1.19	0.51	1.36
III	42.21	57.73	45.03	10.40	7.44	5.77	10.05	35.80	33.54	0.36	0.18	0.71
IV	120.89	48.37	76.08	61.80	65.58	65.91	0.49	0.21	0.02	6.91	6.34	0.18
V	63.00	78.47	63.88	24.23	2.21	23.64	1.62	16.88	10.02	1.47	0.15	0.25
VI	47.73	69.10	52.18	4.30	3.85	5.75	14.10	30.96	32.63	3.81	0.10	0.40
VII	59.06	76.41	69.18	3.15	10.44	9.29	15.27	34.74	32.80	4.85	0.18	0.19
VIII	65.62	90.29	79.24	4.95	11.28	10.00	12.52	38.25	36.34	1.98	0.20	0.23

Note: S_{us} - unbiodegradable soluble COD, FSA - free and saline ammonia, NO_3 - nitrate, PO_4 - orthophosphate.

"Site" - measured "site" effluent data for Module A.

BioWin default - *BIOWIN* using the default kinetic and stoichiometric model constants

BioWin adjust. - *BIOWIN* using adjusted kinetic and stoichiometric model constants of De Haas *et al*. (2001) and Wentzel *et al*. (2002).

Table 5.24 : Comparison of measured effluent data with the default and adjusted *BIOWIN* model simulation results for Module B.

Long Term Period	Effluent S_{us} (mgCOD/ℓ)			Effluent FSA (mgN/ℓ)			Effluent NO_3 (mgN/ℓ)			Effluent PO_4 (mgP/ℓ)		
	"Site"	*BioWin* Default	*BioWin* Adjust.	"Site"	*BioWin* Default	*BioWin* Adjust.	"Site"	*BioWin* Default	*BioWin* Adjust.	"Site"	*BioWin* Default	*BioWin* Adjust.
I	35.88	36.72	38.69	0.60	1.61	0.95	14.60	25.98	15.77	5.22	7.46	4.82
II	33.42	31.18	31.96	0.68	0.92	1.92	15.79	22.33	24.86	3.83	9.99	1.78
III	47.41	54.47	42.85	2.37	3.54	1.17	16.25	31.66	20.99	1.30	0.46	1.22
IV	48.67	58.34	59.76	1.02	0.78	1.09	13.57	24.90	18.34	7.66	0.31	0.49
V	58.29	65.62	60.97	5.20	6.18	2.34	13.17	27.11	18.40	3.26	4.37	0.30
VI	57.00	64.94	49.07	1.21	2.22	2.45	16.96	29.05	28.70	3.43	0.24	0.41
VII	79.50	70.76	71.93	28.01	5.92	27.62	7.29	29.58	9.30	2.62	0.59	0.16
VIII	83.54	83.84	78.81	2.78	6.95	5.50	17.16	33.80	31.64	0.78	2.18	0.83

Note: S_{us} - unbiodegradable soluble COD, FSA - free and saline ammonia, NO_3 - nitrate, PO_4 - orthophosphate.

"Site" - measured "site" effluent data for Module B.

BioWin default - *BIOWIN* using the default kinetic and stoichiometric model constants.

BioWin adjust. - *BIOWIN* using adjusted kinetic and stoichiometric model constants of De Haas *et al.* (2001) and Wentzel *et al.* (2002).

Table 5.25 : Comparison of measured ("site" data) sludge production with the default and adjusted *BIOWIN* and *UCTPHO* model results for Module A.

Long Term Period	Aerobic VSS (mgVSS/ℓ)				Aerobic TSS (mgTSS/ℓ)			Aerobic OUR (mgO/ℓ/h)		
	"Site"	*UCT-PHO*	*BIOWIN* Default	*BIOWIN* Adjusted	"Site"	*BIOWIN* Default	*BIOWIN* Adjusted	*UCT-PHO*	*BIOWIN* Default	*BIOWIN* Adjusted
I	3824	2758	2295	2547	4257	2639	3178	48.7	44.3	45.1
II	2621	2223	2058	2312	3604	3266	3460	44.8	42.4	46.0
III	2322	2123	2344	2519	3150	3226	3336	49.0	45.1	51.3
IV	2085	2191	3399	2381	2503	3887	2959	23.3	23.7	20.8
V	3787	3058	2916	3063	5006	3609	3802	46.8	38.7	42.9
VI	2860	3317	2568	2628	3878	3331	3338	64.9	42.7	49.8
VII	2593	2601	2365	2412	3343	3085	3178	57.5	39.0	39.0
VIII	2702	2922	2689	3249	3626	3891	4439	65.3	46.5	49.5

Table 5.26 : Comparison of measured ("site data) sludge production with the default and adjusted *BIOWIN* and *UCTPHO* model results for Module B.

Long Term Period	Aerobic VSS (mgVSS/ℓ)				Aerobic TSS (mgTSS/ℓ)			Aerobic OUR (mgO/ℓ/h)		
	"Site"	*UCT-PHO*	*BIOWIN* Default	*BIOWIN* Adjusted	"Site"	*BIOWIN* Default	*BIOWIN* Adjusted	*UCT-PHO*	*BIOWIN* Default	*BIOWIN* Adjusted
I	5142	2715	2381	2796	5473	3008	3470	48.6	44.5	50.2
II	3146	2213	1863	2301	4082	2597	3431	45.5	45.6	46.7
III	2893	1948	2124	2226	3829	2904	2869	45.3	43.8	47.2
IV	3204	1889	1627	1838	4321	2115	2281	32.5	31.7	33.5
V	2123	2578	2315	2580	2819	2706	3193	44.5	39.8	44.2
VI	2958	2755	2309	2628	3914	3063	3338	49.5	47.4	49.8
VII	2580	2195	2114	2412	3330	2873	3178	40.4	33.7	39.0
VIII	2249	2172	2015	2524	3012	2828	3446	49.7	45.7	49.5

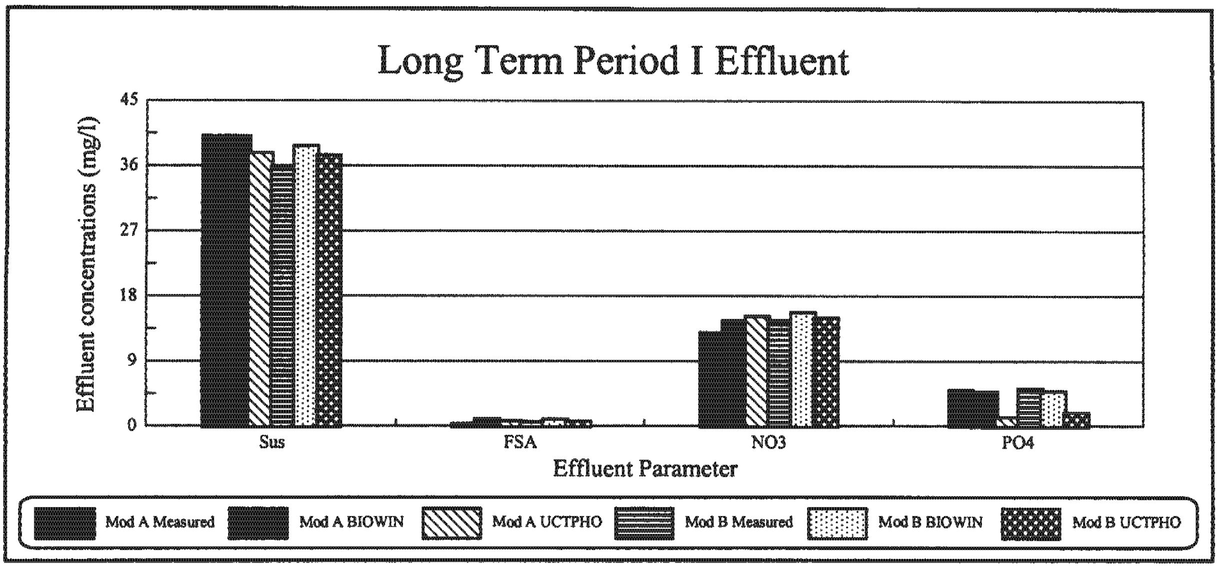


Figure 5.48 : Comparison of measured versus predicted (*BIOWIN* and *UCTPHO*) effluent parameters for Long Term Period I.

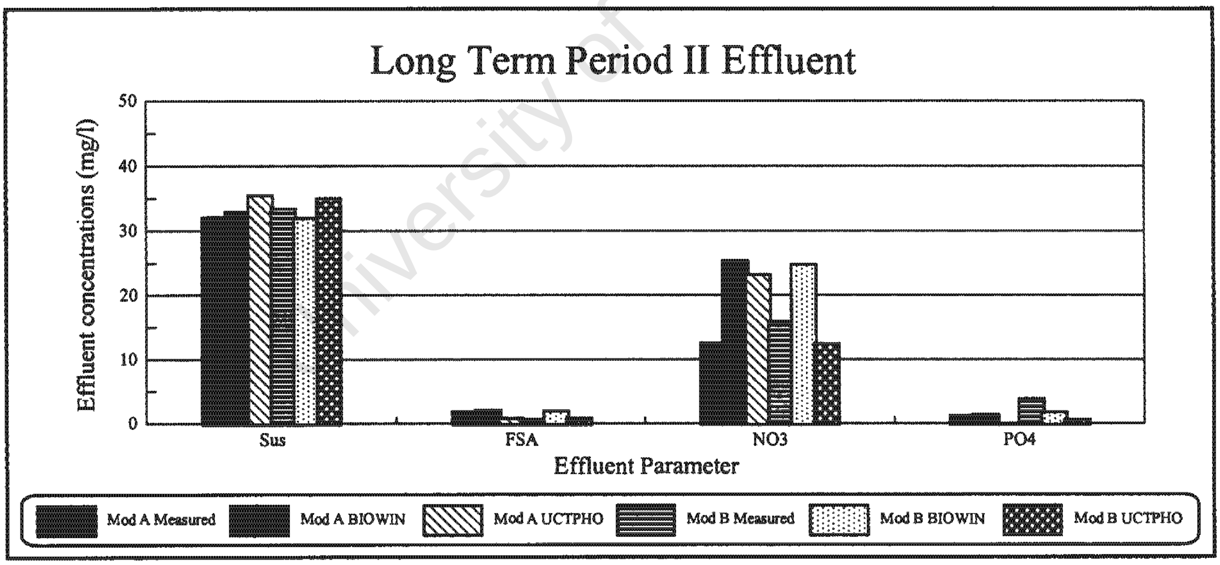


Figure 5.49: Comparison of measured versus predicted (*BIOWIN* and *UCTPHO*) effluent parameters for Long Term Period II.

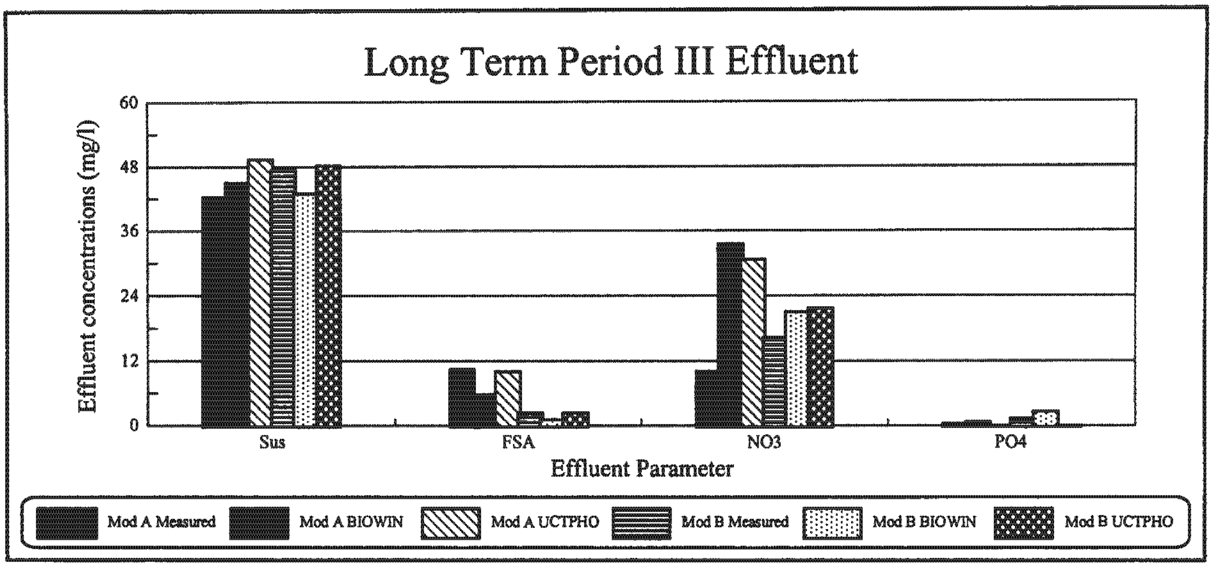


Figure 5.50: Comparison of measured versus predicted (*BIOWIN* and *UCTPHO*) effluent parameters for Long Term Period III.

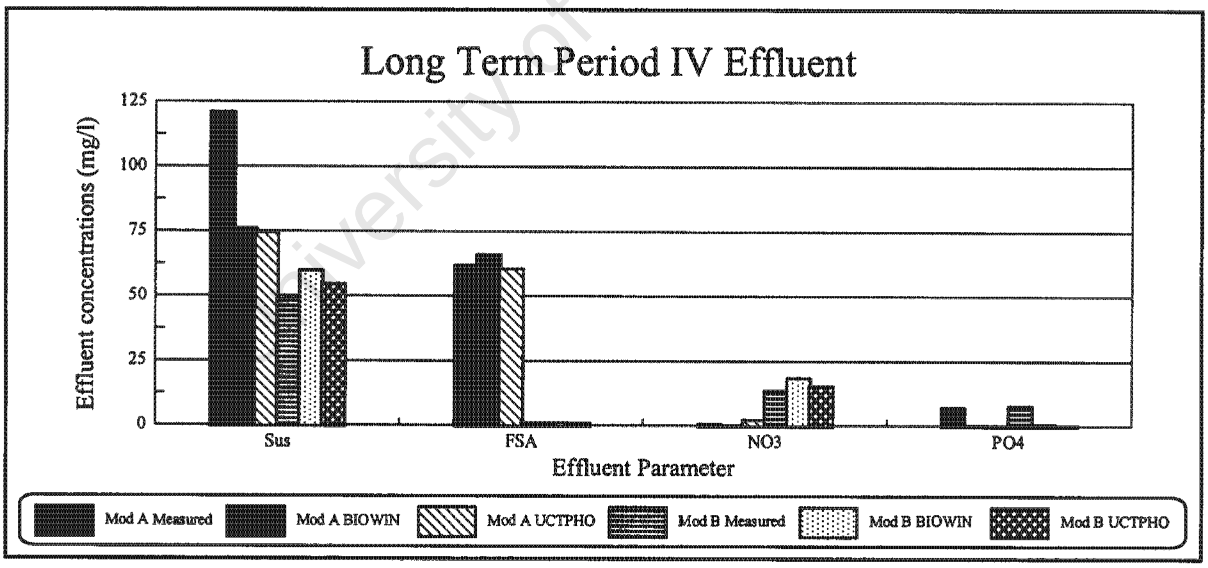


Figure 5.51: Comparison of measured versus predicted (*BIOWIN* and *UCTPHO*) effluent parameters for Long Term Period IV.

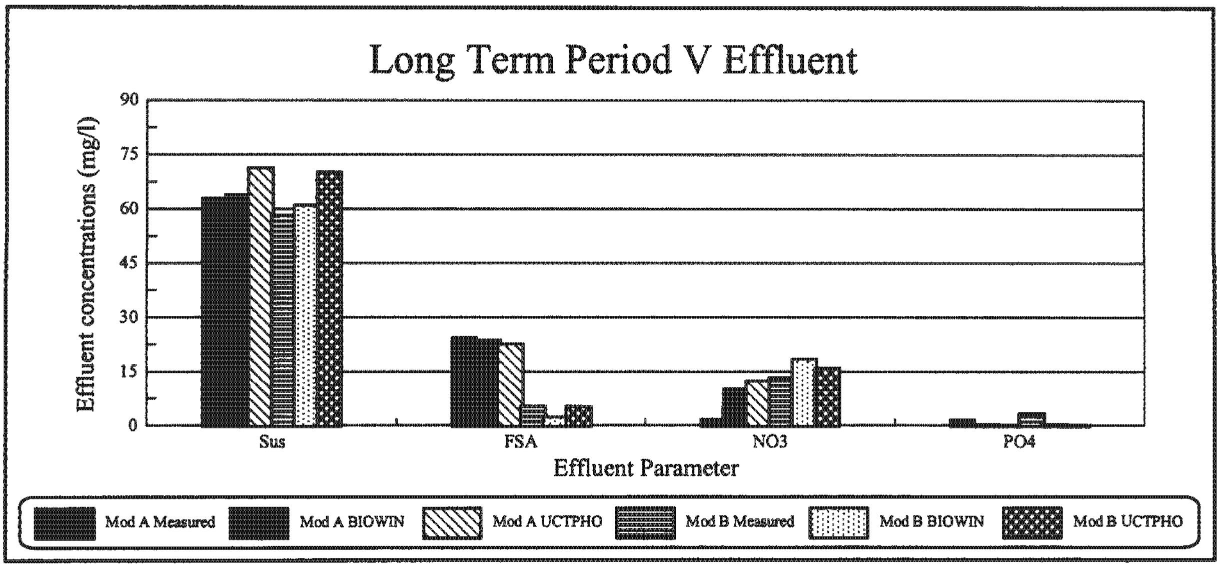


Figure 5.52: Comparison of measured versus predicted (*BIOWIN* and *UCTPHO*) effluent parameters for Long Term Period V.

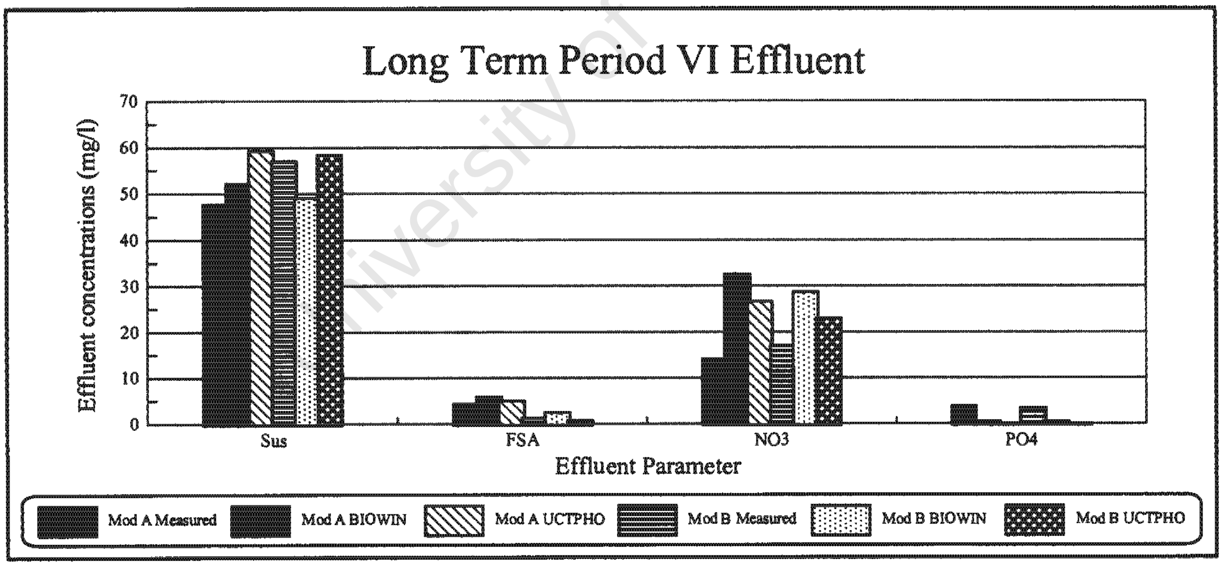


Figure 5.53: Comparison of measured versus predicted (*BIOWIN* and *UCTPHO*) effluent parameters for Long Term Period VI.

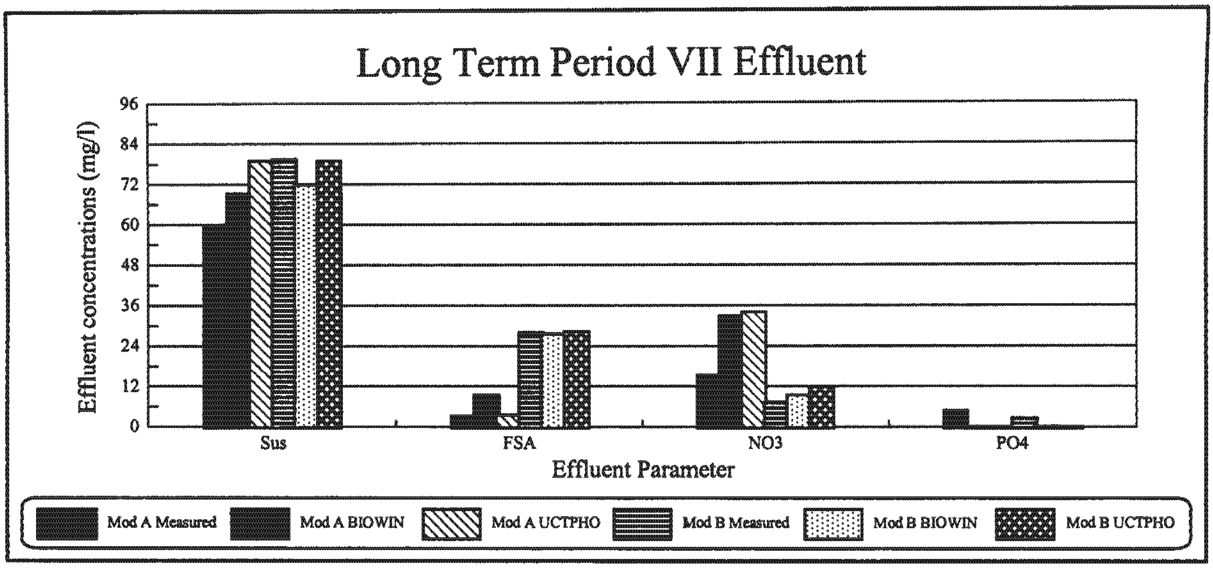


Figure 5.54: Comparison of measured versus predicted (*BIOWIN* and *UCTPHO*) effluent parameters for Long Term Period VII.

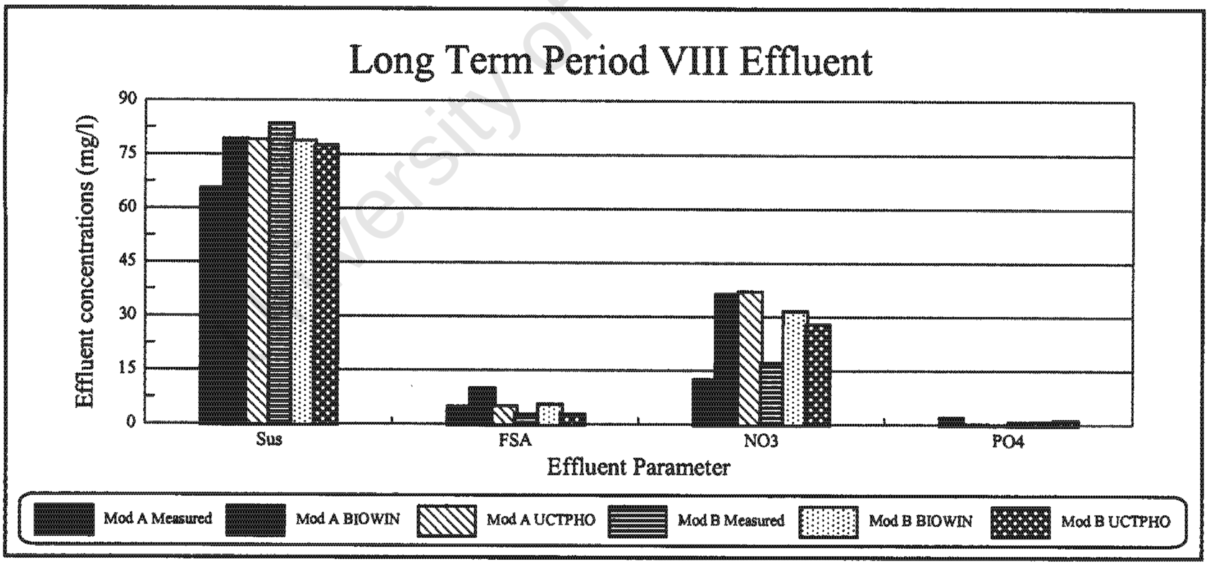


Figure 5.55: Comparison of measured versus predicted (*BIOWIN* and *UCTPHO*) effluent parameters for Long Term Period VIII.

5.7.4.2 Reactor parameters

From Tables 5.27 and 5.28 below, it can be seen that:

- There is a good correlation between the measured and predicted anaerobic NO_3 concentrations. This is not difficult as all NO_3 entering it is denitrified.
- The comparison of the measured and predicted anoxic NO_3 values is inconsistent and varies throughout the long term periods.
- with the exception of Long Term Period VII, Module B, the predicted NO_3 values are consistently higher than the measured.

The poor correlation between the measured and predicted anoxic & aerobic NO_3 concentrations in both modules can be attributed to the poor anoxic denitrification and the significant aerobic denitrification experienced in the full-scale plants.

- With the exception of Long Term Periods III and VIII, Module B, the predicted anaerobic Ortho P concentrations are higher than the measured values indicating greater P release predicted.
- For Module A, the predicted anoxic Ortho P concentrations are consistently and significantly higher than the measured. The lower measured Ortho P concentrations can be attributed to periods of excessive DO ingress into the anoxic reactor stimulating P uptake under aerobic conditions. In Module B, a much better correlation between the measured and predicted anoxic Ortho P concentrations is achieved.
- With the exception of Long Term Period III, Module B, the predicted aerobic Ortho P concentrations are consistently lower than the measured values indicating greater aerobic P uptake predicted.
- The simulation results of *UCTPHO* and the adjusted *BIOWIN* for the reactor parameters of Modules A and B are very similar for most long term periods of the investigation.

Table 5.27 : Comparison of measured "site" reactor data and *BIOWIN* & *UCTPHO* model results for Module A.

Long Term Period	Anaerobic NO_3 (mgN/ℓ)			Anoxic NO_3 (mgN/ℓ)			Aerobic NO_3 (mgN/ℓ)			Anaerobic PO_4 (mgP/ℓ)			Anoxic PO_4 (mgP/ℓ)			Aerobic PO_4 (mgP/ℓ)		
	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.
I	N/A	0.00	0.01	N/A	5.00	4.79	N/A	15.20	14.46	N/A	37.90	29.49	N/A	11.50	11.94	N/A	1.20	4.90
II	1.40	0.00	0.02	7.22	9.80	11.70	11.75	23.2	25.40	18.60	35.50	33.55	6.04	12.30	12.65	2.20	0.00	1.36
III	0.21	0.00	0.00	3.39	0.10	0.09	10.00	30.70	33.55	29.99	66.80	25.29	11.14	45.70	22.82	1.55	0.00	0.71
IV	0.11	0.00	0.00	0.07	0.00	0.00	2.00	2.10	0.02	13.03	57.60	39.38	9.24	33.00	35.02	0.44	0.00	0.18
V	0.21	0.00	0.00	0.13	0.20	0.05	1.59	12.40	10.02	34.10	77.50	58.62	12.66	32.80	26.52	3.78	0.00	0.25
VI	0.51	0.00	0.01	6.94	0.40	6.15	11.73	26.60	32.50	25.69	64.50	61.38	10.26	34.50	35.84	3.61	0.00	0.75
VII	0.48	0.00	0.00	6.73	0.50	1.34	10.09	34.00	32.80	23.92	49.90	44.56	10.05	31.70	28.33	5.87	0.00	0.19
VIII	0.18	0.00	0.00	8.32	0.30	1.29	13.51	37.10	36.34	24.48	53.40	43.82	7.25	35.60	29.31	2.17	0.00	0.23

Note: NO_3 - nitrate, PO_4 - orthophosphate.

N/A - for Long Term Period I no NO_3 and PO_4 reactor data are available.

"Site" - measured "site" data for Module A.

BioWin adjust. - *BioWin*32 using adjusted kinetic and stoichiometric model constants of De Haas *et al*., 2001 and Wentzel *et al*., 2002.

UCTPHO - Default *UCTPHO* (Wentzel *et al*., 1992)

Table 5.28 : Comparison of measured "site" reactor data and *BIOWIN* & *UCTPHO* model results for Module B.

Long Term Period	Anaerobic NO_3 (mgN/ℓ)			Anoxic NO_3 (mgN/ℓ)			Aerobic NO_3 (mgN/ℓ)			Anaerobic PO_4 (mgP/ℓ)			Anoxic PO_4 (mgP/ℓ)			Aerobic PO_4 (mgP/ℓ)		
	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.	"Site"	*UCT-PHO*	*BioWin* Adjust.
I	N/A	0.00	0.01	N/A	6.10	6.41	N/A	15.00	15.65	N/A	33.70	27.50	N/A	10.20	11.24	N/A	1.90	5.03
II	0.39	0.00	0.03	8.01	12.40	14.15	14.78	22.90	24.86	22.22	31.20	30.16	9.38	9.20	9.85	4.45	0.60	1.78
III	0.18	0.00	0.00	5.17	5.70	4.14	14.91	21.70	21.00	31.49	44.30	16.68	13.33	17.40	9.49	1.26	0.00	2.62
IV	0.13	0.00	0.02	5.01	5.70	8.52	10.57	15.30	18.34	27.85	35.10	32.01	15.05	11.00	10.43	7.56	0.00	0.50
V	0.10	0.00	0.01	3.29	5.20	7.30	11.07	16.00	18.40	28.25	62.40	49.43	10.21	19.10	15.42	1.74	0.00	0.30
VI	0.27	0.00	0.04	5.34	9.30	14.75	15.03	23.00	28.51	31.33	43.50	46.79	13.05	14.10	16.32	3.43	0.00	0.70
VII	0.14	0.00	0.00	1.67	0.50	0.33	9.51	11.80	9.30	20.39	41.20	38.26	13.03	15.80	14.94	2.06	0.00	0.16
VIII	0.26	0.00	0.02	4.44	8.90	13.02	13.58	27.90	31.64	31.02	32.60	24.21	16.19	13.90	10.52	5.06	1.20	0.82

Note: NO_3 - nitrate, PO_4 - orthophosphate.

N/A - for Long Term Period I no NO_3 and PO_4 reactor data available.

"Site" - measured "site" data for Module B.

BioWin adjust. - *BioWin*32 using adjusted kinetic and stoichiometric model constants of De Haas *et al.*, 2001 and Wentzel *et al.*, 2002.

UCTPHO - Default *UCTPHO* (Wentzel *et al.*, 1992)

CHAPTER 6

CONCLUSIONS

6.1 BACKGROUND AND OBJECTIVES

Biological nutrient (N & P) removal (BNR) by nitrification and denitrification (ND) and biological excess phosphorus removal (BEPR) in single sludge activated sludge systems (NDBEPR) has become an established practical technology implemented widely at full-scale. However, implementation of BNR has brought with it a new set of difficulties (Ekama and Wentzel, 1997), *viz.* (1) it's tendency to develop bulking sludges due to filamentous organism proliferation, (2) it's requirement for a long sludge age to ensure nitrification, (3) the limitation of the N and P removal placed on the system by the influent wastewater characteristics, in particular the readily biodegradable COD (RBCOD) fraction and the TKN/COD & P/COD ratios (Pitman, 1991) and (4) the problems that arise in the treatment of P rich waste sludge (Pitman *et al.*, 1991). The focus of this investigation was on the control of filamentous organism bulking.

It has been shown by Ekama and Marais (1986) that an important factor limiting the treatment capacity of an activated sludge plant is the inefficient separation of solids from the liquid phase in the secondary settling tank (bulking) caused by poor sludge settleability (DSVIs > 150 mℓ/g). The large potential savings from increasing the treatment capacity of activated sludge plants through improvement in sludge settleability have motivated considerable research into the causes of bulking.

Extensive research on low F/M (Jenkins *et al.*, 1984) filamentous organism bulking in biological N and N & P removal plants has been undertaken principally at laboratory-scale. This research has shown that the promoted specific control method of selectors, which stimulate removal of influent RBCOD in anaerobic, anoxic or aerobic selectors by metabolic or kinetic selection, is not successful in controlling bulking by biological N and N & P removal plants (Ekama *et al.*, 1996).

A growing body of laboratory-scale evidence and observations from full-scale plants support the findings that the conditions that stimulate biological N removal are conducive to bulking, *viz.* alternating anoxic-aerobic conditions with the presence of oxidized nitrogen at the transition from anoxic to aerobic. Hence, the low F/M filaments were renamed anoxic-aerobic (AA) (Casey *et al.*, 1994), to more accurately reflect the conditions under which they proliferate. From a review of the experimental results collected at laboratory-scale, a hypothesis on AA filamentous organism bulking was developed - stated simply (but not completely), if denitrification is not complete (nitrate/nitrite concentrations > 2 mgN/ℓ) at the time conditions switch from anoxic to aerobic, then proliferation of AA filaments occurs and *visa versa*.

Application of this specific method to control AA filamentous organism bulking derived from the hypothesis of Casey *et al.* (1994) needs to be demonstrated at full scale to check the validity of this new specific bulking control approach. *The principal objective of this research project was, therefore, to demonstrate at full-scale the specific control methodology developed at laboratory-scale.*

A second important phenomenon observed repeatedly in the laboratory-scale investigations on NDBEPR systems as well as on external nitrification (EN) biological nutrient removal (BNR) activated sludge (AS) systems (Moodley *et al.*, 1999; Sotemann *et al.*, 2000; and Hu *et al.*, 2001), is that in these systems low COD mass balances (80 to 90 %) are observed. In contrast, on ND systems (*i.e.* no anaerobic reactor) invariably the COD mass balances are much higher (90-95 %) and closer to the theoretically expected 100 %. This inexplicable loss of COD in NDBEPR systems has also been observed in other research laboratories (*e.g.* Virginia Tech, Randall *et al.*, 1988). Because the COD mass balance is based on reconciling the COD mass exiting the system via effluent flow, sludge VSS wastage and carbonaceous oxygen demand, with the influent wastewater COD mass, the lower COD mass balance results in lower sludge production <u>and</u> carbonaceous oxygen demand. Indeed so often and repeatedly has this low COD mass balance been observed over the past decade, that certain BNR models coded into commercially available computer simulation packages, include this COD loss (~15 %) and so calculate reduced sludge production and oxygen demand. The mechanism whereby this COD loss has taken place is via the fermentation process which transforms the readily biodegradable (RB) COD to volatile fatty acids (VFA) in the anaerobic reactor - instead of an equal concentration of VFA being generated from the RBCOD, only a fraction (~50 %) of the RBCOD becomes VFA, the balance is COD that is lost. The fermentation process has been selected for this COD loss because it is one of the few biological processes confined to the anaerobic reactor. The COD loss cannot be due to a lower anoxic heterotrophic yield coefficient (0.54 mgCOD/mg COD instead of 0.66 mgCOD/mgCOD) because this (i) doesn't affect the COD balance and (ii) happens in both ND and NDBEPR systems. The question that arises from this COD loss phenomenon is - does this COD loss also happen at large or full scale so that it is scientifically defensible to include this COD loss and design full scale plants on this basis? Because the full-scale plant is potentially a large well controlled and monitored plant, it provides an opportunity *to check the COD mass balance at a scale 200 000 x larger than laboratory scale.*

For this purpose, two parallel full-scale plants at the Mitchell's Plain Wastewater Treatment Plant were made available by the Cape Metropolitan Council. The two full-scale plants (Modules A and B) were redesigned as N & P removal UCT configuration systems, such that the two systems had the same design and operating parameters. The sludge age was 15 d and the anaerobic, anoxic and aerobic mass fractions 0.091, 0.350 and 0.559 respectively. The treatment capacity of the two modules (1361 and 2043 m^3) each with its own SST (25 m diameter, 3 m side water depth & hydraulic suction) was estimated to be 2.0 and 2.7 Mℓ/d respectively for a DSVI of 250 mℓ/g and reactor concentrations of around 4 gTSS/ℓ. However, due to aeration capacity limitations of the old fine bubble ceramic dome aeration system, the flows were reduced to 1.4 and 2.1 Mℓ/d giving a hydraulic retention time of about 24 h. Sludge was wasted hydraulically from the end of the main reactor over a calibrated weir and discharged by gravity to the main plant's sludge treatment facilities. The idiosyncrasies of the old aeration system and persistent problems with the sludge back flow into the full-scale plants from the sludge treatment facilities resulted in the anoxic and aerobic reactors not functioning as such (leading to poor anoxic denitrification and significant aerobic simultaneous nitrification-denitrification) and poor sludge age control. These problems compromised achieving the two research objectives.

To test the AA filament bulking hypothesis at large scale, in the one system (Module B), the nitrate/nitrite concentration in the anoxic reactor would be controlled to be > 2 mgN/ℓ and hence in terms of the hypothesis should bulk, while in the other parallel system (Module A) it would be controlled to < 1 mgℓ and hence in terms of the hypothesis should not bulk. To control the nitrate/nitrite concentrations leaving the anoxic reactors and entering the subsequent aerobic reactors, the 'a-recycles' (aerobic to anoxic) were varied to under and overload the anoxic reactors of Modules A and B respectively. In operation, the 'a-recycles' for Modules A and B were initially set at about 2:1 and 5:1 respectively with respect to the influent. However, from plant performance monitoring it was noted that the nitrate concentrations in the anoxic reactors of both modules were excessively high, which caused significant nitrate to be recycled to the anaerobic reactor, adversely influencing biological P removal. These high anoxic nitrate concentrations were due in part to the high TKN/COD ratio of the settled wastewater and the high underflow 's-recycle' ratios (~ 2:1) required to maintain the hydraulic syphons on the suction lift SSTs (see Section 6.4 below). Accordingly, the 'a-recycle' ratios for Modules A and B were reduced to 0:1 and about 3:1 respectively.

In the 589 day operation of the full-scale plants, from an examination of the influent, operational parameters and measured system performance, eight 'steady state' long term periods where these remained approximately constant were identified. System performance monitoring commenced on 31 October 1999 (day 1). Initially the plant was monitored once a week on Sundays by the Scientific Services Department of the CMC. From 12 June 2000 (day 225) more extensive sampling and analysis was simultaneously carried out on the full-scale plants every second day, excluding Sundays. The "CMC" data was primarily used as a cross check on the more extensive "site" data. The experimental results and evaluation of this investigation are summarised below in Sections 6.2 to 6.7.

6.2 Operation Problems

1. Progressive blocking of the ceramic diffuser domes increased the back pressure in the aeration system which caused thermal trip-out of the compressor. The compressor pulley wheel diameters were reduced, which solved the trip-out problem but reduced the air supply by about 10 %. On 11 June 2001 (day 589) the pipe distribution system irreparably ruptured and forced cessation of the investigation.

2. Even though the influent flow was reduced to match the aeration capacity, the air supply was too low for the aerobic reactors to be properly aerobic resulting in significant

simultaneous denitrification. Also, leaks in the distribution pipework in the anoxic reactors (part of which were aerobic reactors in the former configuration) as well as considerable back mixing from the aerobic to anoxic reactor in Module A, resulted in poor denitrification in the anoxic reactors. As a consequence the anoxic and aerobic reactors did not operate as such and were both quasi anoxic quasi aerobic to different degrees in the two modules.

3. Sporadic ingress of main treatment plant sludge via the sludge wastage drain resulted in significantly higher (30 to 50 %) sludge concentrations in the modules than would develop from the settled wastewater itself, particularly in the earlier stages of the investigation. As a consequence "steady state conditions" could not be achieved. Due to its labour intensiveness it was planned to measure the oxygen utilisation rates only when this problem was eliminated but the investigation had to be terminated before this could be achieved. As a consequence, COD balances could not be done.

4. An identical laboratory scale system (~1:200000) was operated for 163 days from day 470 to day 632 (43 days after the termination of the full-scale plant investigation) to evaluate the magnitude of the above problems on the full-scale plant results.

6.3 COD Removal Performance

5. Over the 589 day investigation which was divided into eight periods ranging from 40 to 224 days during which influent and operating conditions were relatively unchanged, the average (for the eight steady state periods) percentage COD removal was 87 and 89 % for Modules A and B respectively. With the exceptions of Period IV Module A and Periods VII and VIII Module B, consistently good COD removals were achieved with unfiltered effluent COD concentrations < 75 mgCOD/ℓ. The membrane filtered effluent COD concentration was 53 mg/ℓ giving an unbiodegradable soluble COD fraction of 0.086 for the settled wastewater.

6. The COD mass balance of the two modules over the investigation could not be determined because steady state conditions were not achieved and therefore the oxygen utilisation rates (OUR) were not measured.

7. The overall average TSS and VSS concentrations were 3622 mgTSS/ℓ and 2710 mgVSS/ℓ & 3661 mgTSS/ℓ and 2787 mgVSS/ℓ for Modules A & B respectively. This is ~10 % higher than expected from 100 % COD mass balance models (*UCTPHO* - see 24 below) and ~60 % higher than measured in the lab-scale system, indicating that sludge ingress was substantial, taking due account of the lower influent COD to the lab-scale system.

6.4 Nitrogen Removal Performance

8. The influent TKN/COD ratio varied between 0.10 to 0.24 with an average of 0.16 mgN/mgCOD which is above the estimated upper limit (0.14 mgN/mgCOD) to avoid nitrate recycle to the anaerobic reactor.

9. For Periods I and II (332 days), the nitrification performance was reasonable, with effluent FSA concentrations at about 1 mgN/ℓ. For all the other periods nitrification was partial only, indicated by the relatively high effluent TKN and FSA concentrations (5 - 30 mgN/ℓ). From Period III to midway Period VI (140 days), nitrification was particularly poor in Module A (effluent FSA > 5 mgN/ℓ), which indicated inadequate aeration. From Period VI, more air was directed to Module A at the expense of Module B. This reduced the effluent FSA from Module A to < 5 mgN/ℓ but increased it from Module B to > 20 mgN/ℓ.

10. The nitrite (NO_2) concentrations were negligible (<0.5 mgN/ℓ) in the anoxic and aerobic reactors throughout the investigation. For most periods, the effluent nitrate concentrations were low (10 to 17 mgN/ℓ) in Module A and B compared with the very high influent TKN/COD ratio and indicates that denitrification in the system was very good (~50 - 55 mgN/ℓ), except for Periods IV and V Module A where nitrification failed (< 2 mgN/ℓ). The nitrate concentrations in the anoxic zones of both Modules A and B

were higher than expected (5 - 8 mgN/ℓ) which resulted in (i) nitrate feed back to the anaerobic reactor and (ii) not achieving low nitrate at the anoxic-aerobic transition in Module A. Reducing the 'a-recycle' ratios on Module A and B from 2:1 and 5:1 to 0:1 and 3:1 respectively did not solve this problem. Later in the investigation it became apparent that these high anoxic reactor nitrate concentrations were due to back mixing from the aerobic reactor and air leaks in the air distribution network.

11. To examine the nitrification and denitrification performance, nitrate and nitrite mass balances were calculated around each reactor and the SST. Net denitrification in the anoxic zones was very low, on average only 3 and 24 mgN/ℓ influent for Modules A and B respectively. Compared with the influent TKN of 95 to 98 mgN/ℓ, with such low denitrification it is impossible to achieve effluent nitrate concentrations between 10 and 17 mgN/ℓ unless significant simultaneous nitrification-denitrification was taking place in the anoxic and aerobic reactors. This was confirmed during Periods VII and VIII when the air supply to Module A was increased (at the expense of Module B) and resulted in a net nitrate production (nitrification) in the anoxic reactor. This simultaneous nitrification-denitrification in the anoxic and aerobic reactors invalidates the N balance calculations which assumes that no denitrification takes place in the aerobic reactor and no nitrification in the anoxic reactor. The average N balances calculated for Modules A and B were 57 % and 76 % respectively indicating that Module B was closer to the desired operation conditions (*i.e.* sufficient air in the aerobic reactor only) than Module A.

12. The overall average N removal was 77 % for Modules A and B. Accepting a 100 % N balance in the system for the eight steady state periods, the total N concentration removed (via denitrification + N in the waste sludge) was exceptionally large, on average at about 74 mgN/ℓ influent for both modules. Of this N, about 21 and 25 mgN/ℓ influent for Modules A and B respectively was removed with the waste sludge leaving about 53 and 49 mgN/ℓ influent for Modules A and B respectively as nitrate denitrified. From the nitrate mass balance around the anoxic and aerobic reactors, of this nitrate, only about 3 and 24 mgN/ℓ influent for Modules A and B respectively was denitrified in the anoxic reactor and 17 and 42 mgN/ℓ nitrified in the aerobic reactor, confirming simultaneous

nitrification-denitrification in the anoxic and aerobic reactors. While such simultaneous N removal can have advantages, it comes at considerable risk to nitrification, indicated by the relatively incomplete nitrification (see 11 above).

13. On average over the 589 day investigation the N mass balances for both modules were poor - 57 and 76 % for Modules A and B respectively. Two possibilities for this were identified, (i) the simultaneous nitrification-denitrification already mentioned and (ii) error in nitrate measurements. While supporting evidence for the latter was identified- separate independent analysis of nitrate samples gave about 10 % higher concentrations, by far the greatest contribution to the poor N balances was simultaneous N removal in the anoxic and aerobic reactors. Furthermore, a parallel laboratory-scale UCT system with the same design parameters as the Module A full-scale plant and fed the same wastewater as influent but with none of the operating problems gave a good N balance (99 %) and a much higher effluent nitrate concentration (38 mgN/ℓ).

6.5 PHOSPHORUS REMOVAL PERFORMANCE

14. The average influent Total P (TP) concentration was 12.7 mgP/ℓ making the influent P/COD ratio 0.021 mgP/mgCOD. This is not a high value, and with the influent readily biodegradable (RB) COD of 217 mgCOD/ℓ (measured as the difference between floc/filtered influent and effluent COD concentrations) has the potential to achieve very good P removal with effluent TP < 1 mgP/ℓ.

15. With the exception of Module A Period III, the filtered (< 0.45 μm) effluent TP concentration > 2 mgP/ℓ, indicating that the P removal was not limited by the influent P concentration. This allowed the overall average system P removal capacity for Modules A and B to be measured, which based on unfiltered influent and filtered effluent TP was 10.0 and 9.3 mgP/ℓ respectively. The unfiltered effluent TP was 2.9 and 4.0 mgP/ℓ making the P/VSS ratio of the ESS 0.06 mgP/mgVSS (similar to that in the reactor).

16. The percentage P removal of Modules A and B were similar at 69 and 64 % respectively

based on unfiltered influent and effluent samples. The P removal attained was considerably reduced below that potentially achievable due to the high concentration of nitrate recycled to the anaerobic reactors; on average at 5.6 and 5.0 mgN/ℓ for Modules A and B respectively. This reduced the P removal by an estimated 3 mgP/ℓ. Nevertheless, consistently good biological P removal was obtained at 0.015 and 0.014 mgP/mg influent COD for Modules A and B respectively.

17. In contrast to the N mass balance, the overall average P mass balance for Modules A and B were excellent, at 103 and 97 % respectively. The good overall averages indicate that the data relating to P was reliable. The P/VSS ratio of the sludge mass in the reactors was 0.065 mgP/mgVSS, which is significantly above the 0.025 mgP/mgVSS for non-BEPR activated sludge. However, it should be noted that had sludge from the non-BEPR main treatment plant not sporadically entered the full-scale plants, the P/VSS ratio of the sludge mass would have been significantly higher.

18. The average anaerobic P release was very similar in both modules at 26 and 29 mgP/ℓ influent for Modules A and B respectively. The average aerobic P uptake in Module B was significantly higher than in Module A at 45 compared to 19 mgP/ℓ influent respectively. In the anoxic zones the two modules appeared to exhibit divergent behaviour. Throughout the investigation P uptake occurred in the anoxic reactor of Module A, while in Module B P release occurred in the anoxic reactor. For Module A, over the investigation 48 % of the P uptake occurred in the anoxic reactor. Initially it was thought this was anoxic P uptake in Module A. Hu *et al.* (2001) noted that anoxic P uptake tends to be stimulated by an overload of nitrate on the anoxic reactor and has been observed quite often in laboratory-scale and full-scale plants. When it takes place, the BEPR is only two thirds to three quarters of BEPR with predominantly (>90 %) aerobic P uptake (Ekama and Wentzel, 1997). However, its occurrence in Module A is apparently not real because (i) both modules were overloaded with nitrate, (ii) had similar average anoxic nitrate concentrations and (iii) aerobic P uptake took place in Module B and (iv) the BEPR was the same in both modules. Although not apparent during the investigation, the occurrence of P uptake in the anoxic reactor therefore is best explained as aerobic P uptake as a result of excessive DO ingress into the Module A anoxic reactor.

In Module B, DO ingress into the anoxic reactor was much less, and air supply to the aerobic reactor greater than Module A, with the result that the anoxic and aerobic reactors were closer to these conditions than the anoxic and aerobic reactors of Module A. Thus for Module A the circumstantial (and experimental) evidence suggested P uptake by PAOs under aerobic conditions rather than under anoxic conditions.

19. The BEPR performance of the full-scale plants (Modules A and B) was assessed by comparing the measured P removal with the theoretical P removal calculated by the steady state model of Wentzel *et al.* (1990). In doing this calculation procedure, the unbiodegradable particulate COD fraction ($f_{S,up}$), the two active heterotrophic organism fractions of the VSS [*i.e.* polyphosphate accumulating organisms (PAOs), $f_{av,PAO}$ and ordinary heterotrophic organisms (OHOs), $f_{av,OHO}$] and the P content of the PAOs ($f_{XBG,P}$) are determined. To determine the unbiodegradable particulate COD fraction ($f_{S,up}$) of the sewage fed to the full-scale plants, the appropriate $f_{S,up}$ value was selected so that the system VSS mass calculated with the BEPR model of Wentzel *et al.* (1990) was equal to the measured VSS mass using the measured influent readily biodegradable COD (RBCOD) concentration, and the influent characteristics of the sewage (*i.e.* fraction of unbiodegradable soluble COD/total influent COD, $f_{S,us}$ and total influent COD, S_{ti}) and the known system parameters (anaerobic mass fraction and sludge age) as input. An overall average $f_{S,up}$ value of 0.239 was estimated. The OHO and PAO active VSS mass fractions were determined from the ratio of the masses of OHO and PAO VSS to the total VSS giving overall average $f_{av,OHO}$ and $f_{av,PAO}$ values of 0.210 and 0.140 respectively. The P content of the PAOs ($f_{XBG,P}$) was estimated as that value which set the calculated P removal equal to the measured P removal. An overall average $f_{XBG,P}$ value of 0.322 mgP/mgPAOAVSS was estimated for the full-scale plants. A $f_{S,up}$ value of 0.239 for the settled wastewater is far too high and is the result of the sludge ingress from the main treatment plant. Accordingly a more realistic $f_{S,up}$ of 0.05 was selected for the settled wastewater (the lab-scale system yielded a $f_{S,up}$ of 0.03) and the calculations repeated. The $f_{S,up}$ of 0.05 yielded a PAO P content ($f_{XBG,P}$) of 0.39 mgP/mgPAOVSS which is very close to the Wentzel *et al.* (1990) model standard of 0.38 for 100 % aerobic P uptake BEPR, confirming that the BEPR in the full-scale plants was normal aerobic uptake BEPR.

6.6 SLUDGE SETTLEABILITY AND FILAMENT IDENTIFICATION

20. In both modules the anoxic nitrite concentrations were very low throughout the investigation with an overall average of 0.17 and 0.25 mgN/ℓ for Modules A and B respectively. In both modules anoxic nitrate concentrations were high, except for Module A Periods IV and V where nitrification failed, with an overall average of 5.36 and 5.17 mgN/ℓ for Modules A and B respectively. The high nitrate concentrations in the anoxic zones indicated that the proposed control of nitrate in the Module A anoxic zone to low concentrations had not been achieved in practice, even though the 'a-recycle' was set to zero from Period III onwards. However, the proposed control of nitrate in the Module B anoxic zone to high concentrations had been achieved in practice. Thus, it would not be possible to demonstrate the effect of complete anoxic denitrification on sludge settleability, though the effect of incomplete anoxic denitrification could be demonstrated. However, because the intended anoxic and aerobic conditions were not achieved in the anoxic and aerobic reactors, and these reactors were a continuous quasi anoxic quasi aerobic reactor, it is difficult to apply the AA filament bulking hypothesis to the results. Nevertheless, in single reactor Carousel, Orbal and other intermittently aerated ND plants in which substantial simultaneous ND takes place, sludge settleability often is poor (DSVI > 200 mℓ/g) caused by AA filaments like *M. Parvicella* and Type 1851. So apart from the fact that the full-scale plants include BEPR, from the quasi anoxic quasi aerobic conditions in the anoxic and aerobic reactors of the full-scale plants, the expectation is that the sludge should bulk due to AA filament proliferation.

21. The sludge settleability of the two systems was monitored by means of the Diluted Sludge Volume Index (DSVI). In terms of the hypothesis and the bulking control strategy, since both modules have high anoxic nitrate concentrations both should produce a bulking sludge due to AA filament proliferation. In contrast both modules produced good settling sludges with low overall DSVIs of 97 and 102 mℓ/gTSS. At no time during the 589 day investigation did the 7 day moving average exceed 120 mℓ/gTSS.

22. From 17 monthly microscopic identifications the filament most frequently dominant in both Module A and B was *M. parvicella* (41 and 44 % respectively). The next most frequently dominant filaments were type 0092 and type 1851. All of these filaments are

classified as typical of the low F/M category (Jenkins *et al.*, 1984) later renamed Anoxic-Aerobic(AA) (Casey *et al.*, 1994) and are almost always observed in full scale NDBEPR systems whether bulking or not (Blackbeard *et al.*, 1986, 1988). The five most frequently occurring filament types in Modules A and B in descending order of frequency were, *M. parvicella* present in 82 and 94 % of samples, type 0092 present in 77 and 69 %, type 1851 in 53 and 63 %, type 1701 in 6 and 13 % and *N. limicola* in 6 and 6 % respectively.

6.7 SIMULATION OF THE FULL-SCALE PLANTS

23. The 24h intensive monitoring tests were conducted by Diale and Modipa (2000) for their BSc thesis project on the two full-scale plants during which all the influent, reactor and effluent concentrations were measured every 2 hours and the OUR every hour mid-way along the length of the aerobic reactor. These indicated that diurnal variation in all these concentrations was not significant and the grab samples taken for the "CMC" and "site" data sets could be accepted as daily average values. Owing to the operation problems mentioned above and difficulty obtaining representative OUR samples, poor COD and N balances were obtained in these tests.

24. By giving the same influent flow and concentrations and system design parameters as input, the system performance was modeled with two NDBEPR simulation programmes, *UCTPHO* (Wentzel *et al.*, 1992) and *BIOWIN* (Envirosim & Associates, Canada 2001 release). These two programmes were selected because of their distinct model differences (i) *UCTPHO* is COD conservative (*i.e.* 100 % COD balance) whereas *BIOWIN* includes COD losses in the anaerobic processes and (ii) the BEPR in *UCTPHO* is based on 100 % aerobic P uptake whereas *BIOWIN* includes anoxic-aerobic P uptake BEPR. The measured effluent and reactor concentrations of Modules A and B were compared to the predicted values of the *BIOWIN* and *UCTPHO* kinetic models. Because the modules could not be operated with well defined aerobic and anoxic conditions and without sporadic sludge ingress, the measured results cannot be used to comment on the model predictions.

25. The *BIOWIN* simulations with the default kinetic and stoichiometric constants produced results which were at an unacceptably large variance with steady state ND and BEPR models and *UCTPHO* predictions, particularly in regard to denitrification rates in the anoxic reactor. This was in part due to anoxic P uptake BEPR and in part due to too high kinetic rate constants. Also the predicted VSS and OUR were significantly below (~10 %) those of *UCTPHO* due to anaerobic COD loss. Hence, adjusted *BIOWIN* model parameters (De Haas *et al.*, 2001 and Wentzel *et al.*, 2002) were adopted in the simulation of the full-scale plants to closely emulate the *UCTPHO* model parameters *i.e.* (i) eliminated the COD loss, (ii) reduced the denitrification rate and (iii) stopped anoxic P uptake and its associated denitrification. It was found that in general for Modules A and B, the combination of results obtained from the *BIOWIN* simulations using the adjusted model parameters were closer to the measured data than the default *BIOWIN* simulation results. However, the full-scale plant data cannot be accepted as a basis for model validation.

26. A reasonably good correlation between the measured and predicted effluent unbiodegradable soluble COD (S_{us}) and free and saline ammonia (FSA) concentrations was achieved. The predicted effluent and reactor nitrate (NO_3) concentrations were consistently higher than the measured values. This can be attributed to the significant denitrification in the aerobic reactors of both Modules A and B which were not modelled in *BIOWIN* and *UCTPHO*. As the effluent and reactor Ortho P concentrations are greatly affected by the predicted NO_3 recycled from the anoxic to the anaerobic reactor, a poor correlation between the measured and predicted values was achieved.

27. For some long term periods, the measured VSS and TSS are significantly greater than the predicted values of *BIOWIN* and *UCTPHO*. This can be attributed to the inadequate sludge wasting from the full-scale plants particularly in the earlier stages of the investigation.

6.8 CLOSURE

The principle aim in this research project was to investigate at full-scale the implementation of the proposed strategy to control bulking by AA filaments, namely that by limiting the anoxic nitrate/nitrite concentrations to < 1mgN/ℓ at the anoxic to aerobic transition by controlling the 'a-recycle' ratio, a good settling sludge could be achieved. In the investigation, the two full-scale plant modules were run in parallel, one (Module A) with a low 'a-recycle' ratio to give low anoxic nitrate concentrations and the other (Module B) with high 'a-recycle' ratio to give high anoxic nitrate concentrations. In terms of the AA filament bulking hypothesis and the control strategy derived from it, this should cause the module with high anoxic nitrate concentrations to bulk due to AA filament proliferation (Module B) and the module with low anoxic nitrate concentrations (Module A) not to bulk.

In operation of the two full-scale plant modules, it was found that despite the difference in 'a-recycle' ratio, both modules had high anoxic nitrate concentrations. This was caused by the poor anoxic denitrification performance in the two modules due to air ingress and back mixing from the aerobic reactor, particularly in Module A. Thus, the effect of low anoxic nitrate concentration on sludge settleability could not be examined. However, since both modules had high anoxic nitrate concentrations, the effect of this on sludge settleability could. In terms of the AA bulking hypothesis this should stimulate AA filament proliferation and hence bulking. However, this did not occur in practice: In both modules, throughout the investigation (589 days where monitoring took place) relatively low DSVIs (< 110mℓ/gTSS) were measured. Clearly, this is contrary to the AA bulking hypothesis. However, the difficulties with sludge ingress from the main plant (see point 3 in Section 6.2 above) makes drawing definitive conclusions in this regard difficult. Furthermore, because of inadequate aeration in the aerobic reactors, and air and DO ingress into the anoxic reactors, these were in effect quasi anoxic quasi aerobic reactors in which substantial simultaneous ND took place (~50 % of N removal). These conditions are similar to Orbal and Carousel ND systems which frequently experience high DSVI due to AA filament proliferation. Even so the full-scale plants had very good settling sludge. Curiously, the lab-scale system had a poor settling sludge (DSVI > 200 mℓ/gTSS) throughout its 163 day operation, and appeared to conform to the AA bulking hypothesis, with DSVI increasing as anoxic NO_x increased. In seeking an explanation for this divergent behaviour one possibility is the difference in aerobic DO concentration; Casey *et al.* (1994) have demonstrated that aerobic DO does influence DSVI.

This is an area that requires further research. Clearly finding the cure for AA filament bulking in NDBEPR systems remains elusive despite the international research attention it has received over the past twenty years.

With regard to the second objective, that of establishing whether or not the unexplained COD loss observed in laboratory scale NDBEPR systems also takes place in large scale systems, could not be validated also. This was due to the sporadic sludge ingress into the full-scale plants from the main ND activated sludge plant via the waste sludge drainage system leading to significantly greater masses of sludge in the modules than would accumulate from the influent flow.

REFERENCES

Barker P.S. and Dold P.L. (1997). General model for biological nutrient removal activated sludge systems: Model presentation, *Water Environment Research*, **69**(5), 969-984.

Beeharry A.O., Wentzel M.C. and Ekama G.A. (2001). Measurement of active organism mass in activated sludge systems fed different unbiodegradable particulate COD fractions.

Blackbeard J.R., Ekama G.A. and Marais G.v.R. (1986). A survey of filamentous bulking and foaming in activated sludge plants in South Africa. *Water Pollution Control*, **85**(1), 90-100.

Blackbeard J.R., Gabb D.M.D., Ekama G.A. and Marais G.v.R. (1988). A survey of filamentous organisms in nutrient removal activated sludge systems. *Water SA*, **14**(1), 29-33.

Carr G.J. and Ferguson S.J. (1990). Nitric oxide formed by nitrite reductase of *Paracoccus denitrificans* is sufficiently stable to inhibit cytochrome oxidase activity and is reduced by its reductase under aerobic conditions. *Biochim. Biophys.* Acta. **1017**, 57-62.

Casey T.G., Wentzel M.C., Ekama G.A. and Marais G.v.R (1994b). *Causes and control of anoxic-aerobic (AA) (or low F/M) filament bulking in long sludge age nutrient removal activated sludge systems.* Water Research Commission, P O Box 824, Pretoria, 0001, South Africa. WRC 286/2/94.

Casey T.G., Wentzel M.C. and Ekama G.A. (1999a). Filamentous organism bulking in nutrient removal activated sludge systems. Paper 9: Review of biochemistry of heterotrophic respiratory metabolism. *Water SA*, **25**(4), 409-424.

Casey T.G., Wentzel M.C. and Ekama G.A. (1999b). Filamentous organism bulking in nutrient removal activated sludge systems. Paper 10: Metabolic behaviour of heterotrophic facultative aerobic organisms under aerated/unaerated conditions. *Water SA*, **25**(4), 425-442.

Casey T.G., Wentzel M.C. and Ekama G.A. (1999c). Filamentous organism bulking in nutrient removal activated sludge systems. Paper 11: A biochemical/ microbiological model for proliferation of anoxic-aerobic (AA) filamentous organisms. *Water SA*, **25**(4), 443-451.

Casey T.G. and Alexander W.V. (2001). *Design and operating strategies to minimize bulking by anoxic-aerobic filamentous organisms in nutrient removal activated sludge plants.* Water Research Commission, PO Box 824, Pretoria, 0001, South Africa. WRC 775/1/01.

Chudoba J., Ottova V. and Madera V. (1973a). Control of activated sludge filamentous bulking. I Effect of hydraulic regime or degree of mixing in an aeration tank. *Water Research*, **7**, 1163.

Chudoba J., Grau P. and Ottova V. (1973b). Control of activated sludge filamentous bulking. II Selection of micro-organisms by means of a selector. *Water Research*, **7**, 1389-1406.

Clayton J.A., Ekama G.A., Wentzel M.C. and Marais G.v.R. (1991). Denitrification kinetics in biological nitrogen and phosphorus removal systems treating municipal wastewaters. *Water Sci. Technol.*, **23**(4/6-2), 1025-1035.

Cronje G.C., Wentzel M.C. and Ekama G.A. (2000). Measurement of active heterotrophic organism concentration in nitrification-denitrification activated sludge systems.

de Haas D.W., Wentzel M.C. and Ekama G.A. (2000). The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological excess phosphate removal. Part 5:Experimental periods using a ferrous-ferric chloride blend. *Water SA*, **27**(2), 117-134.

de Haas D.W., Wentzel M.C. and Ekama G.A. (2001). Comparison between combined biological N & P removal in the UCT and *BIOWIN* models for actvated sludge systems. Report to *G.H.D.* Dept. of Civil Engineering, University of Cape Town, Rondebosch, Cape Town, 7701.

De Villiers M.E., Casey T.G., Wentzel M.C. and Ekama G.A. (1994). "The effect of nitrite and nitrate concentrations on low F/M filament bulking in N removal activated sludge systems". Dept. of Civil Eng., Univ. of Cape Town.

Dold P.L., Ekama G.A. and Marais G.v.R. (1980). A general model for the activated sludge process. *Prog. Wat. Tech.*, **12**, Tor 47-77.

Eikelboom D.H. and Van Buijsen H.J.J. (1981). Microscopic sludge investigation manual. Report A 94a. TNO Research Institute for Environmental Hygiene, Delft, Netherlands.

Ekama G.A., Siebritz I.P. and Marais G.v.R. (1983). Considerations in the process design of nutrient removal activated sludge processes. *Water Sci. Technol.*, **15**(3/4), 283-318.

Ekama G.A. and Marais G.v.R. (1986). Sludge settleability and secondary settling tank design procedures. *Water Pollut. Control*, **85**(1), 101-113.

Ekama G.A., Wentzel M.C., Casey T.G. and Marais G.v.R. (1996). Filamentous organism bulking in nutrient removal activated sludge systems. Paper 6:Review, evaluation and consolidation of results. *Water SA*, **22**(2), 147-152.

Ekama G.A., Wentzel M.C., Lakay M.T., Pilson R.A., Mellin H.K.O., Casey T.G.(1999). *Causes and control of low F/M filament bulking in nutrient removal activated sludge systems.* Water Research Commission, P O Box 824, Pretoria, 0001, South Africa. WRC 542/1/99.

Ekama G.A. and Wentzel M.C. (1999). Difficulties and developments in biological nutrient removal technology and modelling. *Water Sci. Technol.*, **39**(6), 1-11.

Envirosim (2001). BIOWIN32, 7 Innovation Drive, Suite 205, Flamborough, Ontario, L9H 7H9, Canada.

Gabb D.M.D, Still D.A., Ekama G.A., Jenkins D., Wentzel M.C. and Marais G.v.R. (1988). Final report to the Water Research Commission on a three year contract on development and full scale evaluation of preventative and remedial methods for control of activated sludge bulking (1985-1988) (Contract K 165). Research Report W62, Dept. of Civil Eng., Univ. of Cape Town.

Gabb D.M.D., Ekama G.A., Jenkins D. and Marais G.v.R. (1989). Incidence of Sphaerotilus natans in laboratory activated sludge systems. *Water Sci. Technol.*, **21**(Brighton), 29-41.

Henze M., Grady C.P.L. Jr), Gujer W., Marais G.v.R. and Matsuo T. (1987). Activated Sludge Model No. 1. IAWQ Scientific and Technical Report No. 1, IAWQ, London 32pp.

Henze M., Gujer W., Mino T., Matsuo T., Wentzel M.C. and Marais G.v.R. (1995). *Activated sludge No. 2,* IAWQ Scientific and Technical Report No. 3, IAWQ, London. 32pp.

Hu Z., Moodley R., Sotemann S., Vermande S., Lakay M.T., Wentzel M.C. and Ekama G.A. (2001). External nitrification in biological nutrient removal activated sludge systems - final report to the Water Research Commission on contract K5/970.

Hulsman A., Casey T.G., Ekama G.A., Wentzel M.C. and Marais G.v.R. (1992). "The effect of type, size, position and recycle ratio of the anoxic zone on low F/M filament bulking in nitrogen removal activated sludge systems". Research Report W73, Dept. of Civil Eng., Univ. of Cape Town.

Jenkins D., Richard M.G. and Daigger G.T. (1984). *Manual on the causes and control of activated sludge bulking and foaming.* Published by Water Research Commission, PO Box 824, Pretoria, 0001, South Africa.

Ketley D.A., Casey T.G., Ekama G.A., Wentzel M.C. and Marais G.v.R. (1991). "The effect of fully anoxic conditions and frequency of exposure to anoxic and aerobic conditions on the growth of low F/M filaments in nitrogen removal systems".

Krul J.M. (1976). Dissimilatory nitrate and nitrite reduction under aerobic conditions by an aerobically and anaerobically grown *Alcaligenes* sp. And by activated sludge. *J. Appl. Bact.*, **40**, 245-260.

Lakay M.T., Hulsman A., Ketley D.A., Warburton C.A., De Villiers M.E., Casey T.G., Wentzel M.C. and Ekama G.A. (1999). Filamentous organism bulking in nutrient removal activated sludge systems. Paper 7: Exploratory experimental investigations. *Water SA*, **25**(4), 386-396.

Lee S.E., Koopman B., Bode H. and Jenkins D. (1983). Evaluation of sludge settleability indices. Water Research **17** (1), 421-426.

Mbewe A., Wentzel M.C. and Ekama G.A. (1995). Simple batch test method for characterizing municipal wastewaters for design of biological nutrient removal activated sludge systems. *Procs. 68th Water Environment Federation Conference and Exhibition*, Miami.

Mellin H.K.O., Lakay M.T., Wentzel M.C. and Ekama G.A. (1997). The effect of high temperatures (30 °C) on biological nutrient removal performance, Dept. of Civil Eng., Univ of Cape Town, Rondebosch, 7700, RSA.

Modipa M.J., Diale T.V. and Ekama G.A. (2000). Performance evaluation of the Mitchell's Plain BNR Pilot Plants. BSc Theses, Dept. of Civil Engineering, University of Cape Town, Rondebosch, Cape Town, 7701.

Musvoto E.V., Casey T.G., Wentzel M.C., Ekama G.A. and Marais G.v.R. (1992). "The effect of large anoxic mass fractions and concentrations of nitrate and nitrite in the primary anoxic zone on low F/M filament bulking in nutrient removal activated sludge systems". Research Report No. W77, Dept. of Civil Eng., Univ. of Cape Town

Pilson R., Wentzel M.C., Casey T.G. and Ekama G.A. (1994). Denitrification kinetics and AA filament bulking in biological nutrient removal system at 14°C. Dept. of Civil Eng., Univ. of Cape Town

Pitman A.R., Venter S.L.V. and Nicholls H.A. (1983). Practical experience with biological phosphorus removal plants in Johannesburg, *Water Science Technology*, **15**(Cape Town), 230-260.

Pitman A.R. (1991). Design considerations for nutrient removal plants. *Water Sci. Technol.*, **23**(4/6), 781-790.

Randall E.W., Wilkinson A. and Ekama G.A. (1991). An instrument for the direct determination of oxygen utilization rate. *Water SA*, **17**(1), 11-18.

Siebritz I.P., Ekama G.A. and Marais G.v.R. (1983). A parametric model for biological excess phosphorus removal. *Water Sci. Technol.*, **15**(3/4), 127-152

Sneyders M.J., Ekama G.A. and Wentzel M.C. (1998). Treatability of unstabilized landfill leachate in a nutrient removal activated sludge system. IWM Landfill Interest Group seminar, Milnerton, 3 June, 1998.

STANDARD METHODS (1985) *Standard Methods for the Examination of Water and Wastewater* (16th edn.) American Public Health Assoc., 1015 15th Str. NW, Washington DC 20005, USA.

Swanepoel A.M. and Wentzel M.C. (1996). Evaluation and redesign of the Mitchell's Plain Wastewater Treatment Plant. BSc Thesis, Dept. of Civil Engineering, University of Cape Town, Rondebosch, Cape Town, 7701.

Ubisi M.F., Jood T.W., Wentzel M.C. and Ekama G.A. (1997). Activated sludge mixed liquor heterotrophic biomass. *Water SA,* **23**(3), 239-248.

Van Haandel A.C., Ekama G.A. and Marais G.v.R. (1981). The activated sludge process Part 3 - Single sludge denitrification. *Water Research*, **15**(10), 1135-1152.

Wable M.W. and Randall C.W. (1992). Investigation of reduction in oxygen requirements of biological phosphorus removal systems. *Water Sci. Technol.*, **26**(9-11), 2221-2223.

Warburton C.A., Lakay M.T., Casey T.G., Ekama G.A., Wentzel M.C. and Marais G.v.R. (1991). "The effect of sludge age and aerobic mass fraction on low F/M filament bulking in intermittent aeration nitrogen removal systems".

Wentzel M.C., Dold P.L., Ekama G.A. and Marais G.v.R. (1990). Biological excess phosphorus removal-steady state process design. *Water SA*, **16**(1), 29-48.

Wentzel M.C., Ekama G.A. and Marais G.v.R. (1992). Processes and modelling of nitrification denitrification biological excess phosphorus removal systems - a review. *Water Sci.Technol*, **25**(6), 59-82.

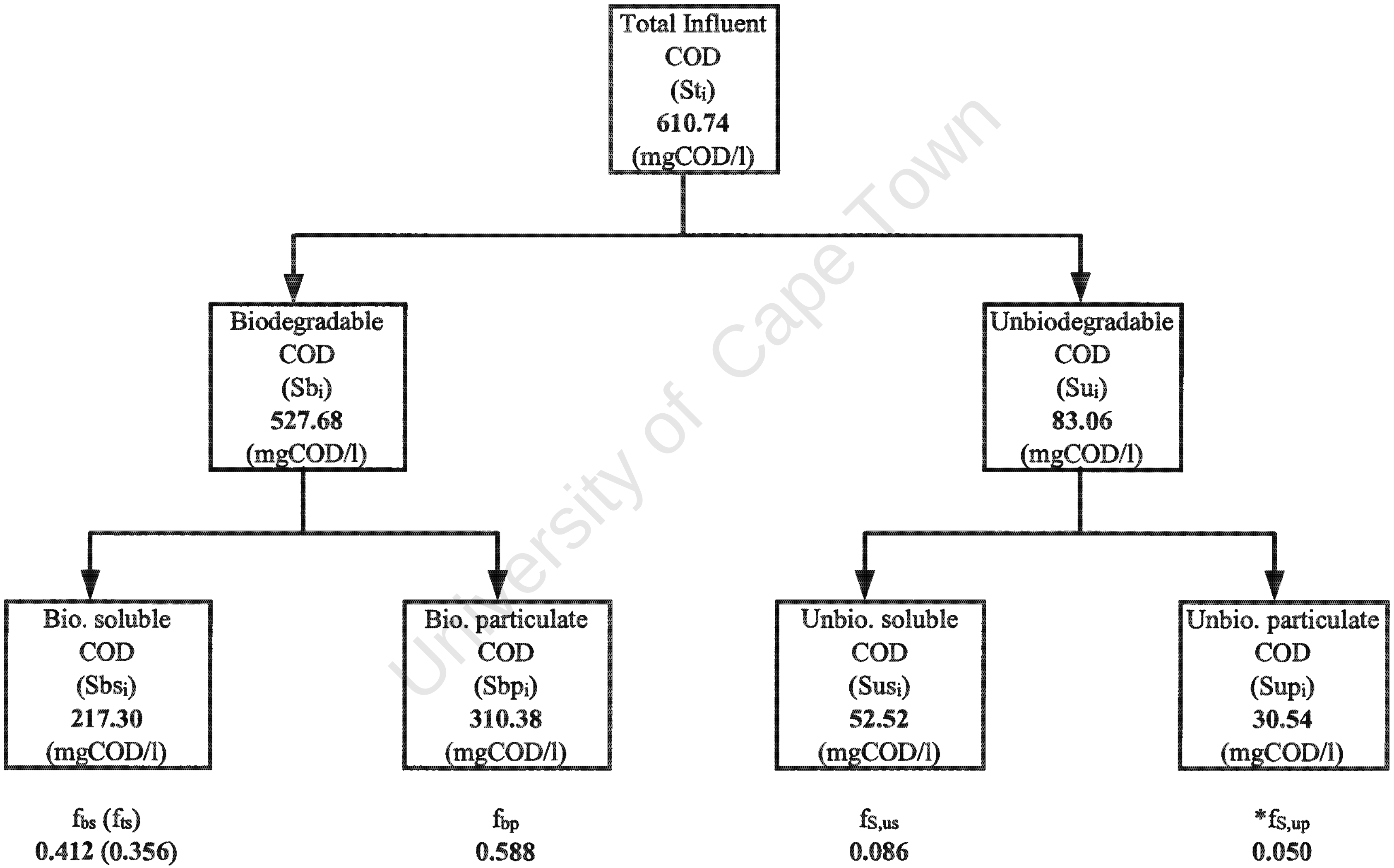
Wentzel M.C. and Ekama G.A. (2002). Comparison between *UCTPHO* and *BIOWIN* NDBEPR computer programmes. Personal communication. Dept. of Civil Engineering, University of Cape Town, Rondebosch, Cape Town, 7701.

WRC (1984). *Theory, design and operation of nutrient removal activated sludge processes.* Water Research Commission, PO Box 824, Pretoria 0001, South Africa.

APPENDIX A

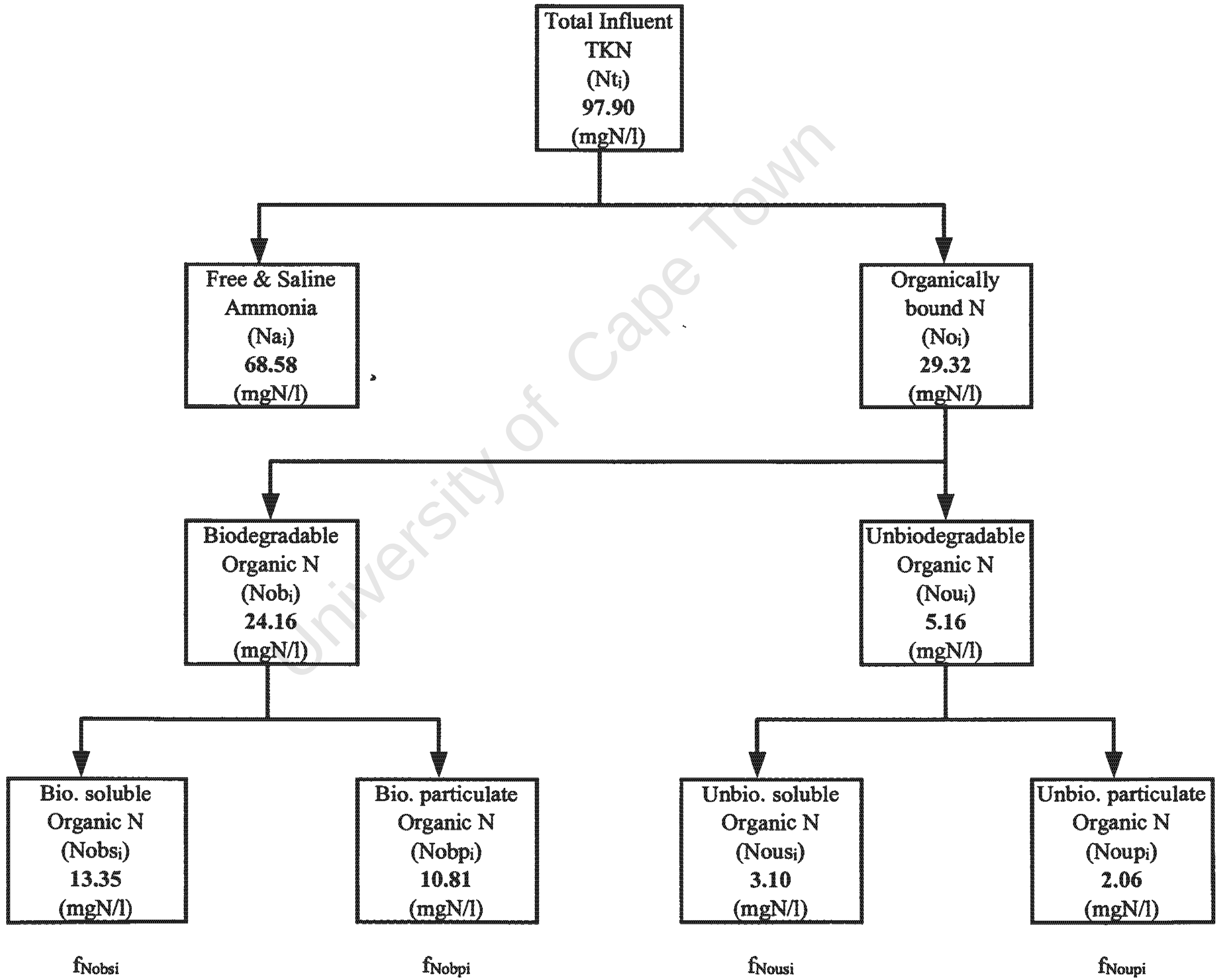
CHARACTERISATION OF INFLUENT COD, TKN & TP

CHARACTERISATION OF INFLUENT COD

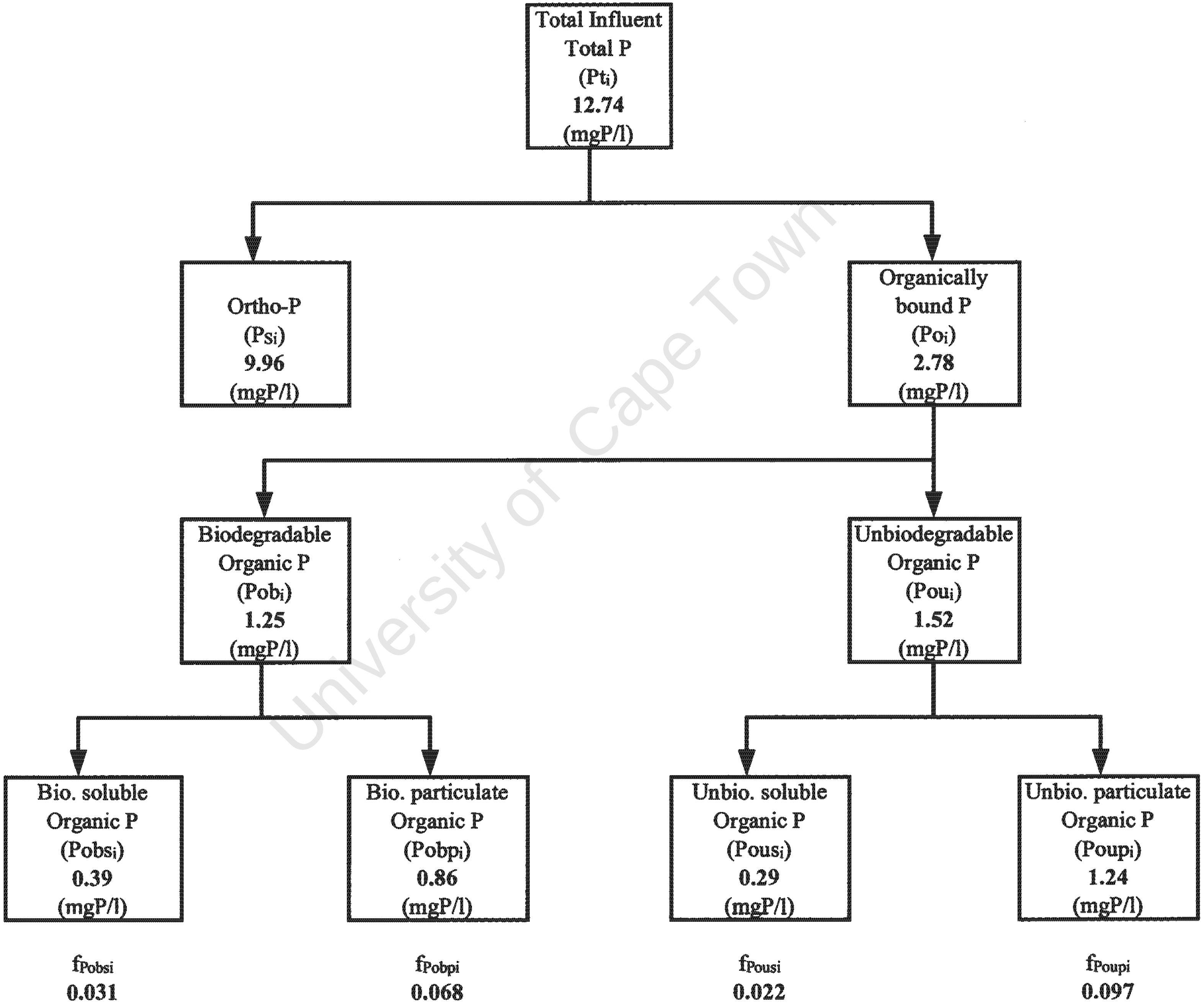


Note : * The more realistic value for $f_{s,up}$ = 0.05 is used rather than the calculated value of 0.239 (see Section 5.3.4.1).

CHARACTERISATION OF INFLUENT TKN



CHARACTERISATION OF INFLUENT TP



Characterisation of influent COD

S_{ti} = total unfiltered influent COD
S_{usi} = flocculated/filtered effluent COD
$S_{upi} = f_{s,up} \times S_{ti}$
$S_{ui} = S_{usi} + S_{upi}$
$S_{bi} = S_{ti} - S_{ui}$
S_{bsi} = flocculated/filtered influent COD - S_{usi}
$S_{bpi} = S_{bi} - S_{bsi}$
$f_{s,up}$ = obtained by setting the calculated VSS = measured VSS using the BEPR model of Wentzel *et al*. (1990).
$f_{s,us} = S_{usi} / S_{ti}$
$f_{bs} = S_{bsi} / S_{bi}$
$f_{ts} = S_{bsi} / S_{ti}$
$f_{bp} = S_{bpi} / S_{ti}$

Characterisation of influent TKN

N_{ti} = total unfiltered influent TKN
N_{ai} = influent FSA
$N_{oi} = N_{ti} - N_{ai}$
$N_{oupi} = f_n \times S_{upi} / f_{cv}$ [f_n = 0.10 mgN/mgVSS, WRC, (1984); f_{cv} = 1.48 mgCOD/mgVSS]
N_{ousi} = flocculated/filtered effluent TKN - effluent FSA
$N_{oui} = N_{oupi} + N_{ousi}$
$N_{obi} = N_{oi} - N_{oui}$
N_{obsi} = (filtered influent TKN - influent FSA) - N_{ousi}
$N_{obpi} = N_{obi} - N_{obsi}$
$f_{Noupi} = N_{oupi} / N_{ti}$
$f_{Nousi} = N_{ousi} / N_{ti}$
$f_{Nobsi} = N_{obsi} / N_{ti}$
$f_{Nobpi} = N_{obpi} / N_{ti}$

Characterisation of influent TP

P_{ti} = total unfiltered influent TP
P_{si} = influent Ortho P
$P_{oi} = P_{ti} - P_{si}$
$P_{oupi} = f_p \times S_{upi} / f_{cv}$ [f_p = unfiltered reactor TP / reactor VSS; f_{cv} = 1.48 mgCOD/mgVSS]
P_{ousi} = filtered effluent TP - effluent Ortho P
$P_{oui} = P_{oupi} + P_{ousi}$
$P_{obi} = P_{oi} - P_{oui}$
P_{obsi} = (filtered influent TP - influent Ortho P) - P_{ousi}
$P_{obpi} = P_{obi} - P_{obsi}$
$f_{Poupi} = P_{oupi} / P_{ti}$
$f_{Pousi} = P_{ousi} / P_{ti}$
$f_{Pobsi} = P_{obsi} / P_{ti}$
$f_{Pobpi} = P_{obpi} / P_{ti}$

Table A1 : Comparison of estimated with calculated characterisation of influent COD, TKN and Total P for the redesigned full-scale plants.

Settled Wastewater Parameter	Symbol	Units	Estimated Value	Calculated Value
Total COD	S_{ti}	mgCOD/ℓ	861	611
Unbiodegradable COD	S_{ui}	mgCOD/ℓ	116	84
Biodegradable COD	S_{bi}	mgCOD/ℓ	745	527
Unbiodegradable soluble COD (fraction)	S_{usi} ($f_{S,us}$)	mgCOD/ℓ	82 (0.095)	53 (0.086)
Unbiodegradable particulate COD (fraction)	S_{upi} ($f_{S,up}$)	mgCOD/ℓ	34 (0.039)	31* (0.050)
Biodegradable soluble COD (fraction)	S_{bsi} (f_{bs})	mgCOD/ℓ	239 (0.32)	217 (0.41)
Biodegradable particulate COD (fraction)	S_{bpi} (f_{bp})	mgCOD/ℓ	506 (0.68)	310 (0.59)
Total TKN	N_{ti}	mgN/ℓ	96	98
Free and saline Ammonia (fraction)	N_{ai} (f_{nai})	mgN/ℓ	79 (0.82)	69 (0.70)
Organically bound N	N_{oi}	mgN/ℓ	17	29
Unbiodegradable organic N	N_{oui}	mgN/ℓ	6	5
Biodegradable organic N	N_{obi}	mgN/ℓ	11	24
Unbiodegradable soluble N (fraction)	N_{ousi} (f_{Nousi})	mgN/ℓ	4 (0.037)	3 (0.032)
Unbiodegradable particulate N (fraction)	N_{oupi} (f_{Noupi})	mgN/ℓ	2 (0.024)	2 (0.021)
Biodegradable soluble N (fraction)	N_{Nobsi} (f_{Nobsi})	mgN/ℓ	5.5 (0.058)	13 (0.136)
Biodegradable particulate N (fraction)	N_{Nobpi} (f_{Nobpi})	mgN/ℓ	5.5 (0.058)	11 (0.110)
Total P	P_{ti}	mgP/ℓ	19.2	12.7
Ortho P (fraction)	P_{si} (f_{psi})	mgP/ℓ	14.9 (0.776)	9.96 (0.784)
Organically bound P	P_{oi}	mgP/ℓ	4.3	2.7

Note : * The more realistic value for $f_{S,up}$ of 0.05 is used rather than the calculated value of 0.239 for the full-scale plants.

APPENDIX B

Bi-DAILY "SITE" RESULTS

Table B1 : Bi-daily "site" unfiltered and filtered data.

MITCHELL'S PLAIN WASTEWATER TREATMENT - PILOT PLANT : BI-DAILY LABORATORY DATA

Date	Day No	Module A Influent flow Q (l/d)	Module B Influent flow Q (l/d)	Influent COD S_{ti} (mgCOD/l)	Influent TKN N_{ti} (mgN/l)	Influent Total P P_{ti} (mgP/l)	Influent NH4 N_{ai} (mgN/l)	Influent NO3+NO2 N_{oi} (mgN/l)	Module A VSS X_v (mgVSS/l)	Module B VSS X_v (mgVSS/l)	Module A TSS X_t (mgTSS/l)	Module B TSS X_t (mgTSS/l)	Module A aerobic DSVI (ml/g)	Module B aerobic DSVI (ml/g)	Module A Effluent NO3 N_{oe} (mgN/l)	Module B Effluent NO3 N_{oe} (mgN/l)	Module A Effluent COD S_{te} (mgCOD/l)	Module B Effluent COD S_{te} (mgCOD/l)	Module A Effluent TKN N_{te} (mgN/l)	Module B Effluent TKN N_{te} (mgN/l)	Module A Effluent NH3 N_{ae} (mgN/l)	Module B Effluent NH3 N_{ae} (mgN/l)	Module A Effluent TP P_{te} (mgP/l)	Module A Effluent P_{se} (mgP/l)	Module B Effluent TP P_{te} (mgP/l)	Module B Effluent P_{se} (mgP/l)
12/06/2000	225	1392006.4	2106087.2	750	129.7	12.16	81.53	0.02	2149	3085	3608	4029	72	80	12.727	14.346	60	51	1.6	1	0.38	0.34	0.37	7.24	0.09	1.82
19/06/2000	232	1450137.6	2280614.4	738	87.8	12.4	70.17	0.13	2149	3871	3994	4930	96	85	10.993	17.606	48	61	0.6	0.8	0.43	0.37	0.32	1.09	0.2	3.41
21/06/2000	234	1574612.8	2158617.6	508	82	12.95	67.04	0.02	2160	2309	3869	4596	98	83	8.892	14.533	26	29	3.8	0.5	2.8	0.19	0.31	1.21	0.2	0.93
23/06/2000	236	1329399.6	2120688.0	660	87	11.1	65.87	0.17	1757	3108	3396	4493	97	86	10.884	19.800	24	19	1	3.1	1.15	0.28	2.37	2.19	0.1	2.69
27/06/2000	240	1519308.8	2400137.6	596	102.5	12.31	64.85	0.00	2324	3428	3031	4007	105	88	10.819	10.773	32	34	1.1	3	1.15	0.16	0.9	2.69	0.08	2.46
29/06/2000	242	1163786.6	2136672.0	573	81.5	12.3	59.32	0.26	2321	3523	3412	4414	109	85	10.461	15.632	38	47	0.8	2.1	0.7	0.12	0.45	2.36	0.07	2.17
04/07/2000	247	1168667.2	2066774.4	651	86	14.33	64	0.04	2676	2513	3891	4484	109	82	10.941	10.749	32	37	1.3	1	1.6	0.2	0.74	1.55	0.3	0.83
06/07/2000	249	1262266.4	1619325.2	603	98.3	13.61	68.37	0.31	2610	2790	3695	3867	108	83	8.124	12.979	31	41	1.37	4.67	1.4	0.28	2.75	2.1	0.32	2.01
08/07/2000	251	2024016.4	2121772.0	596	101	13.97	74.85	0.13	2727	3082	3622	3941	110	82	9.225	14.657	25	37		4.5	30.81	2.27	12.55	4.1	0.1	3.9
10/07/2000	253	1579460.4	2201195.6	640	93.7	12.56	78.4	0.10	2577	3796	3625	3740	108	91		16.011	47	56	3.5	0.7	3.47	0.3	0.4	3.02	0.1	2.2
12/07/2000	255	1542948.0	2282880.0	570	81.5	25.21	67.4	0.15	2915	2752	3678	3910	112	84	10.618	15.028	42	37	3	–	5.86	0.3	0.3	2.8	0.2	2.4
14/07/2000	257	2409936.0	2485584.0	426	84.9	–	–		2446	3043	3380	3731	113	70	–	–	42	37	0.3	0.5		–	–	–		–
18/07/2000	261	2450687.2	2423484.8	437	88	13.63	72.6	0.11	2835	3019	3814	4021	108	92	16.322	18.519	39	33	1.3	1.8	0.6	0.3	0.2	4.7	0.2	4.1
20/07/2000	263	1403730.6	2231462.4	418	91	15.88	66.3	0.29	2364	2359	3103	4404	97	88	22.933	18.416	30	35	1.3	0.5	0.5	0.4	0.4	1.6	1.2	0.4
22/07/2000	265	1380412.8	2150323.2	391	89		72	0.10	2134	2897	3171	3828	98	97	20.894	17.371	18	33	1.3	1.6	–	0.2			1.8	3
24/07/2000	267	1521060.8	2053443.2	606	91.5	13.88	69.9	0.20	2195	3260	3849	4147	97	96	15.087	17.526	46	48	0.4	0.1	0.4	0.1	3.13	8.46	2.8	4
26/07/2000	269	2139777.6	2360070.4	503	91	13	72.2	0.20	2235	3149	3814	4151	90	92	–	–	23	23	5.5	0.4	5.57	0.3	3.2	5.9	3.7	8.4
28/07/2000	271	2007764.8	2363040.0	491	93.5	13.7	71.8	0.12	2338	2297	3146	4093	92	96	12.326	15.193	40	40	3	3	2.68	0.16	1.6	3.3	1.45	2.09
01/08/2000	275	1052436.8	2248992.0	845	108	15	58.1	0.07	2338	2629	3778	4070	95	85	8.610	11.932	35	41	21.5	1.5	13	0.2	0.4	0.4	0.2	0.1
03/08/2000	277	1235211.2	2212876.8	381	94	10.5	57.7	0.35	1913	3134	4726	5319	110	96	9.124	14.978	48	48	16.8	1	14.8	0.4	0.4	0.4	0.2	0.13
05/08/2000	279	1591385.6	2340422.6	395	99.5	13.7	67.9	1.50		3309	4139	4741	106	91	11.345	15.263	51	59	1	0.6	0.3	0.1	0.3	0.7	0.1	0.3
08/08/2000	282	1110220.8	2051096.8	305	102	13.8	69.4	0.08	3079	3509	4600	4021	105	89	11.165	14.216	24	55	1.6	0.5	0.5	0.02	0.5	0.5	0.2	0.3
11/08/2000	285	1482960.0	2349648.0	404	93	12.6	69.6	0.08	3037	3672	4875	5409	105	81	11.349	19.513	29	29	0.0	1	0.2	0.2	0.1	0.7	0.06	0.21
13/08/2000	289	1469836.8	2321134.4	528	98.3	12.7	68.5	0.10	3077	2993	4960	5096	97	83	10.990	16.308	37	29	2	0.6	1.5	–	1.6	2.5	0.09	3.4
17/08/2000	291	1646784.0	2354749.6	504	90.9	13.2	70.9	0.35	3379	3692	4604	5605	104	83	11.790	17.020	–	–	–	–	0.8	0.069	1.5	8.4	1	5.4
19/08/2000	293	1589790.5	2389792.0	452	100.1	13	64	0.10	3124	3565	4335	3792	106	92	14.256	17.398	24	12	3.8	3	0.1	0.1	0.3	3.3	0.01	4.04
21/08/2000	295	1671251.6	2329388.0	375	105.5	12.7	71.4	0.10	3020	3868	4121	3641	95	92	15.185	12.053	28	35	2.3	10.8	0.2	7.7	2.2	2.3	1.8	4.3
23/08/2000	297	1577404.8	2413584.0	519	105.5	12.7	70	0.19	2796	3848	3668	3649	91	81	15.290	11.920	29	45	3.8	10	0.3	5.2	2.3	3.6	2.2	0.9
25/08/2000	298	1481328.0	2317792.4	530	86	13.6	64.5	0.20	2779	2779	3618	3936	95	87	12.528	13.220	29	55	5.5	5	0.5	0.1	0.4	3.7	0.5	0.3
29/08/2000	301	1737990.4	2409316.4	541	95.5	12.5	65	0.34	2870	3567	3912	3917	95	87	11.145	16.959	81	57	5.5	3	2.7	8.7	0.2	0.5	0.1	6.2
31/08/2000	303	1646593.2	2337446.4	583	58	12.6	63	0.30	2760	2765	3275	3591	96	89	12.083	–	81	55	3.5	3.6	1.4	0.1	0.3	0.6	0.3	0.2
02/09/2000	307	1414780.9	2267226.2	603	98	–		0.35	2736	2664	3597	3487	113	90	–		84	54	2.8	1.6	–	–		–	–	
04/09/2000	308	1582906.8	2210283.9	632	86	12.8	72.4	0.19	2548	2793	3620	3643	95	85	13.364	15.12	53	44	1	1	4.9	0.9	0.3	5.6	0.2	5.2
06/09/2000	310	1167207.5	2118064.7	583	105.5	–		0.35	2465	2817	3227	3536	81	85	–	–	54	48	2.3	1.1	–	–		–	–	
08/09/2000	313	1399066.6	2275764.7	485	95	14.50	55.81	0.19	2420	2019	3737	3434	93	93	13.709	15.911	49	49	1.5	1.3	0.06	0.19	0.29	1.98	0.1	
12/09/2000	317	1482876.0	2319445.1	586	99.6	13.53	70.72	0.01	2277	3187	3782	4121	90	90	13.229	16.847	48	57	1.5	3	0.46	0.27	0.26	4.46	0.16	3.81
14/09/2000	319	–	–	590	97	10.69	66.78	0.16	2675	3568	3853	4446	93	88	11.466	15.754	42	47	2.3	1.1	0.33	0.32	0.29	2.19	0.06	3.91
16/09/2000	321	–	–		–	15.54	72.87	0.17	2884	2901	3584	3741	120	110	15.981	15.492		–			0.15	0.73	1.6	10.76	1.25	10.2
18/09/2000	323	–	–	543	108.5	11.32	52.51	0.46	2880	3183	3621	4064	99	93	32.386	15.874	42	47	1.5	2.1	5.26	0.09		12.49	4.09	12.36
20/09/2000	325	1051741.4	1899966.5	533	104	14.36	73.66	0.38	2870	2518	3399	3914	103	93	13	17.488	33	23	1.8	1.1	0.34	0.07	15.02	29.67	3.4	11.71
22/09/2000	327	1662467.1	1713869.6	512	99	13.47	62.7	0.35	2919	2925	3410	3767	103	98	11.385	15.166	37	27	2.3	1	0.09	0.09	6.22	3.77	3.92	8.45
27/09/2000	332	1529282.5	2059150.8	599	86	13.78	71.71	0.83	2769	2965	3298	3917	103	92	12.327	18.086	43	63	2.8	3.3	0.31	0.09	10.99	26.37	7.57	9.37
29/09/2000	334	1667269.4	2317749.1			12.59	60.14	0.19	2735	2927	3158	3303	108	92	6.968	16.205	39	49	–		34.43	1.2	16.15	5.46	15.72	5.46
03/10/2000	338	1127867.2	1892217.8	633	106.5	13.3	73.4	0.61	2586	2912	2691	4482	95	90	4.824	25.979	44	68	25.8	5.8	18.8	1.1	0.2	1.8	0.4	0.4
05/10/2000	340	1473457.9	1815369.0	572	86	11.4	65.9	0.02	2616	3123	3575	4124	101	87	5.164	17.271	34	48	–	3.1	14.9	0.8	0.4	3.3	0.2	–
07/10/2000	342	1681032.5	2322760.3	644	99.2	13.17		0.34	2762	3003	3721	3981	91	91	13.567	12.116	39	49	3.5	3.1	–	–	0.39	4.27	–	–
09/10/2000	344	1609981.0	2159041.0	647	102.8	15.02	72.64	0.29	2806	2754	3759	4192	92	91	3.961	17.082	46	69	22.8	3.1	21.56	0.68	0.27	1.55	0.14	2.32
11/10/2000	346	1587495.3	2049182.6	575	98	15.78	68.53	1.03	2890	3034	3645	4007	97	90	18.235	17.864	52	67	12	2	9.47	0.54	0.18	1.47	0.1	2.06
13/10/2000	348	1642604.5	2246974.1	580	96	12.9	64.7	0.37	2869	2893	3471	3790	99	91	13.388	16.172	52	57	0.7	2.3	1.6	0.2	0.1	2.6	0.1	2.4
17/10/2000	352	1444227.3	2126969.3	624	99.5	13	67.6	0.31	2485	2590	3371	3516	90	88	32.58	17.134	47	45	7.5	2.1	0.1	0.09	0.2	1.5	0.1	1.2
21/10/2000	356	1615175.1	2174541.4	616	97.5	12.7	67.1	0.30	2243	2550	3037	3318	86	90	83.85	17.121	52	57	3	1.3	0.8	0.4	0.9		0.09	0.8
24/10/2000	359	1675981.3	2260771.2	545	91	12.3	62.7	0.40	2090	2285	3009	3074	90	91	8.567	17.216	49	57	37	1.4	15.3	0.8	0.2	1.1	0.03	0.7
26/10/2000	361	1665229.3	2213401.7	587	104	14.3	76.2	0.18	2269	2454	3126	3338	76	31	13.272	18.001	52	47	10	1.5	10.3	0.5	0.5	1	–	–
28/10/2000	363	1567035.7	2207962.7	684	98.1	14.3	81.6	0.03	2274	2361	3131	3535	76	30	15.091	14.193	57	82	20	2.5	15.6	0.6	0.1	0.8	0.1	0.3
01/11/2000	367	1736789.5	1723720.8	663	104	13.2	78.7	0.17	2361	2558	3257	3423	80	38	13.330	17.335	43	48	7.8	3.25	4.8	0.4	0.2	1.2	0.08	0.9
03/11/2000	369	1216602.9	1952601.9	553	94	13.5	81.3	0.09	–	2898	–	3768	–	30	–	14.349		82		2.25		0.4		2		1.4
07/11/2000	373	1661231.2	2296664.2	597	97	17.1	83.6	0.19	1813	3216	2664	4395	81	77	8.37	15.021	51	56	16.3	19.2	7.7	17.9	0.1	0.8	0.1	0.3
09/11/2000	375			756	93	12	64.8	0.25	1663	3132	3581	4380	73	78	8.78	16.032	46	51	15.8	8.75	11.9	2.2	0.2	1.2	0.1	0.3
11/11/2000	377			925	87	17.4	81.5	0.16	1909	2992	3596	4069	81	48	60.23	15.207	42	46	10.8	3.3	18.3	0.7	2.4	0.8	0.2	0.3
13/11/2000	379			771	102.5	13.3	78.2	0.02	1851	2900	2517	3872	68	95	8.84	15.621	52	57	31	2	35.1	1.6	2.2	0.8	0.1	2.6
15/11/2000	381			738	96	13.5	67.1	0.17	1893	3090	2614	4086	84	98	9.111	14.631	48	49	4.8	2.75	11.2	0.7	0.4	1	0.1	0.6
17/11/2000	383	1090052.7	2358720.9	590	93.5	13.5	72.8	0.14	979	2803	879	3351	75	115	12.538	15.364	56	41	7.5	2.25	4.2	0.4	2.9	0.9	2.6	0.8
21/11/2000	387	837136.6	2355125.3	824	100.5	13	65.4	0.08	–	2913		3912	–	97	–	4.481	–	56		26.3		24.9		2.1	–	1.8

B.2

Date	Day No.	Module A Influent flow Q_i (l/d)	Module B Influent flow Q_i (l/d)	Influent COD S_{ti} (mgCOD/l)	Influent TKN N_{ti} (mgN/l)	Influent Total P P_{ti} (mgP/l)	Influent NH_4 N_{ai} (mgN/l)	Influent NO_3+NO_2 NO_{xi} (mgN/l)	Module A VSS X_v (mgVSS/l)	Module B VSS X_v (mgVSS/l)	Module A TSS X_t (mgVSS/l)	Module B TSS X_t (mgVSS/l)	Module A settled DSVI (ml/g)	Module B settled DSVI (ml/g)	Module A Effluent NO_3 NO_{3e} (mgN/l)	Module B Effluent NO_3 NO_{3e} (mgN/l)	Module A Effluent COD S_{te} (mgCOD/l)	Module B Effluent COD S_{te} (mgCOD/l)	Module A Effluent TKN N_{te} (mgN/l)	Module B Effluent TKN N_{te} (mgN/l)	Module A Effluent NH_4 N_{ae} (mgN/l)	Module B Effluent NH_4 N_{ae} (mgN/l)	Module A Effluent TP P_{te} (mgP/l)	Module B Effluent TP P_{te} (mgP/l)	Module A Effluent OP P_{se} (mgP/l)	Module B Effluent OP P_{se} (mgP/l)
23/11/2000	389	1617972.8	2205807.2	860	52	63.3	62.9	0.17	2081	3172	2230	4183	136	81	0.082	10.906	430	105	135	3	63.3	8.5	21.1	19	17.0	1.7
25/11/2000	391	1860654.9	2324965.8	861	58	62.7	58.4	0.02	3074	3272	2457	4438	125	83	0.41	13.75	437	76	53	2	67	0.4	22.1	10.9	16.8	0.7
27/11/2000	393	1659993.5	2242903.4	827	96	62.9	64	0.01	2925	3378	2325	4528	120	88	0.787	9.317	448	45	100.2	17		20.2	17.8	1.1	15.3	0.5
29/11/2000	395	682117.8	1027797.1	882	75.5	62.9	71.5	0.02	1826	3308	2502	4605	134	87	0.572	15.473	392	45	82	4	87.9	2.8	3.8	13.8	0.7	12.7
01/12/2000	397	476899.7	1079950.0	863	52	62.9	66.7	0.05	1841	2955	2375	3994	98	87	0.086	11.522	386	60	80.7	1.75	85.7	1.26	3.3	1.7	2.5	8.1
06/12/2000	402	719872.0	858263.0	657	58	35.6	64.4	0.00	1840	3030	2328	4070	103	79	0.409	11.486	524	58	80.3	2	82.6	0.7	1.2	8.2	0.2	9.9
08/12/2000	404	809091.2	1163350.1	846	96	62.7	64.4	0.01	2005	3095	2525	4103	103	102	0.532	11.472	172	78	77.8	2.25	89.9	0.8	1	13.8	0.4	13.4
12/12/2000	408	1235692.2	1503380.8	833	59	12.9	71.3	0.12	2827	3170	3540	4559	99	101	0.801	10.702	79	59	72.9	2.75	55.9	0.5	0.8	13.8	0.5	12.3
14/12/2000	410	1052007.0	1886455.0	803	52	62.7	66.5	0.16	2555	2509	3091	4602	107	101	0.684	14.550	64	49		1.5	24.0	0.1	0.6	5.4	0.09	3.1
08/01/2001	435	968767.4	1085090.1	704	100.5	13.7	74.6	2.34	3640	3058	3508	3019	100	102	10.96	13.102	90	70	21.1	4	15.5	1.2	0.6	11.4	0.1	12.8
10/01/2001	437	2209827.4	2352079.4	675	95.5	62.2	78.9	0.26	3022	3249	3501	3147	116	91	0.402	10.777	116	85	22	3.75	21.9	1.3	18.5	11.4	15.8	10.0
12/01/2001	439	1839061.5	2354045.8	650	92.6	62.1	68.3	0.05	2681	3812	3510	3180	100	93	0.32	12.987	120	60	63.8	3.25	37	0.7	3.1	5.4	2.5	10.1
16/01/2001	443	1778034.2	2241337.0	766	104	62.8	74.3	0.19	2820	3580	3381	3430	89	95	1.023	12.427	84	61	75.4	4	26.9	3.7	0.5	5.3	0.5	5.1
18/01/2001	445	1782156.2	2243033.1	677	92.5	62.3	60.5	0.73	2442	300	5602	3012	74	179	1.752	12.424	70	65	78.1	3	19.8	1.8	0	3	7	3
20/01/2001	447	1850161.0	2229899.1	574	95.2	62.3	67.7	0.01	3873	264	6738	5103	124	91	1.341	8.389	68	64	39	20.5	18.8	10.6	0.6	1.4	3.5	7.3
22/01/2001	449	1231026.9	2208579.2	709	100.4	62.6	70.1	0.02	3087	782	4937	8239	170	97	0.092	3.927	68	74	39.8	23.5	15.7	26.1	1.2	1.4	1.1	2.5
24/01/2001	451	1221997.8	2258886.4	–	–	61.5	51.9	0.24	4055	1334	6371	1589	170	96	6.091	8.437	–	–	20.1	47.5	15.8	33.7	0.3	0.7	0.2	0.5
26/01/2001	453	1884369.2	2138147.8	–	–	17.5	67.2	0.02	2897	1874	4166	2962	139	97	1.425	11.892	–	–	24.5	48.6	27.8	12.0	0.2	0.9	0.09	0.1
30/01/2001	457	1962674.7	2308157.2	697	99.6	13	67.7	0.18	3234	3238	4166	4248	131	88	5.182	9.671	51	72	25.5	31.5	0.2	2.1	0.2	0.1	0.1	0.2
01/02/2001	459	1715271.4	2219860.7	640	99	61.8	55.4	0.16	3406	3643	3124	4019	102	94	1.742	22	52	57	12	6.5	–	–	0.2	0.7	0.1	0.1
03/02/2001	461	1771011.7	2212926.7	659	96.8	61.7	68.3	0.12	1912	2681	2665	5299	102	118	15.59	15.98	57	82	17.5	1.8	0.00	0.09	0.2	0.4	0.1	0.1
05/02/2001	463	2003169.4	2156891.9	755	102.1	63.7	–	0.26	2719	3064	3774	2568	105	105	13.08	17.97	62	82	4.5	2.3		0.6	5.2	1.9		1.7
07/02/2001	465	1054021.1	2246751.8	655	96.8	11.4	65.1	0.21	3517	2920	5312	2722	101	97	2.73	16.24	32	47	2.8	1.8	0.6	0.1	0.4	0.5	0.2	0.2
09/02/2001	467	2167068.2	2232569.5	751	90.5	13	70.6	0.54	2195	3327	3082	4689	105	108	20.0	20.41	20	62	4.5	2.5	0.3	0.1	6.6	1.6	4.1	1.1
13/02/2001	471	1763242.5	2323589.0	660	104.6	12	75.4	0.47	657	4140	5001	5453	111	99	6.13	15.8	62	52	22.5	2.8	17.9	0.5	6.6	7	0.7	0.2
15/02/2001	473	1035094.0	2025020.0	677	93.6	12.1	62.5	3.87	563	4008	1321	5262	90	103	1.70		51	65	42.3	2.5	35.7	0.6	10.5	3.4	0.6	6.6
17/02/2001	475	2067389.9	2320021.4	615	97.5	12.3	64	4.84	3825	1482	5258	3915	100	99	–		56	101	3	2.6	1.1	0.1	4.7	11.6	4.5	1.1
19/02/2001	477	1489627.3	1912578.9					0.30																		
21/02/2001	479	1949887.4	2169330.6	540	95.3	61.6		0.30	4058	2383	5387	3796	104	106	13.1	12.91	41	46	2.3	9.5	–	7.1	0.4	2.1	–	5.8
23/02/2001	481	2221300.4	2332377.1	615	104.5	12.7	69.6	0.75	4081	1956	3524	3086	98	92	11.36	18.27	36	42	2.3	2.3	0.4	5.2	2.6	4.1	2.2	3.2
25/02/2001	483	2234490.5	2311129.6	596	99.6	–	72.4	0.42	1900	4136	2457	3574	86	101	19.83	14.2	64	39	4	2.5	0.4	0.3	8.4	0.6	8.1	0.4
01/03/2001	487	1930386.8	2144441.7	657	97.8	62.5	78.9	0.87	937	4619	1390	6099	75	92	20.787	15.36	64	82	5	6.3	1.7	0.1	0.3	5.9	6.3	5.3
03/03/2001	489	1861881.5	2548978.9	726	106.5	13.6	56.9	0.82	1663	2723	4720	3489	91	106	18.726	25.078	68	77	4.5	2	0.6	0.3	6.6	11.4	0.6	10.7
05/03/2001	491	1255959.0	2210980.5	509	103.8	12.3	57.6	0.80	4614	1560	6259	2109	88	62	10.091	18.501	53	53	3	7.7	0.41	0.1	4.3	6.1	4.1	0
07/03/2001	493	1369967.5	2945312.8	665	107.2	11.6	58.5	0.28	4680	691	6276	2548	84	89	10.098	11.190	59	68	4.5	8.7	0.3	5.2	3.3	1.2	3.3	3.6
09/03/2001	495	1720292.0	2390233.8	644	97.1	12.8	36	0.09	3072	451	6465	941	82	128	9.785	4.380	24	73	3	24.5	10.7	24.5	7.1		2.9	4.3
13/03/2001	499	1717357.1	2298324.8	653	98.0	63.3	78.8	0.25	1591	480	2120	748	91	81	18.937	7.421	67	120	8.7	91.6	7.7	43.1	12	7	10.3	6.7
15/03/2001	501	1594571.1	2298164.6	577	85.6	12.2	62.8	0.42	5121	1029	6689	1389	75	79	14.672	11.769	49	65	3.7	29.2	5.4	22.2	4.2	0.9	4	5.6
17/03/2001	503	1678320.0	2317206.4	642	111.8	13	64.3	0.27	4850	1320	6739	1739	78	81	19.171	8.708	66	76	3.5	20.81	0.5	26.4	3.8	3.4	7.4	3
19/03/2001	505	1646873.6	2265114.2	577	99.9	12.6	61.8	0.16	5072	896	6791	1229	76	78	17.762	11.642	51	58	3	55	0.4	26.0	6.6	5.3	0.2	4.8
23/03/2001	509	1136215.0	2198511.6	509	97	13.2	60.9	0.29	4793	376	6280	637	79	56	14.898	3.456	39	123	5.6	55.3	0.7	42.1	8	6	8.4	5
29/03/2001	515	1646421.6	2308697.5	615	94.1	15	72.2	0.45	3321	3544	938	4162	106	88	17.646	9.945	72	62	22.5	15.3	13.4	10.0	12.4	3.3	11.4	2.8
31/03/2001	516	1600901.6	2350137.7	612	111.6	12.3	83	0.56	2904	2618	7119	3796	76	82	21.197	14.704	68	140	5.5	5.5	8.9	0.6	8.7	9.6	8.6	5
02/04/2001	520	1560128.7	2162772.4	618	107.5	11.4	73.4	0.60	3849	1067	4766	1593	80	84	15.255	11.02	36	40	15.8	25.8	10.2	17.9	6.3	1.6	5.8	1.2
04/04/2001	522	1866940.0	2106472.1	610	105.2	62.6	86.4	0.78	3214	1448	4022	1871	88	85	17.115	17.192	62	176	5.8	11.2	0.4	1.7	0.4	6.8	0.2	2.1
10/04/2001	526	1262796.6	2196762.9	774	101.9	11.6	79.1	0.80	3462	1175	4250	1474	90	56	11.82	8.528	28	135	3.8	8.8	0.4	3.8	5.4	0.5	6.4	2.7
17/04/2001	532	2314932.2	2340122.3	501	111.1	13.1	78.1	0.05	4106	1251	4795	1801	103	56	8.24	0.18	121	93	70.8	42.3	53.8	50.8	40.1	1.7	30.4	0.8
19/04/2001	536	1516855.8	2190465.7	585	99.1	10.8	79.3	0.41	4063	1136	4962	1581	87	101	12.967	5.737	70	80	7.2	53	2.5	19.9	0.4	0.6	0.2	0.3
23/04/2001	538	1707192.8	2657168.6	617	96.3	11.8	89.5	0.37	4036	1245	5071	1784	98	97	14.844	9.425	63	90	6	20.8	3.8	22.7	0.4	0.5	0.2	0.3
25/04/2001	540	1989238.9	2240183.4	614	106.3	10.7	28.7	0.17	3010	1127	3179	1725	103	162	2.564	5.067	39	66	29	54	15	16.3	0.1	0.5	0.1	0.3
25/04/2001	542	1697387.2	2155972.8	315	98.8	12.7	69.8	0.17	3042	1278	4797	1699	11	116	8.135	1.628	119	73	40.7	42.3	55.1	22.7	47.6	0.5	38	0.3
02/05/2001	548	1723403.72	2292228.16	583.0	103.6	14	70.7	0.02	4575	1370	4891	2129	115	94	8.350	1.367	74	107	34.5	57.5	41.3	46.1	0.3	0.7	0.4	0.7
04/05/2001	551	2014875.92	2297712.64	510.0	99.7	12.7	69	0.11	4062	1002	5166	2032	122	102	18.326	12.199	65	82	14.5	41.3	8.1	34.9		0.6	–	0.7
08/05/2001	555	1868977.48	2257986.88	377.0	103.3	11.5	69.9	0.24	1039	2313	2370	2888	114	99	4.32	20.73	35	101	3.7	24.1	0.5	4.4	0.1	0.1	0.09	0.1
10/05/2001	557	1538936.24	2290040.64	533.0	103.8	11.8	55.7	0.32	3532	1950	4730	2578	131	101	7.18	18.2	03	91	10.5	7.3	0.6	0.5	0.2	1.2	0.8	0.2
12/05/2001	559	1821026.32	2250570.24	610.0	103.8	14.7	71.8	1.09	3530	2918	4614	2832	122	99	6.92	13.4	62	100	–	18.2	9.6	9.7	3.7	8.2	2.9	0.2
14/05/2001	561	1841200.92	2252242.52	618.0	110	12.4	56.8	0.89	2894	2036	2876	2812	120	92	4.57	10.38	50	119	20.2	10.8	9.6	16.1	5.1	1.1	0.8	0.2
16/05/2001	563	2132019.52	2259246.02	647.0	100.0	12.7	61.3	0.21	2573	2042	3464	2833	149	98	17.032	17.85	59	108	10.5	11.5	1.3	2.4	0.4	3	0.2	
18/05/2001	565	1842715.48	2238331.6	508.0	104.1	13.1	55.7	0.37	2377	1598	3305	2266	145	111	15.006	17.163	58	121	4.1	14.1	0.5	4.3	0.2	2.1	0.1	0.2
22/05/2001	569	1727943.04	2609817.44	626.0	106.4	11.9	73.7	0.25	2453	2108	3365	3047	109	138	16.06	17.31	68	97	6.5	15.8	0.5	0.9	1.3	2	1.2	0.4
24/05/2001	571	2025668.2	2253377.6	632.0	100.1	13.1	77.8	0.14	3726	2270	3715	3204	56	128	24.21	16.3	77	153	22.1	34.5	0.4	0.2	1.3	1.2	1.3	0.1
28/05/2001	575	2098926.28	2106370.34	652.0	102.9	12.7	67.8	0.43	456	2510	1201	3327	79	102	15.21	18.24	81	124	17	9.5	5.2	0.4	6.1	3.8	7.5	0.3
30/05/2001	577	1879629.76	2166700.4	571.0	100.0	10.7	69.1	0.31	2662	2390	3570	3214	51	106	61.421	18.823	76	95	15.8	9.5	4.1	0.5	1.5	1.9	1.2	0.3
01/06/2001	579	1606777.76	2253624.96	514.0	97.8	10.4	68.6	0.38	2320	2471	3163	3605	97	106	8.125	19.889	71	80	25.7	8.3	13.3	3.2	4.1	2.1	3.6	0.7
05/06/2001	583	1956692.16	2198548.12	600.0	91.8	11.0	65.7	0.36	1740	2311	3578	2188	91	100	13.117	17.849	91	152	5.5	12	0.8	1.6	1.5	1	0.9	0.5
09/06/2001	587	1987406.64	2264201.76	687.0	102.8	14	70.4	0.84	2531	2421	3707	2534	101	77	10.919	17.872	60	105	13.3	17.4	67.1	9	5.0	5.4	3.6	8.5
11/06/2001	589	1803965.76	2285885.6	710.0	102.6	12.9	72.1	0.28	3251	2720	3154	4011	56	77	11.677	1.156	29	125	16.3	70	2.4	20.0	2.4	19.1	2.2	24.9

Table B2 : Bi-daily "site" filtered data.

MITCHELL'S PLAIN WWTP - PILOT PLANT : Bi-DAILY LABORATORY DATA

Date	Day No.	Influent Floc/filtered S_{ti} (mgCOD/l)	Influent Filtered N_{ti} (mgN/l)	Influent Filtered P_{ti} (mgP/l)	Influent Filtered P_{si} (mgP/l)	Mod A Eff Floc/filtered S_{te} (mgCOD/l)	Mod B Eff Floc/filtered S_{te} (mgCOD/l)	Mod A Eff Floc/filtered N_{te} (mgN/l)	Mod B Eff Floc/filtered N_{te} (mgN/l)	Mod A Eff Filtered P_{te} (mgP/l)	Mod B Eff Filtered P_{te} (mgP/l)
12/06/2000	225	462	86.6	10.78	8.93	58		0.80	0.50	0.14	2.06
19/06/2000	232	490	80.5	9.73	8.64	43	53	0.50	0.30	0.20	3.99
21/06/2000	234	230	76.5	10.80	9.86	33	19	2.80	0.50	0.20	1.04
23/06/2000	236	411	63.0	9.59	8.20	19	10	0.80	1.50	0.10	3.04
27/06/2000	240	260	85.5	10.60	10.60	39	24		0.80	0.23	8.10
29/06/2000	242	272	76.0	11.05	10.86	26	33	0.50	0.80	0.19	2.14
04/07/2000	247	266	64.0	12.52	11.99	28	32	0.80	0.80	0.24	0.85
06/07/2000	249	303	79.3	11.89	11.57	32	37	1.06	2.95	0.31	1.91
08/07/2000	251	257	121.5	11.04	10.80	61	33		3.00	11.10	4.00
10/07/2000	253	271	83.3	10.01	8.50	42	33	1.80	0.30	0.20	2.70
12/07/2000	255	252	76.0	12.92	11.30	33	33			0.60	2.50
14/07/2000	257	307	71.0			33	32	0.30	0.10		
18/07/2000	261	215	90.0	11.28	10.20	28	28	0.80	1.30	0.20	4.10
20/07/2000	263	200	57.5	8.83	8.05	45	33	0.80	0.10	0.40	1.50
22/07/2000	265	218	78.0		16.50	14	14		2.30		
24/07/2000	267	248	75.5	11.00	10.90	42	41	0.40	0.20	1.90	8.00
26/07/2000	269	213		11.40	12.10	19	23	5.45	0.30	4.00	8.40
28/07/2000	271	224	78.5	11.60	11.60	46	36	3.30	0.50	1.50	2.15
01/08/2000	275	291	86.5	12.40	11.40	27	32	19.30	0.80	0.30	0.30
03/08/2000	277	238	75.5	8.60	8.50	43	43	16.00	0.50	0.20	0.20
05/08/2000	279	236	80.0	10.30	9.30	30	34	0.50	0.50	0.10	0.30
08/08/2000	282	248	89.0	12.20	7.90	20	30	1.00	0.80	0.20	0.40
11/08/2000	285	202	75.5	8.90	8.90			0.50	0.80	0.09	0.40
15/08/2000	289	248	83.0	11.80	9.50	29	33	1.50	0.30	0.60	3.30
17/08/2000	291			11.00	9.40					1.30	6.00
19/08/2000	293	165	84.5	11.50	8.20	19	19	1.80	2.00	0.20	4.30
21/08/2000	295	220	95.0	10.60	9.10	24	28	1.50	9.80	2.30	5.30
23/08/2000	297	240	90.5	11.00	10.60	29	38	2.00	9.00	2.40	1.10
25/08/2000	299	343	63.5	8.20		29	29	2.30	2.00	0.30	0.30
29/08/2000	303	220	86.0	10.30	8.90	37	32			0.10	0.10
31/08/2000	305	209	83.5	9.50	8.70	35	45	3.80	1.00	0.30	0.40
02/09/2000	307	245	84.0			39	49	2.00	0.80		
04/09/2000	309	255	87.0	10.50	10.20		39	5.30	1.50	0.30	5.20
06/09/2000	311	271	83.5			29	34	1.80	0.80		
08/09/2000	313	233	76.0	10.44	10.06	34	39	1.00	0.80	0.28	1.84
12/09/2000	317	203	78.9	11.07	10.89	39	43	1.00	2.00	0.21	3.82
14/09/2000	319	236	80.0	9.44	8.96	38	35	1.30	1.00	0.72	2.96
16/09/2000	321			12.52	11.97					1.39	10.31
18/09/2000	323	243	86.5	9.85	8.22	33	42	1.30	2.00		32.55
20/09/2000	325	224	89.5	11.49	11.30	19	23	1.00	1.30	14.87	29.45
22/09/2000	327	233	75.5	10.88	9.55	33	37	1.50	1.50	6.18	8.45
27/09/2000	332	342	90.5	12.11	11.65	43	55	1.80	1.50	18.58	23.58
29/09/2000	334	195		9.87	9.64	39	44			16.05	5.46
03/10/2000	338	282	98.0	11.60	11.40	39	53	25.00	4.50	0.30	0.30
05/10/2000	340	251	86.5	10.20	10.20	34	39	2.00	1.50	0.30	1.10
07/10/2000	342	215	86.9	12.01		29	39	2.00	5.50	0.24	3.79
09/10/2000	344	375	90.5	11.02	9.46	44	64	27.00	2.00	0.18	2.43
11/10/2000	346	343	84.0	11.15	10.20	43	57	11.30	1.50	0.18	2.27
13/10/2000	348	284	75.5		13.10	47	52	3.80	1.50	0.10	2.50
17/10/2000	352	290	91.5	10.90	9.20	39	48	3.50	2.50	0.20	1.30
20/10/2000	355	295	85.0	10.30	9.40	48	52	2.30	1.00	0.00	
24/10/2000	359	276	83.5	16.40	9.70	48	52	16.50	1.50	0.20	1.00
26/10/2000	361	256	95.0	13.20		47	43	14.80	1.75	0.50	0.90
28/10/2000	363	275	82.0	12.30	9.70	47	43	15.00	1.75	0.50	0.90
01/11/2000	367	269	89.5	10.60	9.60	38	43	6.50	1.75	0.20	1.00
03/11/2000	369	191	78.5	15.00	9.40		53		2.00		1.90
07/11/2000	373	259	85.5	11.00	10.40	46	46			0.20	0.00
09/11/2000	375	287	81.5	10.70	10.30	46	46	14.30	5.00	0.20	0.60
11/11/2000	377	306	78.5	15.20	9.50	37	37			0.30	0.60
13/11/2000	379	257	91.5	11.10	10.40	52	48	19.00	1.75	0.10	0.40
15/11/2000	381	308	85.0	11.60	10.60	43	43	13.00	2.00	0.30	0.70
17/11/2000	383	155	81.0	10.70	10.10	36	31	4.50	1.50	5.60	0.70
21/11/2000	387	256	89.5	12.00	10.10		31		24.50		1.80

Date	Day No.	Influent Floc/Filtered S_{ti} (mgCOD/l)	Influent Filtered N_{ti} (mgN/l)	Influent Filtered P_{ti} (mgP/l)	Influent Filtered P_{si} (mgP/l)	Mod A Eff Floc/Filtered S_{te} (mgCOD/l)	Mod B Eff Floc/filtered S_{te} (mgCOD/l)	Mod A Eff Floc/filtered N_{te} (mgN/l)	Mod B Eff Floc/filtered N_{te} (mgN/l)	Mod A Eff Filtered P_{te} (mgP/l)	Mod B Eff Filtered P_{te} (mgP/l)
23/11/2000	389	505	84.0	11.30	9.50	131	61	94.50	2.00	26.10	2.20
25/11/2000	391	211	81.0	10.85	9.10	171	40	77.35	1.50	17.40	10.50
27/11/2000	393	328	82.5	10.90	9.50	224	60	81.50		14.50	0.60
29/11/2000	395	323	59.0	11.00	10.60	123	35	75.30	2.80	0.40	15.00
01/12/2000	397	255	82.5	11.40	11.10	121	55	71.50	1.25	2.50	1.20
06/12/2000	402	338	85.5	11.20	10.40	114	50	75.00	1.25	0.70	7.90
08/12/2000	404	215	83.5	11.20	10.00	98	59	69.50	1.50	0.10	13.80
12/12/2000	408	315	82.5	11.00	10.60	59	34	66.50	1.00	0.40	13.00
14/12/2000	410	236	86.0	11.00	10.60	40	44	60.80	1.25	0.20	9.10
08/01/2001	435	382	90.5	12.00	11.80	75	65	19.50	3.50	0.30	12.60
10/01/2001	437	362	92.0	10.80	10.80	55	45	19.30	3.25	17.30	20.70
12/01/2001	439	500	77.0	10.50	10.30	100	59	53.30	3.50	2.30	0.50
16/01/2001	443	388	90.5	11.50	11.10	75	60	32.50	3.50	0.50	0.30
18/01/2001	445	498	82.5	10.50	8.20	60	63	32.50	1.75	7.00	2.00
20/01/2001	447	356	87.0	10.20	10.00	54	59	23.50	19.50	0.50	1.30
22/01/2001	449	453	92.5	11.30	9.60	59	64	40.30	32.00	1.10	1.60
24/01/2001	451		79.5	9.60	9.50			16.30	41.30	0.20	0.50
26/01/2001	453		82.5	9.60	9.10			33.50	18.50	0.20	0.30
30/01/2001	457	453	91.5	10.90	9.50	31	62	22.50	30.50	0.10	0.30
01/02/2001	459	344	54.0	10.00	9.30	52	52	11.30	4.30	0.20	0.20
03/02/2001	461	392	85.5	9.70	8.80	46	57	1.30	1.00	0.20	0.20
05/02/2001	463	474	90.5	11.10		57	52	2.50	1.80	4.60	1.90
07/02/2001	465	263	79.0	10.00	9.80	37	47	2.00	1.30	0.30	0.40
09/02/2001	467	216	83.5	10.50	10.30	36	57	3.50	2.50	1.50	1.50
13/02/2001	471	273	87.0	11.00	11.00	57	52	25.50	2.00	0.70	1.00
15/02/2001	473	278	80.0	10.40	10.40	71	66	38.50	1.80	9.70	6.80
17/02/2001	475	289	88.0	11.30	9.70	55	60	4.30	2.10	4.60	12.00
19/02/2001	477										
21/02/2001	479	243	81.8	10.00		32	46			0.30	2.00
23/02/2001	481	181	86.6	10.80	9.70	35	35		1.60	2.40	3.90
27/02/2001	485	235	56.9	10.80	10.90	54	59		1.30	6.40	0.50
01/03/2001	487	240	88.4	11.80	10.40	59	74	3.30	1.30	5.00	5.90
03/03/2001	489	275	91.6	11.40	9.70	56	77	5.50	1.30	6.60	10.70
05/03/2001	491	256	90.9	11.00	10.30	48	53	5.00	2.30	3.10	6.00
07/03/2001	493	268		9.90	8.90	59	63	3.00	7.10	3.30	2.80
09/03/2001	495	216	79.6	10.80	9.60	34	63	3.20	33.00	2.90	
13/03/2001	499	215	98.6	10.80	10.20	63	96	4.50	62.80	10.50	6.80
15/03/2001	501	216	85.0	10.20	10.00	45	58	2.30	27.30	4.00	0.80
17/03/2001	503	271	97.1	11.40	10.30	60	70	2.70	19.00	7.50	3.10
19/03/2001	505	199	85.3	10.50	9.00	50	55	2.00	32.50	6.30	4.90
23/03/2001	509	191	95.0	10.10	8.50	54	55	4.00	50.00	8.60	5.10
27/03/2001	513	284	96.3	10.70	10.70	68	59	17.80	14.00	11.60	2.90
29/03/2001	515	233	86.1	10.10	10.10	63	136	4.50	2.00	8.60	8.00
03/04/2001	520	248	95.0	9.60	9.60	61	76	13.30	24.50	5.80	1.30
05/04/2001	522	215	90.7	10.80	10.00	57	76	4.50	4.50	0.20	2.10
09/04/2001	526	236	87.6	10.10	10.00	67	76	3.50	8.50	6.40	5.70
17/04/2001	534	238	95.7	11.10	10.50	54	84	62.00	39.80	46.10	1.30
19/04/2001	536	205	81.6	9.50	9.50	60	75	8.30	24.35	0.30	0.40
21/04/2001	538	239	81.7	10.00	10.00	60	92	4.50	29.30	0.30	0.30
23/04/2001	540	178	96.3	9.30	9.30	54	64	27.80	35.30	0.10	0.50
25/04/2001	542	267	89.4	8.50	8.20	79	69	51.80	39.00	31.40	0.30
02/05/2001	549	254	91.3	11.00	11.00	73	88	53.30	54.50	0.40	0.30
04/05/2001	551	218	87.2	10.20	10.00	53	83	13.20	49.20		0.30
08/05/2001	555	231	90.9	9.30	9.20	48	32	7.60	11.00	0.10	0.30
10/05/2001	557	216	90.4	9.40	9.20	53	67	10.50	5.80	5.10	0.20
12/05/2001	559	238		9.70	9.70		81	19.50	32.50	5.00	0.30
14/05/2001	561	245	89.6	10.10	9.20	64	88	19.50	20.60	2.90	0.50
16/05/2001	563	250	94.3	10.70	9.70	64	68	9.00	7.00	0.30	1.10
18/05/2001	565	240	91.9	8.70	7.50	69	83	4.50	11.00	0.10	0.20
22/05/2001	569	242	92.5	9.90	9.90	63	72	5.30	10.80	1.20	1.00
24/05/2001	571	249	93.6	10.40	10.40	72	96	12.50	10.80	1.20	0.40
28/05/2001	575	238	89.0	10.00	10.00	73	86	3.00	8.50	7.50	0.70
30/05/2001	577	229	90.5	8.70	8.30	71	81	14.00	5.50	1.20	0.70
01/06/2001	579	205	81.3	8.70	8.70	67	81	22.50	7.00	3.80	0.90
05/06/2001	583	222	84.1	9.60	9.60	86	91	4.50	5.30	1.40	1.90
09/06/2001	587	266	91.5	11.40	11.40	73	96	12.00	14.30	5.40	4.70
11/06/2001	589	270	96.3	11.00	11.00	70	35	13.30	46.00	2.30	28.50

Table B3 : Long Term Period II - Averages Report.

MITCHELL'S PLAIN WWTW - PILOT PLANT : LABORATORY REPORT

Averages for Period II

SAMPLE	UNITS	MODULES A & B INFLUENT	MODULE A MIXED LIQUOR / ACTIVATED SLUDGE							MODULE B MIXED LIQUOR / ACTIVATED SLUDGE							MODULE A EFFLUENT	MODULE B EFFLUENT
			Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle		
Unfiltered COD	mg COD/l	558.88															38.49	39.38
Flocculated/Filtered COD	mg COD/l	263.79															31.64	30.74
Unfiltered TKN	mg N/l	92.47															2.89	1.48
Filtered TKN	mg N/l	39.61																
Flocculated/Filtered TKN	mg N/l																2.66	0.97
Filtered FSA	mg N/l	70.44															2.03	0.30
Filtered NO_3	mg N/l	0.22	[illegible]	7.22	7.74	11.72	7.02	8.66	10.37	0.59	6.01	6.02	14.78	7.70	13.97	14.10	12.50	16.12
Filtered NO_2	mg N/l	0.04	0.08	0.13	0.13	0.05	[illegible]	0.06	0.98	0.06	0.30	0.20	0.05	0.19	0.04	0.03	0.13	0.05
Filtered $NO_3 + NO_2$	mg N/l	0.31															12.11	15.76
Unfiltered Total P	mg P/l	13.12															2.28	5.50
Filtered Total P	mg P/l	10.77	18.85	6.04		2.20				22.32	9.28		4.45				2.13	5.13
Filtered Ortho P	mg P/l	10.05															1.49	4.12
pH		7.14				6.51							6.43				6.68	6.48
Alkalinity	mg/l as $CaCO_3$	321.11															56.32	29.60
TSS	mg MLSS/l	147.00				3384.34							4115.67					
VSS	mg MLVSS/l	104.21				2436.31							3157.89					
SVI	ml/g					129.17							115.60					
DSVI	ml/g					96.77							86.85					

Notes :

1. The average long term period concentrations in the above table includes days on which process upsets/incidents occurred.
2. The influent and effluent samples are composite samples. All other samples are grab samples.

Table B4 : Long Term Period III - Averages Report

MITCHELL'S PLAIN WWTW - PILOT PLANT : LABORATORY REPORT

Averages for Period III

SAMPLE	UNITS	MODULES A & B INFLUENT	MODULE A MIXED LIQUOR / ACTIVATED SLUDGE: Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	MODULE B MIXED LIQUOR / ACTIVATED SLUDGE: Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	MODULE A EFFLUENT	MODULE B EFFLUENT
Unfiltered COD	mg COD/l	611.10															46.04	53.84
Flocculated/Filtered COD	mg COD/l	266.88															42.20	46.92
Unfiltered TKN	mg N/l	97.89															[illegible]	[illegible]
Filtered TKN	mg N/l	85.81																
Flocculated/Filtered TKN	mg N/l																11.24	3.65
Filtered FSA	mg N/l	67.81															10.19	2.37
Filtered NO_3	mg N/l	0.17	0.21	3.39	4.05	10.06	3.48		6.95	0.18	5.17	5.51	[illegible]	[illegible]	4.34	2.66	8.69	16.09
Filtered NO_2	mg N/l	0.11	[illegible]	0.25	0.25	[illegible]	[illegible]		0.17	0.06	0.21	[illegible]	0.04	0.18	0.04	0.06	0.22	0.08
Filtered $NO_3 + NO_2$	mg N/l	0.13															7.20	15.38
Unfiltered Total P	mg P/l	13.03				[illegible]							[illegible]				1.55	1.80
Filtered Total P	mg P/l	11.09	[illegible]	[illegible]		1.55				[illegible]	13.33		[illegible]				1.48	1.53
Filtered Ortho P	mg P/l	10.02															1.33	1.29
pH		7.38				6.85							6.64				6.97	6.74
Alkalinity	mg/l as $CaCO_3$	328.73															[illegible]	51.20
TSS	mg MLSS/l	106.20				2958.69							3834.80					
VSS	mg MLVSS/l	86.74				2175.83							2895.85					
SVI	ml/g					94.61							92.71					
DSVI	ml/g					86.53							86.85					

Notes :

1. The average long term period concentrations in the above table includes days on which process upsets/incidents occurred.
2. The influent and effluent samples are composite samples. All other samples are grab samples.

Table B5 : Long Term Period IV - Averages Report.

MITCHELL'S PLAIN WWTW - PILOT PLANT : LABORATORY REPORT

Averages for Period IV

SAMPLE	UNITS	MODULES A & B INFLUENT	MODULE A MIXED LIQUOR / ACTIVATED SLUDGE							MODULE B MIXED LIQUOR / ACTIVATED SLUDGE							MODULE A EFFLUENT	MODULE B EFFLUENT
			Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle		
Unfiltered COD	mg COD/l	659.93															276.63	54.73
Flocculated/Filtered COD	mg COD/l	306.25															124.98	48.70
Unfiltered TKN	mg N/l	91.96															90.69	[illegible]
Filtered TKN	mg N/l	79.71																
Flocculated/Filtered TKN	mg N/l																75.41	1.68
Filtered FSA	mg N/l	65.37															63.05	3.58
Filtered NO_3	mg N/l	0.05	[illegible]	[illegible]	0.33	3.00	[illegible]		0.21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10.27	0.28	12.42
Filtered NO_2	mg N/l	0.05	0.16	[illegible]	0.04	[illegible]	[illegible]		[illegible]	0.08	0.07	0.07	[illegible]	[illegible]	[illegible]	0.08	0.21	0.09
Filtered NO_3 + NO_2	mg N/l	0.19															0.42	11.40
Unfiltered Total P	mg P/l	12.79				104.23							[illegible]				12.15	8.24
Filtered Total P	mg P/l	11.08	[illegible]	9.24		[illegible]				[illegible]	[illegible]		[illegible]				7.97	7.76
Filtered Ortho P	mg P/l	10.15															7.67	7.51
pH		7.37				7.51							6.82				7.65	7.06
Alkalinity	mg/l as $CaCO_3$	334.43															320.65	[illegible]
TSS	mg MLSS/l	88.44				2482.25							4532.88					
VSS	mg MLVSS/l	75.40				2079.40							3211.65					
SVI	ml/g					126.88							123.58					
DSVI	ml/g					110.38							92.85					

Notes :

1. The average long term period concentrations in the above table includes days on which process upsets/incidents occurred.
2. The influent and effluent samples are composite samples. All other samples are grab samples.

Table B6 : Long Term Period V - Averages Report.

MITCHELL'S PLAIN WWTW - PILOT PLANT : LABORATORY REPORT

Averages for Period V

SAMPLE	UNITS	MODULES A & B INFLUENT	MODULE A MIXED LIQUOR / ACTIVATED SLUDGE Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	MODULE B MIXED LIQUOR / ACTIVATED SLUDGE Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	MODULE A EFFLUENT	MODULE B EFFLUENT
Unfiltered COD	mg COD/l	676.14															87.00	70.43
Flocculated/Filtered COD	mg COD/l	427.00															68.29	58.29
Unfiltered TKN	mg N/l	96.64															31.08	14.96
Filtered TKN	mg N/l	86.93																
Flocculated/Filtered TKN	mg N/l																30.36	14.07
Filtered FSA	mg N/l	67.63															26.76	10.73
Filtered NO_3	mg N/l	0.15	0.21	0.13	0.35	1.59	0.27	-	2.21	0.10	3.29	4.04	11.07	3.36	10.63	9.94	1.27	11.05
Filtered NO_2	mg N/l	0.22	0.23	0.04	0.21	1.81	0.74	-	1.49	0.10	0.46	0.51	0.37	0.42	0.36	0.63	1.38	0.36
Filtered $NO_3 + NO_2$	mg N/l	0.20															2.13	12.26
Unfiltered Total P	mg P/l	12.67				241.22							257.11				3.14	3.81
Filtered Total P	mg P/l	10.66	34.10	12.66		3.78				23.25	10.21		1.74				2.83	3.34
Filtered Ortho P	mg P/l	10.01															2.57	3.26
pH		7.35				7.02							6.82				7.35	7.02
Alkalinity	mg/l as $CaCO_3$	326.44															189.89	94.44
TSS	mg MLSS/l	90.89				5006.22							2819.44					
VSS	mg MLVSS/l	79.22				3787.44							2122.78					
SVI	ml/g					323.44							109.89					
DSVI	ml/g					98.67							101.67					

Notes :

1. The average long term period concentrations in the above table includes days on which process upsets/incidents occurred.
2. The influent and effluent samples are composite samples. All other samples are grab samples.

Table B7 : Long Term Period VI - Averages Report.

MITCHELL'S PLAIN WWTW - PILOT PLANT : LABORATORY REPORT

Averages for Period VI

SAMPLE	UNITS	MODULES A & B INFLUENT	MODULE A MIXED LIQUOR / ACTIVATED SLUDGE							MODULE B MIXED LIQUOR / ACTIVATED SLUDGE							MODULE A EFFLUENT	MODULE B EFFLUENT
			Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle		
Unfiltered COD	mg COD/l	652.88															53.56	60.38
Flocculated/Filtered COD	mg COD/l	292.38															49.[illegible]9	57.00
Unfiltered TKN	mg N/l	96.91															10.21	5.19
Filtered TKN	mg N/l	85.67																
Flocculated/Filtered TKN	mg N/l																5.15	4.21
Filtered FSA	mg N/l	61.22															4.32	1.02
Filtered NO_3	mg N/l	0.51	0.51	6.95	7.60	11.73	7.64	-	10.44	0.27	5.34	5.63	15.02	4.63	14.29	13.05	12.61	15.00
Filtered NO_2	mg N/l	0.17	[illegible]	0.28	0.25	0.12	0.25	-	0.12	0.1[illegible]	0.42	0.42	0.09	0.30	0.12	0.10	0.13	0.12
Filtered $NO_3 + NO_2$	mg N/l	0.16															10.62	16.35
Unfiltered Total P	mg P/l	12.44				64.50							198.81				4.21	3.74
Filtered Total P	mg P/l	10.64	25.69	10.76		3.61				31.53	13.09		3.43				4.07	3.51
Filtered Ortho P	mg P/l	9.93															3.85	3.43
pH		7.39				6.80							6.57				6.96	6.84
Alkalinity	mg/l as $CaCO_3$	328.64															80.43	56.13
TSS	mg MLSS/l	103.13				3878.39							3914.00					
VSS	mg MLVSS/l	86.44				2860.31							2957.75					
SVI	ml/g					116.06							118.81					
DSVI	ml/g					96.63							98.63					

Notes :

1. The average long term period concentrations in the above table includes days on which process upsets/incidents occurred.
2. The influent and effluent samples are composite samples. All other samples are grab samples.

Table B8 : Long Term Period VII - Averages Report.

MITCHELL'S PLAIN WWTW - PILOT PLANT : LABORATORY REPORT

Averages for Period VII

SAMPLE	UNITS	MODULES A & B INFLUENT	MODULE A MIXED LIQUOR / ACTIVATED SLUDGE: Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	MODULE B MIXED LIQUOR / ACTIVATED SLUDGE: Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	MODULE A EFFLUENT	MODULE B EFFLUENT
Unfiltered COD	mg COD/l	620.71															70.67	100.79
Flocculated/Filtered COD	mg COD/l	231.46															61.92	81.00
Unfiltered TKN	mg N/l	102.07															22.48	38.07
Filtered TKN	mg N/l	83.9[illegible]																
Flocculated/Filtered TKN	mg N/l																20.45	34.99
Filtered FSA	mg N/l	70.37															15.09	27.77
Filtered NO_3	mg N/l	0.08	0.18	6.73	6.85	10.09	6.76	-	7.31	0.14	1.67	[illegible]	9.51	1.63	9.57	7.65	11.25	8.78
Filtered NO_2	mg N/l	0.14	0.53	0.26	0.18	0.15	0.19	-	0.25	0.20	0.18	0.33	1.01	0.20	0.73	0.81	0.22	0.97
Filtered $NO_3 + NO_2$	mg N/l	0.71															15.51	8.64
Unfiltered Total P	mg P/l	12.42															7.22	2.81
Filtered Total P	mg P/l	10.34	23.92	10.05		5.8[illegible]				20.39	3.03		2.96				6.67	2.10
Filtered Ortho P	mg P/l	10.05															5.74	2.00
pH		7.54				6.84							[illegible]				7.03	7.33
Alkalinity	mg/l as $CaCO_3$	323.46															108.92	163.38
TSS	mg MLSS/l	92.83				5025.79							[illegible]812.70					
VSS	mg MLVSS/l	73.92				3942.08							[illegible]350.88					
SVI	ml/g					126.46							83.43					
DSVI	ml/g					95.92							94.10					

Notes :

1. The average long term period concentrations in the above table includes days on which process upsets/incidents occurred.
2. The influent and effluent samples are composite samples. All other samples are grab samples.

Table B9 : Long Term Period VIII - Averages Report.

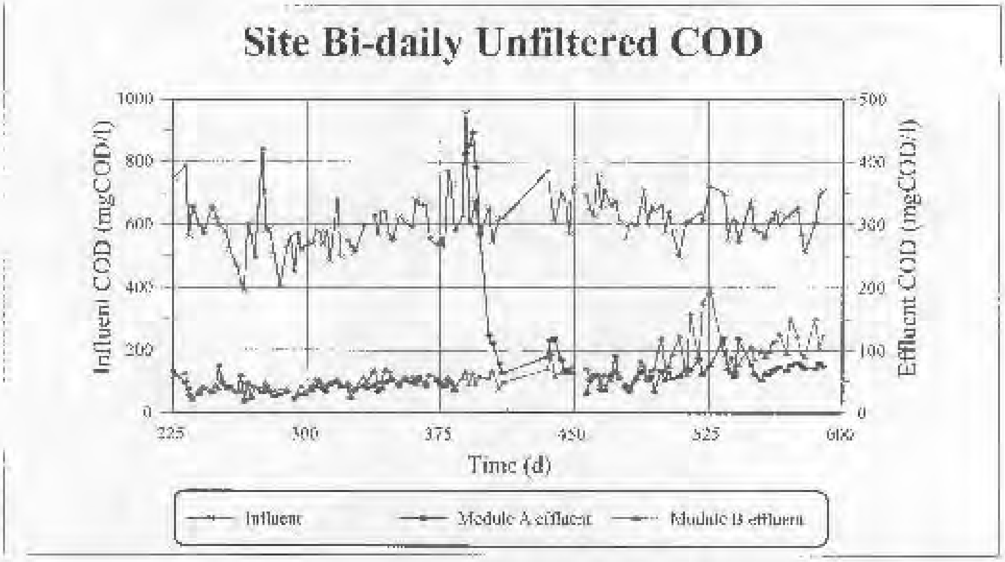
MITCHELL'S PLAIN WWTW - PILOT PLANT : LABORATORY REPORT

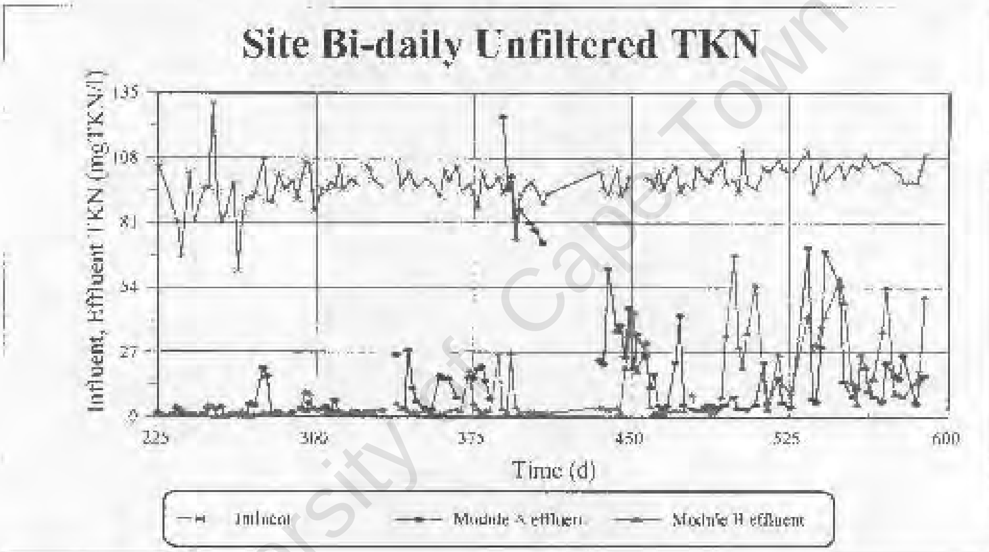
Averages for Period VIII

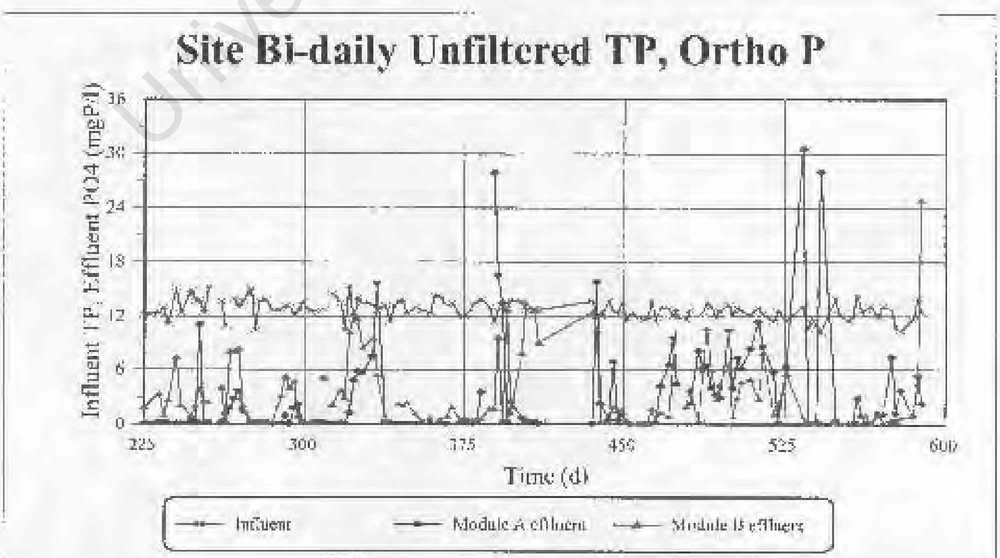
SAMPLE	UNITS	MODULES A & B INFLUENT	MODULE A MIXED LIQUOR / ACTIVATED SLUDGE							MODULE B MIXED LIQUOR / ACTIVATED SLUDGE							MODULE A EFFLUENT	MODULE B EFFLUENT
			Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle	Anaerobic	Anoxic	Anox./Aer. Transition	Aerobic	R-recycle	A-recycle	S-recycle		
Unfiltered COD	mg COD/l	620.18															71.73	114.45
Flocculated/Filtered COD	mg COD/l	239.28															66.59	86.45
Unfiltered TKN	mg N/l	103.50															14.61	21.06
Filtered TKN	mg N/l	89.91																
Flocculated/Filtered TKN	mg N/l																12.23	14.60
Filtered FSA	mg N/l	47.57															5.90	7.37
Filtered NO_3	mg N/l	0.24	[illegible]	8.52	8.21	13.51	8.54	-	11.74	0.26	4.44	6.19	13.58	4.13	13.25	11.52	3.58	14.77
Filtered NO_2	mg N/l	0.13	0.19	0.22	0.17	0.09	0.18	-	0.16	0.16	0.24	0.34	0.58	0.16	0.18	0.60	0.16	0.79
Filtered NO_3 + NO_2	mg N/l	0.29															50.46	18.79
Unfiltered Total P	mg P/l	12.27															2.83	6.09
Filtered Total P	mg P/l	9.95	24.48	7.22		2.17				31.02	6.19		5.06				2.59	4.77
Filtered Ortho P	mg P/l	9.73															2.31	4.08
pH		7.52				6.65							6.70				6.85	6.77
Alkalinity	mg/l as $CaCO_3$	322.40															68.56	65.65
TSS	mg MLSS/l	98.08				3551.09							2053.38					
VSS	mg MLVSS/l	71.78				2564.18							2312.93					
SVI	ml/g					141.18							103.95					
DSVI	ml/g					103.03							91.68					

Notes :

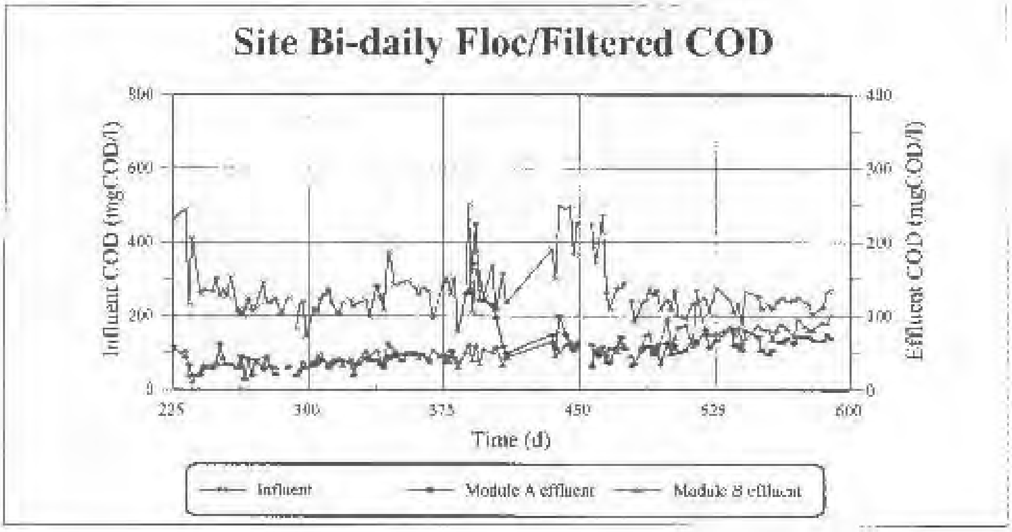
1. The average long term period concentrations in the above table includes days on which process upsets/incidents occurred.
2. The influent and effluent samples are composite samples. All other samples are grab samples.

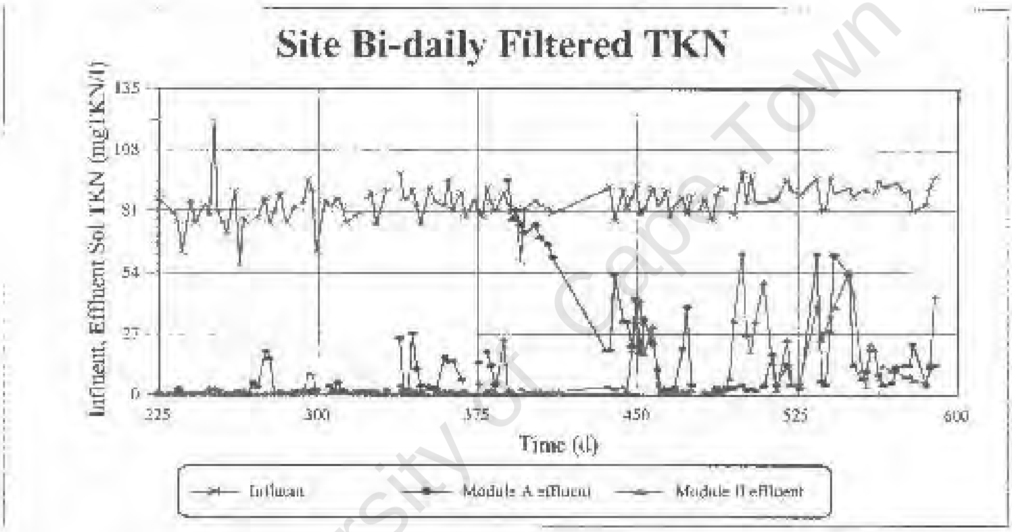


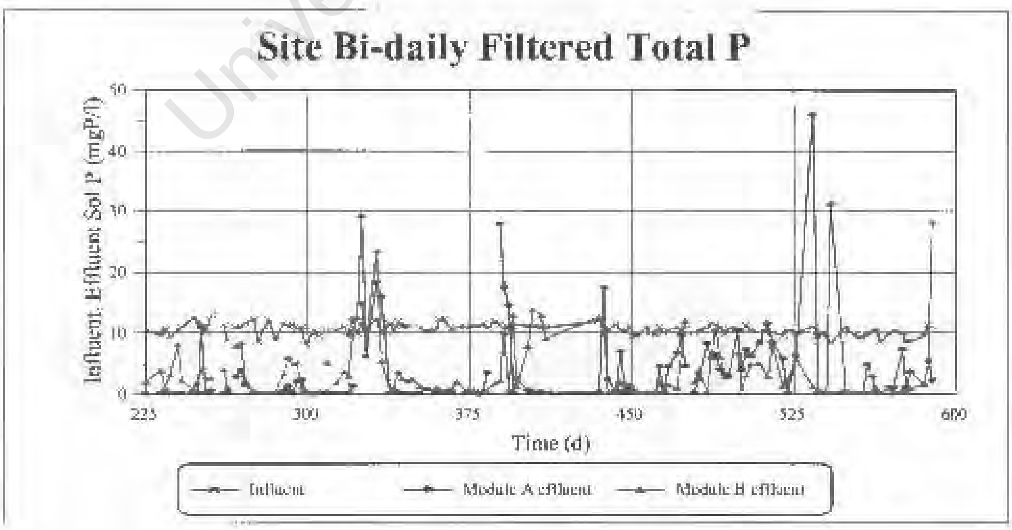




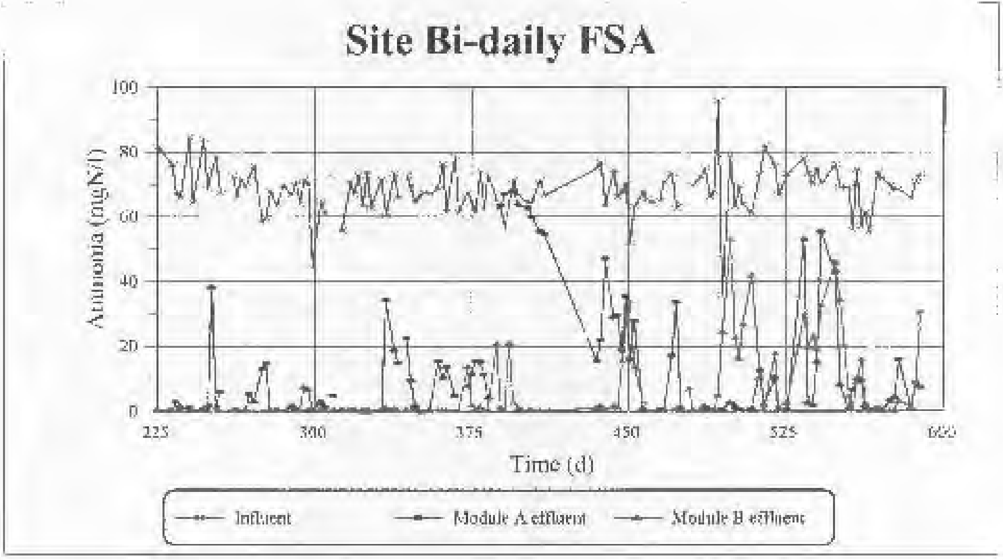
Figures B.1, B.2 and B.3 : "Site" bi-daily unfiltered influent & effluent COD, TKN and TP/Ortho P respectively.

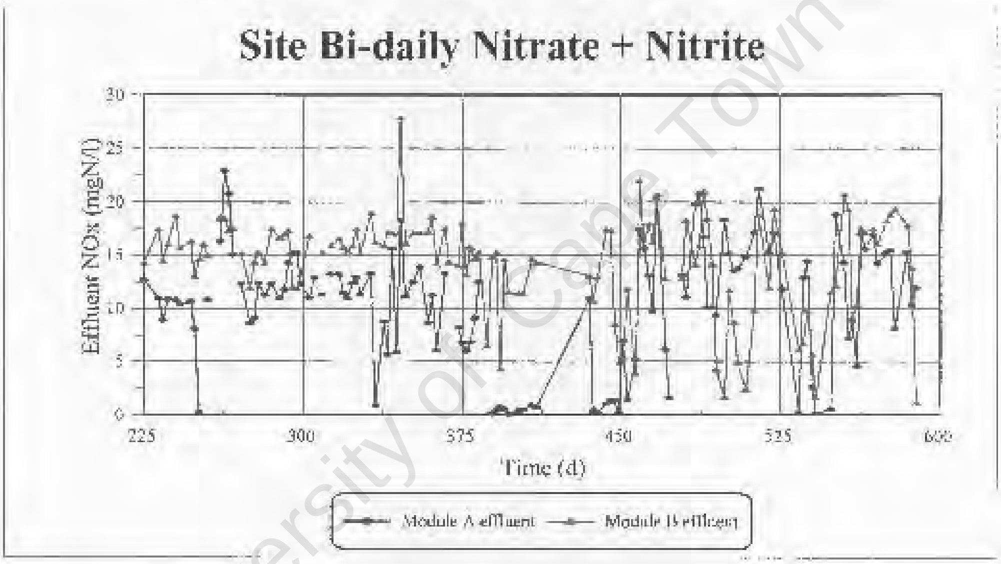


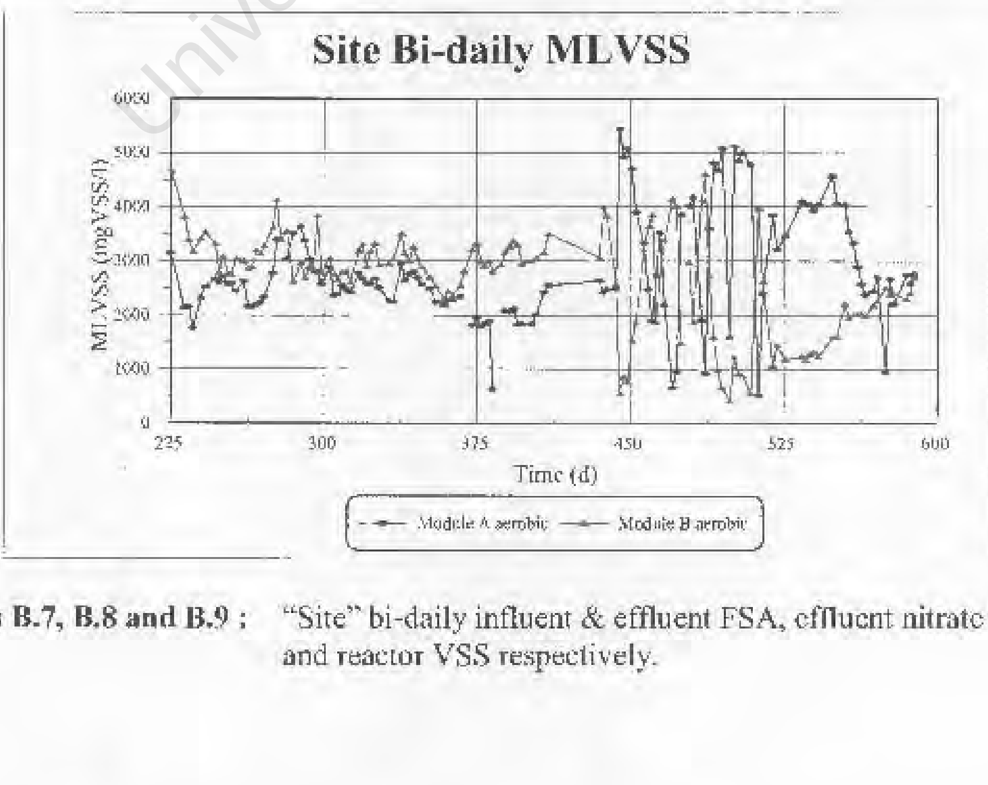




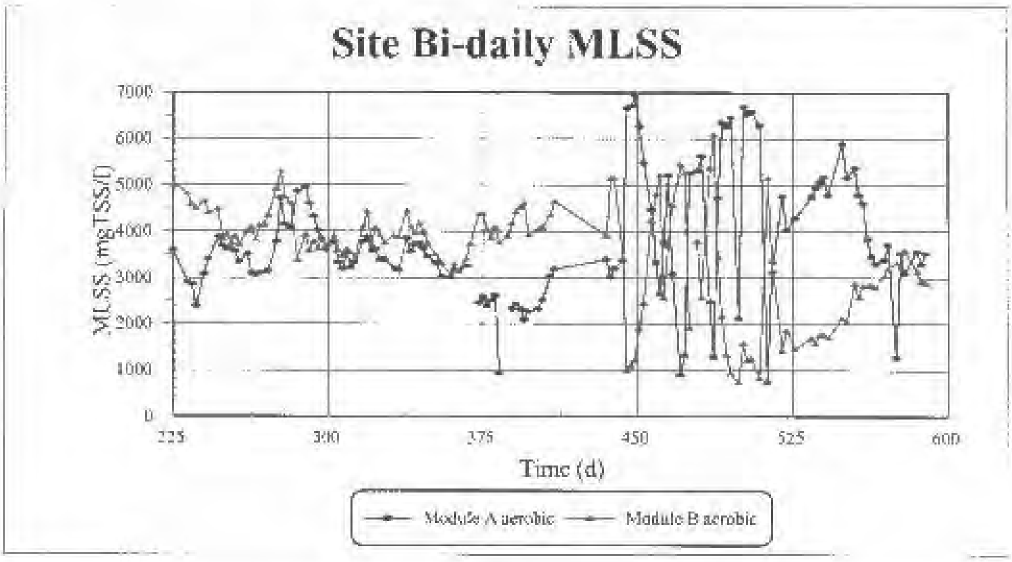
Figures B.4, B.5 and B.6 : "Site" bi-daily floc/filtered influent & effluent COD, filtered influent & effluent TKN and Total P respectively.

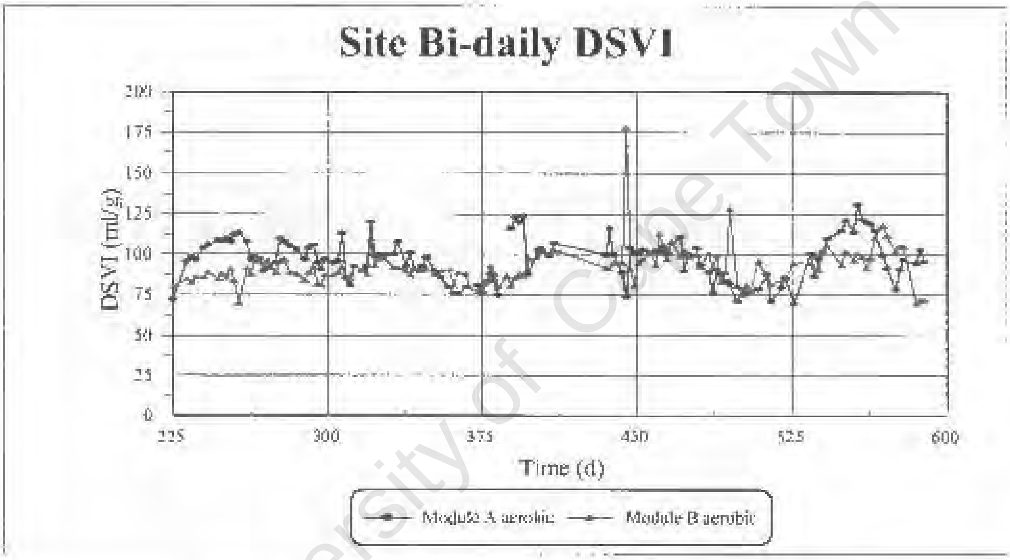


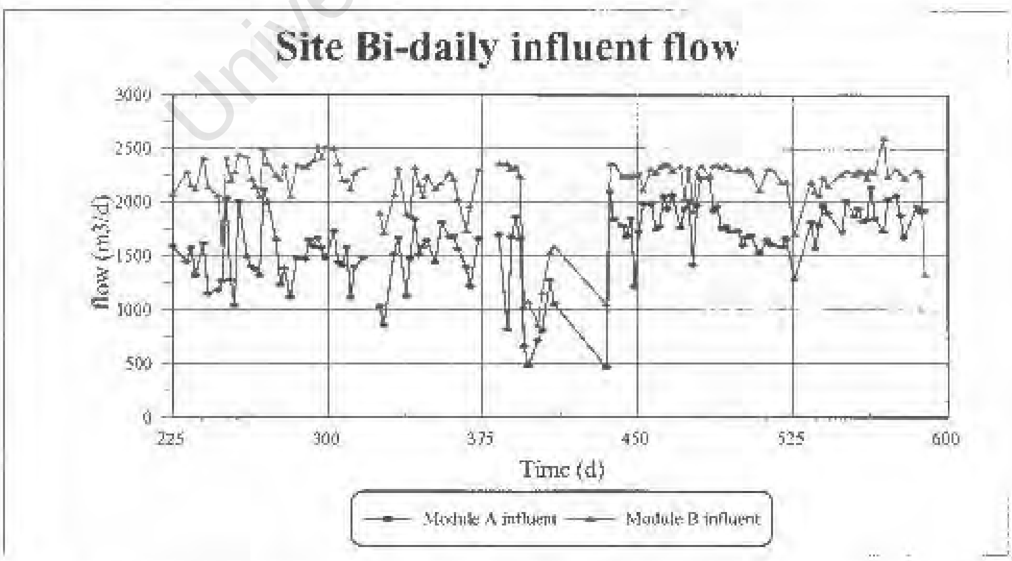




Figures B.7, B.8 and B.9 : "Site" bi-daily influent & effluent FSA, effluent nitrate + nitrite and reactor VSS respectively.







Figures B.10, B.11 and B.12 : "Site" bi-daily reactor TSS, DSVI and influent flow respectively.

APPENDIX C

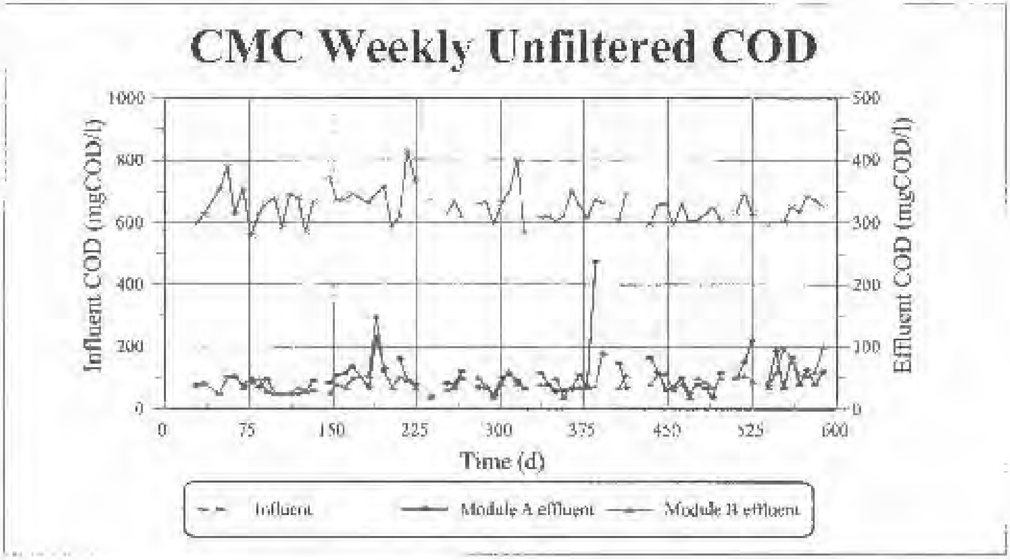
WEEKLY "CMC" RESULTS

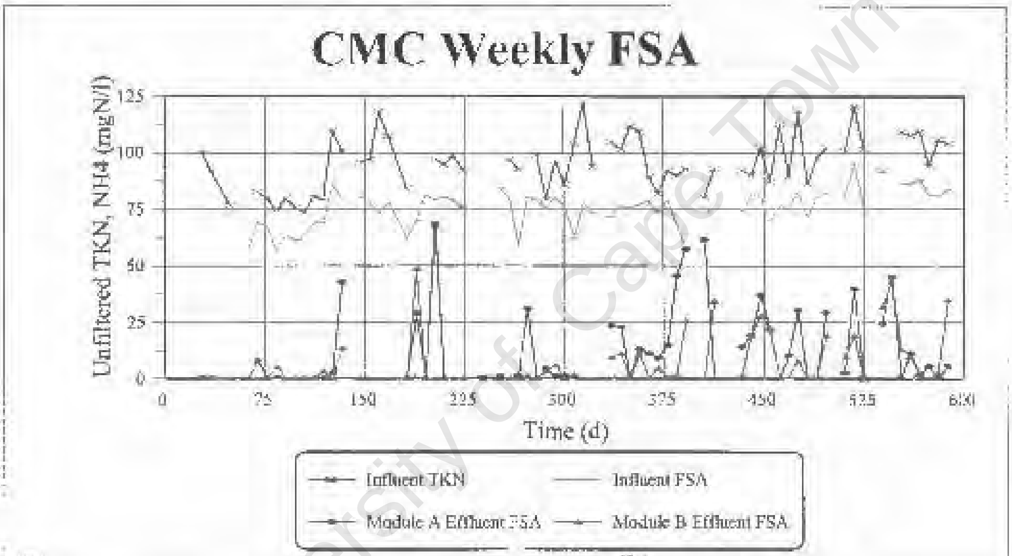
Table C1 : Weekly "CMC" laboratory data.

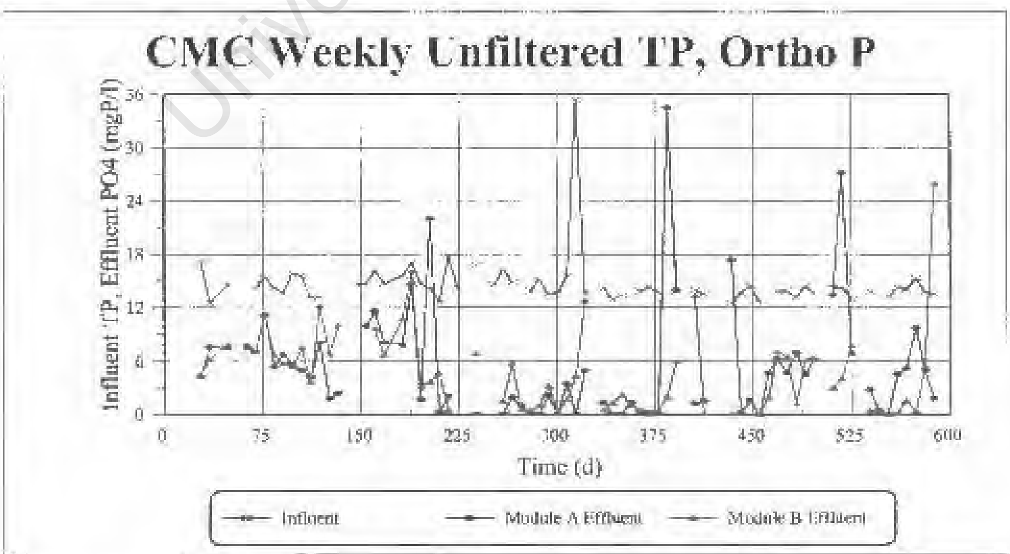
MITCHELL'S PLAIN WWT - PILOT PLANT : LABORATORY RESULTS (Sundays)

Date	Day	TKN/COD	Influent COD	Influent TKN	Influent TP	Influent FSA	Effluent COD		Effluent NO_3		Effluent OrthoP		Effluent FSA		Reactor MLSS		Reactor MLVSS		Sludge DSVI	
of testing	No.	ratio	Modules A&B	Modules A&B	Modules A&B	Modules A&B	Module A	Module B	Module A	Module B	Module A	Module B	Module A	Module B	Module A	Module B	Module A	Module B	Module A	Module B
01/11/99	1	-	-	-	-	-		-	-	-	-	-	-	-	2900.0	4380.0	2210.0	4240.0	-	59.0
15/11/99	14		-	-	-	-	-	-	-	-	-	-	-		4540.0	4950.0	3990.0	4380.0	66.0	69.0
22/11/99	21	-	-	-	-	-	-	-	-	-	-	-	-	-	4820.0	5850.0	-		76.0	72.0
29/11/99	28	0.1685185	594.0	100.1	17.1	84.3	40.0	37.0	14.8	16.4	4.3	4.5	0.5	0.1	3425.0	4795.0	2565.0	4025.0	-	75.0
06/12/99	35	0.1464856	626.0	91.7	12.5	-	41.0	41.0	13.7	17.4	7.6	6.2	0.3	0.5	3420.0	4750.0	-	-	-	72.0
20/12/99	49	0.1084986	706.0	76.6	14.6	72.9	25.0	25.0	11.2	14.6	7.3	7.9	0.2	0.2	3760.0	6210.0	-	-	-	-
27/12/99	56	-	781.0	-	-	-	52.0	52.0	-	-	-	-	-	-	4970.0	6710.0	-	-	76.0	72.0
03/01/00	63	-	626.0	-	-	57.6	51.0	56.0	15.9	17.2	7.5	7.9	0.1	0.1	5230.0	6710.0	-	-	76.0	72.0
10/01/00	70	0.1165021	709.0	82.6	14.2	69.6	39.0	34.0	7.4	13.4	7.1	7.1	8.2	0.4	4380.0	5660.0	-	-	79.0	82.0
17/01/00	77	0.1426523	558.0	79.6	15.4	66.9	48.0	43.0	11.3	12.8	11.3	11.5	0.1	0.2	5770.0	6120.0	4650.0	5060.0	87.0	85.0
24/01/00	84	0.1189793	627.0	74.6	14.2	56.9	34.0	49.0	10.5	7.2	5.4	6.7	0.8	5.8	4580.0	5190.0		-	87.0	89.0
31/01/00	91	0.1200603	663.0	79.6	13.7	63.9	48.0	29.0	16.1	15.6	6.7	5.8	0.1	0.2	4370.0	5810.0	3800.0	5090.0	87.0	90.0
07/02/00	98	0.1111765	680.0	75.6	15.8	60.9	25.0	25.0	15.3	15.5	5.8	5.4	0.2	0.4	3320.0	5110.0	-	-	84.0	90.0
14/02/00	105	0.1260274	584.0	73.6	15.0	62.9	25.0	25.0	13.4	16.0	5.0	7.5	0.3	0.3	2070.0	4580.0	1900.0	3980.0	-	87.0
21/02/00	112	0.1168116	690.0	80.6	13.1	68.9	25.0	25.0	10.9	13.4	4.2	3.7	0.3	0.3	2590.0	3390.0	-	-	-	-
28/02/00	119	0.1161765	680.0	79.0	13.1	68.9	25.0	34.0	14.6	14.5	8.1	12.2	0.3	3.5	2740.0	3600.0	2520.0	3250.0	-	78.0
07/03/00	126	0.1922807	570.0	109.6	-	66.2	29.0	29.0	6.8	14.7	1.8	6.8	2.9	0.1	4570.0	4420.0	-	-	79.0	81.0
14/03/00	133	0.1514243	667.0	101.0	-	80.0	46.0	33.0	0.9	7.0	2.4	10.0	43.0	14.0	4890.0	4400.0	3800.0	3800.0	90.0	118.0
22/03/00	142	-		-	-	-	-	-	-	-	-	-	-	-	3350.0	2190.0	-	-	107.0	100.0
27/03/00	147	0.1282463	747.0	95.8	14.6	80.9	43.0	26.0	17.0	16.4	-	-	0.1	0.3	3960.0	3890.0			95.0	103.0
03/04/00	154	0.1444279	673.0	97.2	14.7	78.9	55.0	40.0	13.0	14.2	9.9	-	0.1	0.1	3030.0	4010.0		-	86.0	90.0
10/04/00	161	0.1756315	673.0	118.2	16.1	73.2	58.0	34.0	13.8	13.5	11.6	9.6	0.1	0.1	2540.0	3680.0	2250.0	3090.0	79.0	82.0
17/04/00	168	0.1549133	692.0	107.2	14.7	75.2	68.0	49.0	12.4	14.4	8.1	6.7	0.1	0.2	2700.0	4190.0	-	-	89.0	76.0
01/05/00	182	0.1269985	663.0	84.2	15.6	62.0	34.0	53.0	14.3	15.9	7.8	10.8	0.6	0.3		-		-	-	
08/05/00	189	-	690.0		17.1	70.2	115.0	150.0	5.3	2.7	14.7	16.5	29.2	48.9	5670.0	5010.0	-	-	70.0	72.0
15/05/00	196	-	716.0	-	14.7	81.3	65.0	60.0	11.3	12.2	1.7	3.2	0.1	0.1	2830.0	5110.0	-	-	149.0	112.0
22/05/00	203	0.1669521	584.0	97.5	14.2	79.3	-	35.0	-	12.8	22.1	3.7	68.2	0.2	2880.0	4820.0	2410.0	4220.0	125.0	89.0
29/05/00	210	0.1527331	622.0	95.0	12.6	80.4	81.0	51.0	7.5	19.0	0.3	4.7	0.3	0.1	2650.0	5370.0	-	-	85.0	104.0
05/06/00	217	0.1193237	828.0	98.8	17.8	79.0	45.0	45.0	14.2	15.2	2.0	0.5	0.1	0.1	2250.0	5950.0	-	-	80.0	87.0
12/06/00	224	0.1267123	730.0	92.5	14.3	76.1	40.0	35.0	13.0	14.8	-	-	0.1	0.1	3070.0	5250.0	-	-	62.0	53.0
19/06/00	231	-		-		-			-	-	-	-		-	2840.0	4060.0	-		-	-
26/06/00	238	-	677.0	-	16.8	72.4	20.0	20.0	12.4	19.4	0.1	6.9	0.7	0.1	2830.0	4240.0	-	-	106.0	94.0
03/07/00	245	-	-	-							-	-	-	-	2950.0	4490.0	-	-	-	-
10/07/00	252	-	629.0	-	14.6	84.9	41.0	30.0	15.7	15.6	-	-	1.2	0.2	4000.0	3710.0	-	-	95.0	53.0
17/07/00	259	0.1454273	667.0	97.0	16.3	77.7	40.0	35.0	17.3	17.7	0.1	1.5	0.1	0.4	3870.0	4030.0	-	-	119.0	98.0
24/07/00	266	0.15	620.0	93.0	14.9	59.6	60.0	50.0	12.9	14.6	1.9	5.8	1.7	0.3	3430.0	4420.0	-	-	105.0	97.0
30/07/00	273	-	-		-	80.5	-	-	4.6	14.3	1.0	0.6	20.9	1.1	4080.0	5180.0	-	-	105.0	96.0
07/08/00	280	0.150303	660.0	99.2	12.9	79.2	35.0	30.0	11.4	13.4	0.1	0.5	0.2	0.3	4510.0	4800.0	-	-	93.0	88.0
14/08/00	287	0.1194903	667.0	79.7	15.2	75.4	35.0	35.0	9.4	12.6	0.1	1.0	4.7	3.2	5290.0	3910.0	-	-	112.0	93.0
22/08/00	294	0.1617712	598.0	96.5	13.6	80.2	23.0	20.0	14.7	13.3	2.1	3.2	1.4	6.2	4210.0	3760.0	-	-	141.0	97.0

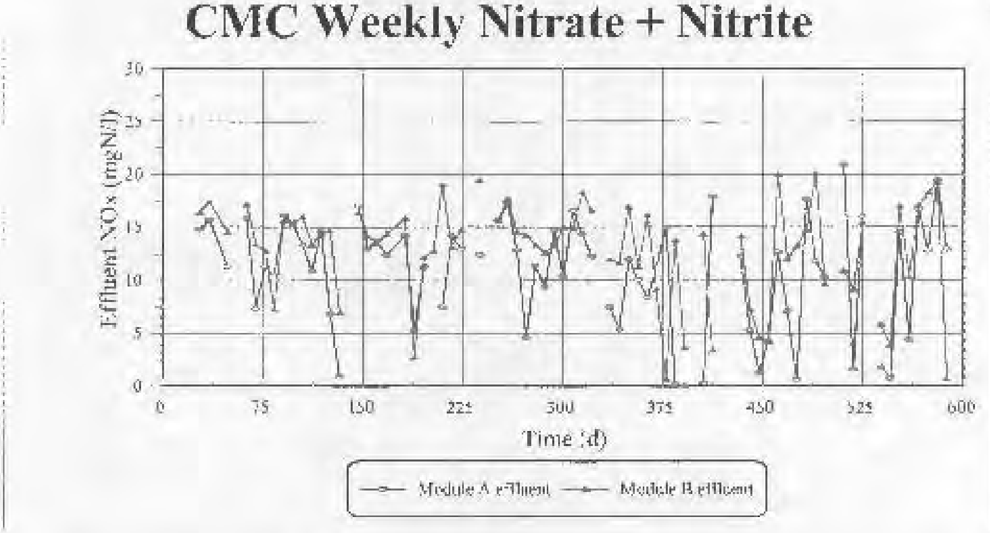
Date of testing	Day No.	TKN/COD ratio	Influent COD Modules A&B	Influent TKN Modules A&B	Influent TP Modules A&B	Influent FSA Modules A&B	Effluent COD Module A	Effluent COD Module B	Effluent NO Module A	Effluent NO Module B	Effluent OrthoP Module A	Effluent OrthoP Module B	Effluent FSA Module A	Effluent FSA Module B	Reactor MLSS Module A	Reactor MLSS Module B	Reactor MLVSS Module A	Reactor MLVSS Module B	Sludge DSVI Module A	Sludge DSVI Module B
29/08/00	301	0.1292609	663.0	85.7	13.7	76.3	50.0	40.0	10.4	15.0	0.1	0.2	1.6	0.0	4150.0	4250.0	-	-	103.0	89.0
05/09/00	308	0.1494978	697.0	104.2	15.6	62.5	55.0	60.0	16.6	14.9	3.4	1.7	1.3	2.3	3590.0	3880.0	-	-	92.0	85.0
11/09/00	315	0.152875	800.0	122.3	35.5	78.1	46.0	41.0	14.4	18.3	0.1	4.3	0.2	0.1	3450.0	3830.0	-	-	105.0	104.0
18/09/00	322	0.1662544	566.0	94.1	13.7	73.7	33.0	33.0	12.3	16.6	4.9	12.8	0.1	0.1	3690.0	4070.0	-	-	98.0	89.0
26/09/00	329	-	-	-	-	-	-	-	-	-	-	-	-	-	3180.0	3810.0	-	-	114.0	95.0
02/10/00	336	0.1695793	618.0	104.8	14.2	71.8	59.0	39.0	7.5	12.0	1.3	0.6	23.4	9.6	3780.0	4500.0	-	-	105.0	88.0
09/10/00	343	0.1636071	621.0	101.6	12.9	76.8	39.0	-	5.4	11.7	0.1	1.3	22.9	11.5	3790.0	4020.0	-	-	113.0	99.0
16/10/00	350	0.1847934	605.0	111.8	13.4	75.8	29.0	49.0	12.0	16.9	0.1	2.2	0.2	0.0	3460.0	3810.0	-	-	95.0	87.0
23/10/00	357	0.1766506	621.0	109.7	-	77.2	30.0	20.0	10.1	11.3	1.4	1.0	13.2	11.0	3380.0	3260.0	-	-	98.0	91.0
30/10/00	364	0.127027	703.0	89.3	13.9	78.9	32.0	35.0	8.4	16.1	0.4	0.4	11.1	0.4	3290.0	3310.0	-	-	80.0	85.0
06/11/00	371	0.1248097	657.0	82.0	14.3	73.2	55.0	35.0	11.2	9.2	0.5	0.1	9.2	4.6	2340.0	4630.0	-	-	94.0	86.0
13/11/00	378	0.15	614.0	92.1	13.8	79.2	35.0	35.0	15.0	0.7	0.1	0.5	15.0	0.7	5020.0	2500.0	-	-	66.0	92.0
20/11/00	385	0.1335312	674.0	90.0	-	68.8	238.0	36.0	0.2	13.8	34.5	2.0	45.6	2.0	-	4070.0	-	-	-	89.0
27/11/00	392	0.1399096	664.0	92.9	14.9	77.8	-	90.0	0.0	3.7	14.0	6.0	57.3	25.9	2620.0	4620.0	-	-	151.0	86.0
04/12/00	399	-	-	-	-	-	-	-	-		-			-	4170.0	4180.0	-	-	63.0	95.0
11/12/00	406	0.1323481	609.0	80.6	14.0	76.3	74.0	54.0	0.3	14.4	1.2	13.4	61.6	0.3	2860.0	4510.0	-	-	104.0	95.0
18/12/00	413	0.1343434	693.0	93.1	13.5	71.2	34.0	54.0	17.9	3.4	1.5	0.1	0.1	34.4	3690.0	4010.0	-	-	135.0	107.0
26/12/00	420	-	-	-		-	-	-	-	-	-		-		2940.0	4000.0	-	-	135.0	99.0
02/01/01	427	-	-	-		-	-	-	-	-	-		-		2950.0	4430.0	-	-	145.0	119.0
08/01/01	434	0.154958	595.0	92.2	12.5	73.8	83.0	39.0	12.3	14.2	17.4	0.1	14.2	1.6	2680.0	750.0	-	-	90.0	-
15/01/01	441	0.1366667	660.0	90.2	13.7	81.7	59.0	54.0	5.3	7.4	6.2	0.1	19.1	18.9	970.0	4860.0	-	-	-	115.0
22/01/01	448	0.154697	660.0	102.1	14.3	79.9	30.0	56.0	1.3	4.6	1.6	1.4	37.1	77.9	6400.0	920.0	-	-	-	-
29/01/01	455	0.1464646	594.0	87.0	12.6	69.6	35.0	30.0	4.3	4.2	6.0	0.0	21.8	22.3	4990.0	3710.0	-	-	126.0	107.0
05/02/01	462	0.1698341	663.0	112.6	-	76.6	50.0	40.0	12.7	20.0	4.6	3.9	0.0	0.0	1740.0	3630.0	-	-	-	125.0
12/02/01	469	0.1478477	604.0	89.3	13.9	75.4	25.0	20.0	7.1	12.0	6.3	7.0	10.3	0.9	530.0	990.0	-	-	76.0	81.0
19/02/01	476	0.1947282	607.0	118.3	13.9	82.8	46.0	50.0	9.6	13.3	4.6	6.5	30.4	7.9	6810.0	1250.0	-	-	106.0	-
27/02/01	483	0.1373206	627.0	86.1	13.2	71.4	34.0	44.0	17.6	14.8	6.9	1.2	0.1	0.6	4420.0	4350.0	-	-	100.0	92.0
05/03/01	490	0.1513138	647.0	97.9	14.4	79.8	20.0	34.0	11.8	20.1	4.5	6.1	0.2	0.2	6120.0	1920.0	-	-	95.0	83.0
12/03/01	497	0.1679276	608.0	102.1	13.7	82.7	59.0	49.0	10.4	9.7	6.2	6.3	29.4	19.4	5540.0	750.0	-	-	94.0	
19/03/01	504	-	-	-	-	-	-			-	-		-	-	6100.0	820.0	-	-	79.0	-
26/03/01	511	0.1594295	631.0	100.6	14.3	81.4	49.0	49.0	20.9	11.0	13.4	3.0	7.9	9.8	1570.0	4510.0	-	-	76.0	71.0
02/04/01	518	0.1736691	695.0	120.7	14.3	94.9	76.0	54.0	1.6	9.2	27.2	4.0	40.0	19.3	4580.0	1520.0	-	-	87.0	-
09/04/01	525	0.1615873	630.0	101.8	12.9	75.6	110.0	45.0	16.0	15.5	6.8	7.8	1.0	0.1	4290.0	1240.0	-	-	75.0	-
17/04/01	532	-	-	-	-	-	-	-	-	-	-	-	-	-	4550.0	1330.0	-	-	96.0	-
23/04/01	539	0.1556684	591.0	92.0	13.9	79.3	39.0	34.0	1.8	5.9	2.8	0.5	24.5	31.8	4736.0	1540.0	-	-	93.0	52.0
01/05/01	546	-	-	-	-	-	94.0	99.0	0.8	3.9	0.5	0.3	45.2	43.4	5600.0	1450.0	-	-	114.0	-
07/05/01	553	0.18203	601.0	109.4	13.3	86.1	34.0	99.0	14.6	17.0	0.1	0.0	0.4	13.0	4980.0	2470.0	-	-	112.0	81.0
14/05/01	560	0.1658462	650.0	107.8	14.3	86.5	84.0	79.0	4.4	10.4	4.5	0.2	21.3	10.1	4220.0	3140.0	-	-	142.0	115.0
21/05/01	567	0.1733017	633.0	109.7	14.1	88.2	40.0	55.0	16.7	17.0	5.2	1.5	1.9	1.1	3210.0	2880.0	2780.0	2440.0	175.0	125.0
28/05/01	574	0.1382138	683.0	94.4	15.3	81.6	64.0	52.0	12.8	18.2	9.7	0.4	6.7	0.2	1350.0	3100.0	-	-	-	104.0
04/06/01	581	0.1575037	673.0	106.0	13.8	80.0	40.0	69.0	19.4	19.3	5.0	5.4	0.3	2.8	3420.0	2840.0	2870.0	2340.0	82.0	70.0
11/06/01	588	0.1603077	650.0	104.2	13.5	83.7	60.0	100.0	13.0	0.7	1.8	26.0	5.7	35.2	3490.0	2830.0	-	-	103.0	57.0

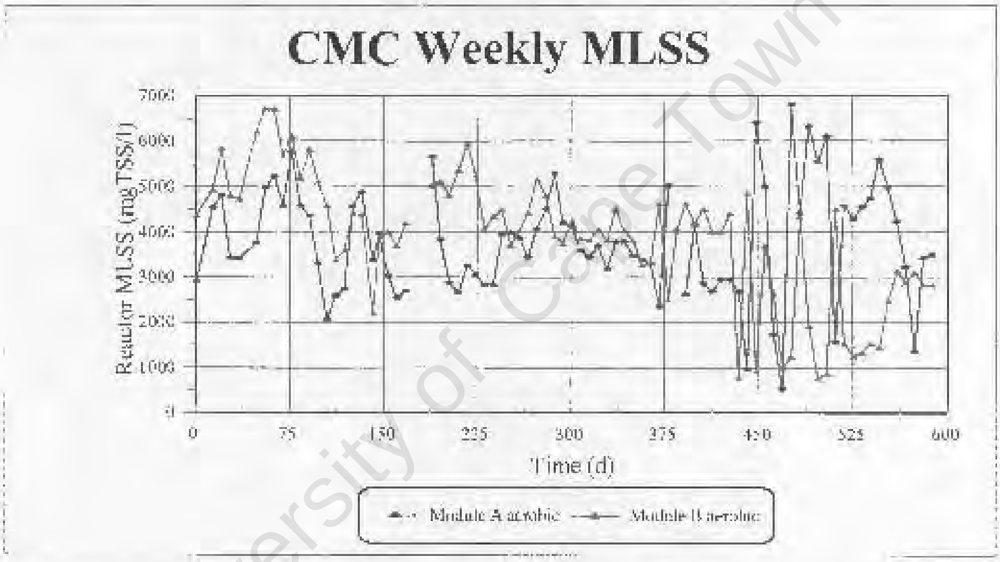


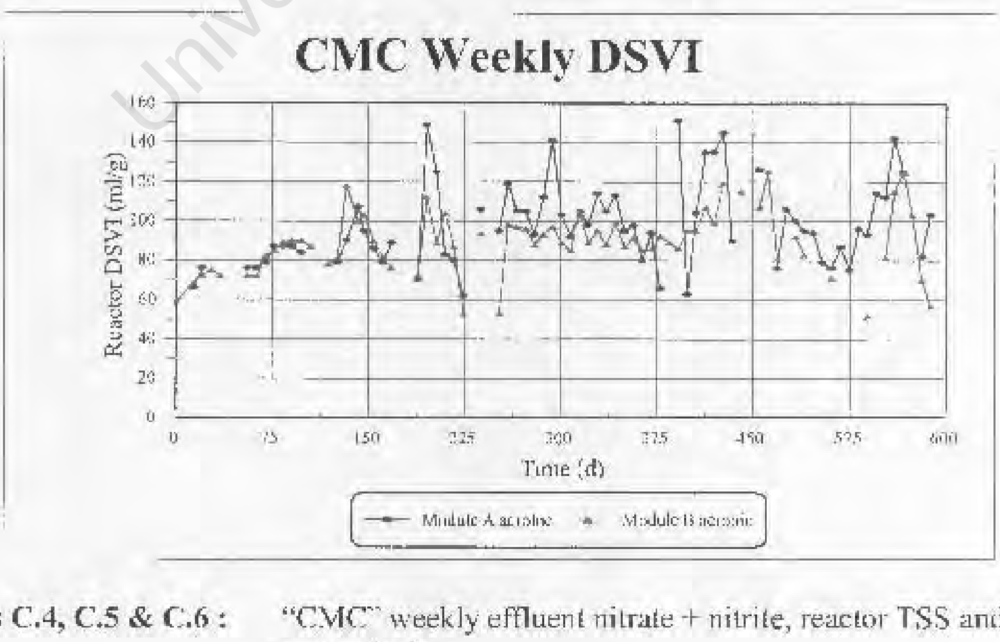




Figures C.1, C.2 and C.3 : "CMC" weekly unfiltered influent & effluent COD, TKN/FSA and TP/Ortho P respectively.







Figures C.4, C.5 & C.6 : "CMC" weekly effluent nitrate + nitrite, reactor TSS and DSVI respectively.

APPENDIX D

Bi-DAILY "SITE" NITROGEN MASS BALANCE

Table D1 : "Site" bi-daily Nitrogen Mass Balance

MITCHELL'S PLAIN WWTP - PILOT PLANT : BI-DAILY - NITROGEN MASS BALANCE

Date	Day No	Module A Influent flow Q (l/d)	Module B Influent flow Q (l/d)	Module A Effluent flow Qe (l/d)	Module B Effluent flow Qe (l/d)	Module A VSS X_v (mgVSS/l)	Module B VSS X_v (mgVSS/l)	Influent TKN N_{ti} (mgN/l)	Influent NO_3+NO_2 NO_x (mgN/l)	Module A Effluent TKN N_{te} (mgN/l)	Module B Effluent TKN N_{te} (mgN/l)	Module A Effluent NO_x NO_{xe} (mgN/l)	Module B Effluent NO_x NO_{xe} (mgN/l)	Module A Aerobic NO_x $NO_{x,aerobic}$ (mgN/l)	Module B Aerobic NO_x $NO_{x,aerobic}$ (mgN/l)	Module A Denitrified D_{cap} (mgN/l)	Module B Denitrified D_{cap} (mgN/l)	Module A %N Recovery (%)	Module B %N Recovery (%)
17/06/2000	225	1598246.40	2066281.20	1509427.20	1935418.20	2149	3289	102.70	0.02	5.80	5.00	12.79	14.95	12.72	13.23	24.30	48.39	50.06	88.47
19/06/2000	227	1450137.60	2230614.40	1362454.60	2147947.40	2129	3551	87.30	0.13	0.80	0.80	10.83	17.51	21.05	14.53	25.04	64.15	56.48	119.35
21/06/2000	234	1574412.80	2138617.60	1487229.80	2025950.60	2160	3298	83.00	0.02	3.10	0.50	8.79	14.35	9.93	10.55	31.14	34.25	59.21	85.25
23/06/2000	236	1323993.00	2120684.00	1234410.60	1982035.00	3757	3241	87.00	0.13	1.20	3.30	10.59	16.01	8.79	13.35	10.10	40.13	59.38	118.35
27/06/2000	240	1619202.80	2409127.60	1531725.80	2276510.60	2234	3424	102.30	0.09	1.30	1.00	10.31	16.77	11.47	19.24	24.00	36.37	47.34	92.86
30/06/2000	242	1153785.80	2136872.00	1066212.00	2004803.00	2521	3523	81.50	0.26	0.80	1.30	10.45	15.65	8.25	13.00	19.39	49.37	60.68	107.40
01/07/2000	247	1185687.20	2080174.40	1098594.20	1934507.40	2674	3312	86.00	0.04	1.10	1.00	10.64	16.39	9.27	13.60	9.14	30.12	41.41	61.09
06/07/2000	249	1208265.00	1617232.20	1130682.00	1484165.20	2610	2709	95.20	0.31	3.17	4.62	8.12	12.96	6.25	10.42	1.95	13.79	40.10	56.68
08/07/2000	251	2034606.80	2421792.80	1947223.40	2290181.00	2727	3292	111.00	0.13		4.30	0.23	14.66	1.14	13.01	3.72	31.67		36.40
10/07/2000	253	1278406.40	2026705.40	1191221.40	2079036.40	2572	2798	95.30	0.15	3.50	0.20		16.08	14.73	13.21	15.06	23.86		62.06
12/07/2000	255	1042448.00	2232947.20	952263.00	2150780.20	2585	2759	81.30	0.15	3.60		10.92	15.01	9.98	12.32	21.01	26.16	76.36	
14/07/2000	257	2009836.00	2445984.00	1922231.00	2313377.00	2446	3043	34.50		0.30	0.40			10.13	13.55				
18/07/2000	261	1495693.20	2427494.40	1408100.20	2294427.40	2625	3272	98.00	0.11	1.20	1.80	10.32	16.52	14.80	17.91	11.40	25.15	45.23	62.10
20/07/2000	263	1407369.60	2223462.60	1319756.60	2089195.40	3164	2959	61.00	0.09	1.50	0.50	22.95	16.43	21.55	15.67	1.86	15.28	64.03	83.89
22/07/2000	265	1380412.80	2150323.20	1292829.60	2017558.20	2154	2901	79.00	0.02	1.30	2.50	20.80	17.57	19.55	15.91	19.36	35.02	64.61	68.82
24/07/2000	267	1321060.80	2057443.20	1234021.80	1924278.20	2195	3209	91.30	0.20	0.40	0.20	15.06	17.28	10.11	16.80	54.91	65.25	92.24	111.46
26/07/2000	269	2139435.00	2299501.40	2052154.60	2164401.40	2225	3148	91.60	0.20	3.50	0.40			10.11	13.55				
28/07/2000	271	2000764.80	2363940.00	1915385.80	2230373.00	2398	3292	95.30	0.33	5.00	1.00	12.36	17.19	7.12	17.92	26.36	59.97	57.43	100.87
01/08/2000	273	1653434.80	2248982.00	1565453.80	2186323.00	2772	3610	109.00	0.01	29.20	1.50	6.01	13.93	9.60	12.78	16.69	14.79	55.80	45.42
03/08/2000	277	2136213.20	2115878.80	1148623.80	2036108.80	3401	4134	90.00	0.39	16.30	1.00	9.12	14.58	14.92	13.85	39.85	43.31	122.03	92.39
05/08/2000	279	1381365.60	2143480.80	1192910.00	2003422.00		2398	79.50	1.36	1.00	0.80	12.35	13.38	13.49	19.46	15.25	13.59	39.11	53.78
08/08/2000	282	1118620.80	2055196.80	1031037.80	1922523.60	3039	3558	102.00	0.08	1.30	1.90	14.27	14.29	12.63	14.51	9.60	20.33	43.56	57.90
11/08/2000	285	1481959.00	2149648.00	1396352.00	2316861.00	2507	2622	95.00	0.39	0.80	1.00	13.35	15.52	12.88	14.39	7.73	17.34	41.54	53.44
15/08/2000	288	1469836.80	2323134.40	1382253.80	2195467.40	2637	2961	48.50	0.10	2.00	0.80	13.99	16.70	10.86	10.64	71.14	19.83	40.44	55.00
17/08/2000	291	1646794.00	2334748.60	1559761.00	2220078.00	2579	2691	90.90	0.35			12.25	17.02	12.44	15.60	12.46	12.43		
19/08/2000	293	1589760.00	2189397.60	1502173.00	2056225.60	2224	2925	100.50	0.08	3.80	3.00	14.30	17.40	11.53	16.56	10.05	14.96	44.56	51.11
21/08/2000	295	1671753.80	2520288.00	1584170.60	2387621.00	2820	2898	100.85	0.10	1.30	10.82	13.20	12.09	14.51	12.61	13.73	22.32	43.60	57.02
24/08/2000	297	1577404.60	2415584.00	1489821.80	2282957.00	2708	3848	785.30	0.19	5.80	10.00	13.20	11.59	13.72	12.63	14.87	24.87	48.21	64.35
26/08/2000	298	1421418.00	2517792.40	1397743.00	2365143.40	2579	2770	86.00	0.30	3.90	3.00	12.52	13.53	11.80	15.84	42.84	29.07	50.90	48.66
29/08/2000	300	1753590.40	2499206.40	1650027.40	2366579.40	2625	1053	95.55	0.20	3.30	2.03	12.05	16.02	11.82	16.57	14.91	22.70	45.73	57.87
31/08/2000	305	1446590.20	2387440.40	1354022.20	2254770.40	2366	2760	94.00	-0.30	4.50	1.50	12.89		13.01	11.97	21.15	19.01	48.47	
02/09/2000	307	1414930.88	2207226.24	1327147.68	2074959.24	2388	3064	98.00	0.35	2.80	1.59			13.17	13.55				
04/09/2000	309	1582099.48	2210258.88	1495315.48	2077591.88	2598	2795	96.00	0.19	7.00	6.00	12.58	13.12	11.74	24.07	16.85	33.49	51.57	70.19
06/09/2000	311	1117005.52	2115054.72	1029220.52	1981787.72	2465	2802	105.50	0.30	2.33	1.30			10.12	13.53				
08/09/2000	313	1399066.36	2025776.72	1311481.56	2703091.72	2420	2625	95.00	0.21	1.30	1.30	13.27	13.88	10.03	14.41	49.43	29.04	41.05	64.53
12/09/2000	317	1483876.80	2319045.22	1396290.80	2185378.22	2717	3157	99.60	-0.01	1.50	3.00	13.23	16.55	12.42	15.94	26.24	27.35	47.52	75.37
14/09/2000	319					2673	3308	97.00	0.16	2.30	1.50	11.47	15.26	9.93	14.34	8.01	22.37		
16/09/2000	321					2584	1901		0.17			10.96	15.47	13.69	25.50	7.63	23.73		
18/09/2000	323					2480	3183	105.50	0.95	1.90	2.50	12.40	15.87	12.04	13.84	10.35	27.99		
20/09/2000	327	1037741.44	1899996.48	945159.44	1767324.48	2670	3314	104.50	0.26	1.80	1.50	13.00	17.46	17.95	13.38	11.41	28.23	46.94	67.27
22/09/2000	327	862462.08	1715605.44	774879.08	1585202.44	2508	2425	99.50	-0.21	2.30	2.00	11.38	13.17	9.59	19.44	13.51	23.97	52.88	60.95
27/09/2000	332	1520283.52	2068158.60	1432700.52	1935489.60	3268	1945	96.00	0.63	2.40	3.30	15.93	16.99	12.53	13.02	10.58	30.54	41.83	60.88
29/09/2000	334	1667268.44	2117749.52	1579686.44	1985097.52	2253	3027		0.20			0.89	16.22	0.62	13.21	2.11	37.46		
03/10/2000	338	1127261.28	1892933.76	1039984.20	1758970.76	2946	3512	106.50	0.52	25.80	5.80	8.82	15.98	13.34	14.13	74.40	31.57	67.63	72.88
05/10/2000	340	1473456.96	1885368.96	1385873.96	1752701.96	2620	3153	96.00	0.02		3.30	5.86	17.23	17.42	18.08	21.98	41.26		87.35
07/10/2000	342	1841833.28	2332760.32	1734090.28	2199098.12	2782	3003	99.20	-0.94	3.50	3.30	15.66	17.15	12.49	15.21	6.14	20.51	38.92	56.59
09/10/2000	344	1509058.04	2159040.96	1421989.64	2026875.96	2706	1284	102.40	0.29	27.80	3.40	5.87	17.05	6.97	15.28	8.77	45.00	53.15	80.00
12/10/2000	346	1587435.84	2049183.16	1499852.84	1915540.76	2650	3021	98.00	2.63	12.00	2.00	28.34	27.87	17.23	25.21	15.89	55.18	61.23	101.44
13/10/2000	348	1643604.48	2240974.08	1556021.48	2106107.08	2589	2893	96.00	0.37	6.30	1.80	11.19	16.12	10.60	14.32	7.14	24.18	39.94	76.92
17/10/2000	352	1444227.84	2236968.28	1356644.84	1991302.28	2496	2699	95.50	-0.02	3.50	2.30	12.54	17.11	13.24	17.19	5.48	35.11	36.81	74.59
20/10/2000	355	1813573.12	2174342.40	1725590.12	2042075.40	2245	2579	92.50	-0.22	3.00	1.30	13.59	17.12	12.82	15.03	5.20	31.32	35.64	66.39
24/10/2000	359	1675382.52	2369771.20	1588300.52	2237104.20	2196	3289	92.00	0.43	17.50	1.80	8.66	17.22	11.89	17.04	18.12	14.66	51.88	72.40
26/10/2000	361	1686125.28	2218310.72	1598748.28	2085610.72	2269	2454	104.50	0.17	16.00	1.50	11.27	16.60	10.58	16.94	4.04	12.90	40.81	64.59
28/10/2000	363	1567926.72	2030303.08	1480343.72	1897816.68	2276	2361	99.30	0.03	16.50	2.30	6.09	14.18	3.81	16.26	7.13	26.55	43.44	59.26
01/11/2000	367	1396595.32	1734230.60	1309012.32	1602583.80	2355	3393	105.50	0.17	7.80	3.25	23.30	17.34	23.67	13.06	8.41	31.98	42.28	60.12
03/11/2000	369	1320802.88	1962401.82	1231019.68	1829914.82		3306	94.60	-0.09		2.25		14.55	10.11	12.65				
05/11/2000	373	7661371.28	2296086.14	1573690.28	2164159.24	1313	3216	99.00	0.15	16.30	19.30	8.27	16.01	6.79	15.17	5.67	59.49	42.00	109.57
09/11/2000	375					1959	3339	98.00	0.25	15.80	5.55	6.76	18.01	8.24	16.20	8.91	39.75		
11/11/2000	377					1780	2959	67.60	0.16	19.80	3.30	6.02	17.94	8.51	13.75	4.92	28.58		
13/11/2000	379					1851	1910	102.50	0.03	21.00	2.60	6.64	15.62	9.55	17.01	10.14	25.44		
15/11/2000	382					1032	3000	96.60	0.17	14.80	2.35	9.21	14.08	10.74	13.91	7.42	27.91		
17/11/2000	384	2098663.77	2346520.09	1999079.72	2124053.80	629	3303	95.50	0.14	2.50	2.25	12.52	15.23	15.13	11.80	9.07	28.62	33.88	62.01
22/11/2000	386	812176.64	2255160.09	729593.64	1872459.36		2435	101.50	0.06		26.50		6.46	10.11	9.12		25.17		84.40
23/11/2000	389	1679572.80	2266802.24	1591989.80	2274105.24	2091	3172	97.50	0.17	123.60	3.50	0.09	13.92	8.28	12.98	2.60	27.35	146.98	68.04
25/11/2000	391	1800554.68	2528961.84	1712972.68	2286295.84	2094	3252	98.00	0.12	99.50	2.60	0.41	15.75	14.82	0.47	33.22	34.77	140.72	64.30
27/11/2000	393	1659674.88	2242303.36	1572085.88	2109936.36	2123	3178	96.20	0.01	100.19	27.50	0.72	6.53	0.05	2.44	0.94	9.96	119.20	43.68
29/11/2000	395	662217.76	1027797.12	574634.76	895130.12	1826	3303	73.50	0.09	85.00	4.90	0.37	14.63	0.10	11.72	9.67	19.02	147.21	108.59
01/12/2000	397	478599.65	1079593.82	389016.58	946926.52	1841	2953	93.00	0.05	86.30	1.75	0.07	11.53	0.29	12.06	2.02	32.41	131.39	80.06
04/12/2000	401	719931.96	858961.04	632149.96	725596.04	1840	3013	88.30	0.00	80.80	2.00	0.41	21.49	0.23	20.02	1.64	25.17	107.36	64.17
06/12/2000	404	809384.16	1163150.04	721501.16	1030623.08	2005	3063	96.00	0.01	77.50	2.25	0.31	11.47	0.85	10.46	2.90	26.71	107.24	78.40
12/12/2000	408	1276860.16	1533340.60	1188277.16	1400675.60	2427	3120	89.60	0.12	72.50	1.78	0.94	14.77	1.12	14.49	5.53	41.62	107.36	93.94
14/12/2000	410	1053100.00	1590450.64	965417.06	1457783.88	2350	3509	93.00	0.11		1.50	0.68	14.40	8.57	13.80	7.60	43.41		95.21
08/01/2001	415	466167.36	2152190.08	370184.36	2020323.08	2640	3048	102.30	2.34	23.60	4.00	16.94	12.10	15.93	11.17	60.81	69.71	328.09	113.85
10/01/2001	417	2039932.40	2352974.40	2072359.40	2220302.40	2422	3989	95.30	0.20	22.00	3.75	0.40	10.28	0.16	13.00	2.02	71.24	35.01	102.70
12/01/2001	439	1179401.52	2354945.76	1752098.52	2022478.76	2481	2821	97.50	0.05	61.80	3.05	0.31	12.00	0.48	11.99	1.97	40.88	93.80	91.59
16/01/2001	443	2758024.24	2241776.96	1690452.24	2109669.96	2498	2586	104.00	0.16	39.80	4.00	1.85	13.42	0.80	14.25	4.47	39.16	51.45	91.16
18/01/2001	445	2682156.16	2245039.20	1594571.16	2109969.20	5842	565	92.50	0.15	38.30	9.60	1.38	17.48	4.33	15.67	24.40	34.51	99.86	71.18
20/01/2001	447	1850560.96	2708690.12	1762577.96	2100026.27	4925	885	95.50	0.05	25.60	20.30	1.28	8.94	0.25	7.61	4.56	37.45	56.50	75.52
22/01/2001	449	3221626.58	2330979.29	1734043.00	2218072.29	5041	192	100.59	0.92	45.50	14.30	0.18	4.92	0.71	4.62	7.00	26.52	54.75	78.19
24/01/2001	451	1723947.84	2208065.40	1636364.84	2225425.40	4995	1536		0.21	20.30	12.80	6.96	5.52	4.04	6.39	22.12	35.21		
26/01/2001	453	2984098.24	2128142.84	1836513.24	1985480.84	3897	1874		0.92	34.30	28.80	1.43	13.89	2.44	13.09	9.97	45.90		
30/01/2001	457	2962078.08	2308167.36	1859225.08	2175500.36	3328	3278	99.50	0.18	25.30	11.50	5.15	3.82	6.54	4.15	12.05	33.45	66.17	75.59
01/02/2001	459	1745271.36	2761189.72	1657688.36	2248520.72	2686	3043	99.50	0.16	12.50	4.30	17.42	22.06	16.94	17.65	6.59	34.47	44.77	63.66
03/02/2001	461	1771451.28	2323426.72	1683850.28	2238233.72	1903	3861	95.80	0.13	17.30	1.40	15.68	15.93	13.00	13.58	6.68	16.74	81.03	79.74
05/02/2001	463	2053766.40	2256801.92	1966583.40	2324124.92	2759	2864	105.30	0.26	4.50	2.30	13.06	17.97	10.69	17.87	24.71	10.61	41.40	77.09
07/02/2001	465	2334038.08	2182501.76	1848455.16	2214044.76	2517	2750	98.80	0.21	3.50	1.80	9.73	16.34	10.27	13.10	5.00	38.41	33.33	73.82

Date	Day No.	Module A Influent flow Q_i (l/d)	Module B Influent flow Q_i (l/d)	Module A Effluent flow Q_e (l/d)	Module B Effluent flow Q_e (l/d)	Module A VSS X_v (mgVSS/l)	Module B VSS X_v (mgVSS/l)	Influent TKN N_{ti} (mgN/l)	Influent $NO_3 + NO_2$ NO_{xi} (mgN/l)	Module A Effluent TKN N_{te} (mgN/l)	Module B Effluent TKN N_{te} (mgN/l)	Module A Effluent NO_x NO_{xe} (mgN/l)	Module B Effluent NO_x NO_{xe} (mgN/l)	Module A Aerobic NO_x $NO_{x,aerobic}$ (mgN/l)	Module B Aerobic NO_x $NO_{x,aerobic}$ (mgN/l)	Module A Denitrified Σ_{DEN} (mgN/l)	Module B Denitrified Σ_{DEN} (mgN/l)	Module A %N Recovery (%)	Module B %N Recovery (%)
09/02/2001	467	2067068.16	2218589.23	1975486.16	2156402.28	2294	5387	99.50	0.54	4.90	2.50	20.60	23.41	18.23	18.90	13.12	59.03	48.41	98.44
13/02/2001	471	1761242.56	2915567.96	1675650.56	2200991.60	457	4149	104.35	0.47	22.50	2.85	0.13	12.80	5.16	12.35	3.03	29.18	33.80	74.82
15/02/2001	473	1659574.36	3035506.00	1546411.88	1892959.60	961	4509	[illegible]	5.83	42.30	1.30	1.59	14.31	2.08	14.77	5.47	46.83	57.94	99.05
17/02/2001	475	2007599.54	[illegible]	1925406.54	[illegible]	3155	1482	97.30	0.94	5.00	2.80			10.13	0.22	210.32	0.52		
19/02/2001	477	1418647.52	1917528.84	1371044.53	1784911.96				0.75					10.12	10.55				
21/02/2001	479	1960897.36	2280739.56	1875304.30	2170603.36	4489	2981	95.39	0.30	[illegible]	8.56	13.10	12.91	12.20	14.63	5.76	20.37	41.19	48.08
23/02/2001	481	2221560.80	2587837.12	2133971.80	2205170.22	4303	1900	104.39	0.35	2.70	3.30	11.06	14.57	11.49	13.19	7.11	53.90	35.45	60.48
27/02/2001	465	2224860.46	2241529.60	2155237.45	2108402.60	1504	4136	99.80	0.42	4.00	2.35	19.85	14.24	16.37	13.80	11.47	51.30	42.66	82.86
01/03/2001	467	1923656.96	2244482.28	1883623.88	2213334.28	922	4619	97.80	0.43	3.00	3.30	20.79	13.80	17.99	15.60	10.11	44.64	40.90	91.55
03/03/2001	489	1961061.28	2546238.83	1873498.28	2213471.88	3612	2723	102.50	0.31	4.50	2.00	16.74	21.08	19.18	20.00	7.11	43.34	43.28	79.78
05/03/2001	491	1755959.94	2320989.48	1668376.04	2188313.48	3914	1596	103.80	0.30	3.00	3.80	10.09	14.90	6.35	16.67	4.70	42.36	40.13	69.78
07/03/2001	493	1769947.20	2347912.60	1682364.20	2214945.80	4680	991	107.20	0.25	4.39	[illegible]	10.10	14.10	10.83	11.51	4.78	30.35	39.60	60.30
09/03/2001	495	1726392.96	2306282.84	1638809.96	2173616.54	5078	668	97.10	0.09	3.05	24.57	9.39	4.24	9.61	0.93	5.65	5.76	46.50	49.88
11/03/2001	497	1729357.12	2294524.80	1640724.12	2161357.60	1597	419	98.60	0.25	5.30	67.80	18.39	1.10	21.22	2.38	17.90	0.90	33.38	79.84
15/03/2001	501	1599971.36	2288464.64	1511986.36	2155797.64	5127	1253	95.60	0.42	[illegible]	29.30	15.17	11.77	12.73	12.61	6.26	31.35	55.99	84.84
17/03/2001	503	2675330.56	2317768.45	1587747.56	[illegible]	4856	955	111.80	0.27	3.50	20.90	17.39	5.79	12.84	7.48	6.50	24.78	43.48	52.90
19/03/2001	505	2694433.60	2265114.24	1606830.60	2132447.24	5600	598	96.95	0.10	3.00	39.00	13.70	4.94	13.40	4.90	3.85	37.17	49.98	64.29
23/03/2001	509	1526713.92	2109531.52	1439110.92	2078264.52	4787	565	95.09	0.29	4.00	55.50	14.86	2.45	2.51	3.22	15.04	10.77	68.65	75.69
27/03/2001	513	1648320.64	2308979.32	1560907.44	2176317.32	538	3399	104.10	0.45	52.90	15.90	17.55	0.15	54.47	12.88	8.79	46.04	48.65	96.75
29/03/2001	515	1627601.60	2299337.28	1520016.60	2166670.28	2404	2638	101.60	0.31	5.50	2.30	52.20	14.79	18.18	18.14	10.96	32.62	48.96	88.32
03/04/2001	520	1389025.28	2197702.40	1497442.28	2060035.40	3840	1907	107.50	0.80	15.00	25.90	15.32	13.90	15.32	13.86	10.49	13.56	57.96	70.97
05/04/2001	522	1666449.00	2187577.12	1578837.00	2057210.12	3218	1145	102.20	0.18	3.80	13.70	17.17	19.39	15.85	20.96	2.96	20.24	45.96	66.71
09/04/2001	526	[illegible]	[illegible]	2196158.48	1574095.18	3062	1175	101.06	0.30	3.80	9.80	11.82	15.28	10.85	16.01	6.49	18.34	44.09	91.48
17/04/2001	534	1814132.24	2199823.72	1726739.24	2067551.72	4108	1230	111.10	0.18	70.80	43.30	0.24	6.18	0.41	6.90	4.16	23.39	85.45	71.33
19/04/2001	536	1582858.84	2100059.60	1491276.84	1967384.56	4001	1163	95.12	0.11	7.10	16.90	12.91	6.74	0.91	10.68	5.22	37.13	45.07	95.86
21/04/2001	538	1789732.80	2067445.60	1702148.80	1934758.60	4058	1383	96.30	0.23	8.00	30.90	14.47	9.83	11.68	13.09	8.34	47.71	48.00	100.37
23/04/2001	540	1968336.88	2224016.84	1880755.88	2191351.88	3950	1422	106.30	0.27	29.00	38.00	[illegible]	3.06	8.40	6.85	6.57	14.34	50.15	73.43
25/04/2001	542	2097387.20	2165973.76	1809824.20	[illegible]	4042	1226	98.80	0.11	69.30	41.30	0.16	1.03	1.27	1.64	4.42	3.01	93.60	86.80
03/05/2001	549	1721489.92	2258228.16	1633830.92	2125561.30	4575	1579	109.60	0.10	54.50	57.80	0.56	11.85	0.36	12.29	2.21	34.08	76.36	106.09
05/05/2001	551	2014879.92	2293713.64	1927230.92	2161035.64	3062	1607	99.70	0.11	14.50	47.80	19.53	12.30	17.51	12.86	9.47	34.64	60.58	104.17
08/05/2001	553	1842877.44	2257594.28	1752294.44	2125027.45	4839	2111	105.30	0.21	8.30	14.30	18.12	24.71	13.19	20.84	2.43	48.68	47.41	93.68
10/05/2001	557	1938306.24	2290040.64	1850723.24	2157373.64	3532	1955	102.30	0.32	13.30	5.30	7.18	19.30	5.39	13.55	0.94	25.45	39.08	95.67
12/05/2001	559	1823035.52	2280579.64	1732452.51	2147912.54	3336	2415	100.10	1.06		26.30	8.92	9.24	16.16	13.71	26.36	48.93		85.35
14/05/2001	561	[illegible]	2212241.56	1751626.93	2095475.56	2394	2655	110.00	0.18	26.30	20.80	4.57	10.39	10.83	13.55	5.40	13.97	40.74	52.26
16/05/2001	563	1733918.50	2197949.92	1685366.52	2161270.92	2577	2944	108.60	0.21	10.50	10.50	12.09	15.55	15.75	16.79	0.15	39.62	44.18	75.17
18/05/2001	565	1647715.84	[illegible]	1700037.08	2143678.80	2377	1991	104.10	0.11	8.30	10.10	10.60	17.19	13.58	16.94	9.50	21.28	41.78	64.43
22/05/2001	569	1727663.04	2060182.00	1640090.08	2467315.58	2471	2184	100.40	0.23	4.30	19.30	10.95	17.51	14.31	16.32	7.64	26.95	49.53	85.60
24/05/2001	571	2029691.20	2236377.60	2036108.20	2103710.80	2705	2270	106.10	0.14	13.30	14.50	14.21	16.13	12.90	15.22	4.27	25.24	49.63	105.09
28/05/2001	575	2058829.28	2306370.24	1997340.28	2173703.24	2966	2514	101.60	0.42	17.00	9.50	15.21	18.23	13.15	17.73	0.50	37.22	41.32	72.04
30/05/2001	577	1876625.76	2264793.40	1701046.36	2134123.40	2667	2290	101.60	0.31	15.60	9.50	15.47	18.38	16.46	16.87	12.12	27.83	54.83	68.87
01/06/2001	579	1669781.76	2233024.96	1582134.76	[illegible]	2209	2401	97.80	0.38	25.90	8.30	8.72	16.35	15.98	19.68	24.37	51.27	71.08	66.76
07/06/2001	585	1956492.16	2298525.12	1845113.16	2169558.12	2346	2411	97.80	0.36	4.90	14.00	15.71	13.85	14.42	16.67	8.54	58.41	41.76	95.14
[illegible]	587	[illegible]	2254901.76	1815876.83	2122254.36	2981	2431	107.00	0.81	13.00	29.50	10.37	17.87	0.41	6.67	12.39	29.90	48.19	74.38
21/06/2001	589	1920966.76	2355709.60	1833381.76	2303342.80	2772	2328	108.40	0.28	17.00	30.00	11.94	6.22	16.38	3.53	18.30	1.93	34.39	73.09
Overall		1805448.53	2186012.60	1717859.93	2083345.60	2817.73	2617.07	97.90	0.35	17.24	10.55	13.38	14.31	10.13	13.55	10.11	31.64	56.06	79.41

Table D2 : "Site" bi-daily NO_x Mass Balance.

MITCHELL'S PLAIN WWTP - PILOT PLANT : NO_x MASS BALANCE over REACTORS & SST											
		Module A					Module B				
Date	Day No.	Δ in NO_x Anaerobic (mgN/l_{inf})	Δ in NO_x Anoxic (mgN/l_{inf})	Δ in NO_x Aerobic (mgN/l_{inf})	Δ in NO_x SST (mgN/l_{inf})	NO_x denitrified Σ-ves (mgN/l_{inf})	Δ in NO_x Anaerobic (mgN/l_{inf})	Δ in NO_x Anoxic (mgN/l_{inf})	Δ in NO_x Aerobic (mgN/l_{inf})	Δ in NO_x SST (mgN/l_{inf})	NO_x denitrified Σ-ves (mgN/l_{inf})
12/06/2000	225	-5.734	-13.397	29.789	2.051	-21.360	-7.682	-34.125	52.242	3.817	-48.389
19/06/2000	232	-6.102	-16.855	34.287	-0.524	-25.042	-6.163	-47.890	61.296	10.136	-64.881
21/06/2000	234	-4.870	-11.019	29.220	-4.460	-21.344	-6.621	-26.403	34.134	11.402	-34.249
23/06/2000	236	-7.978	-6.591	15.952	9.377	-16.477	-9.149	-29.354	49.514	4.867	-40.336
27/06/2000	240	-5.089	-12.534	21.429	-2.785	-24.059	-9.425	-39.559	69.109	-1.439	-56.540
29/06/2000	242	-8.156	-10.533	16.718	12.163	-19.389	-6.995	-40.624	54.041	8.963	-49.172
04/07/2000	247	-8.683	0.529	14.374	4.384	-9.141	-11.299	-7.694	26.546	8.757	-20.222
06/07/2000	249	-5.036	-3.602	10.770	5.680	-8.954	-8.636	4.477	17.969	7.811	-13.789
08/07/2000	251	0.732	-1.330	2.582	1.890	-3.220	-5.108	-2.904	23.279	-0.741	-11.671
10/07/2000	253	-11.270	3.420	24.353	-3.575	-15.063	-10.469	-10.015	35.380	1.434	-23.162
12/07/2000	255	-5.626	-15.217	28.090	5.422	-21.007	-10.907	-14.750	34.669	5.865	-26.763
14/07/2000	257										
18/07/2000	261	-11.308	4.498	18.893	4.124	-11.461	-9.229	-12.837	38.846	1.628	-25.128
20/07/2000	263	-1.297	8.703	10.887	4.571	-1.863	-11.229	-3.227	25.536	7.245	-15.284
22/07/2000	265	7.028	11.493	33.266	5.958	-19.359	-10.963	-23.054	46.413	4.875	-35.120
24/07/2000	267	-7.407	24.873	-47.324	44.715	-54.912	0.468	-65.751	80.425	2.195	-65.751
26/07/2000	269										
28/07/2000	271	1.172	-25.326	16.855	18.734	-26.555	-7.919	-41.781	70.313	-8.650	-59.872
01/08/2000	275	2.544	-13.815	22.942	-2.561	-16.693	-3.317	-7.896	25.198	-2.122	-14.196
03/08/2000	277	3.328	-43.086	65.395	-6.729	-59.847	-7.035	13.424	-36.306	42.084	-43.341
05/08/2000	279	-6.512	-1.706	23.652	-4.695	-13.133	-9.715	-2.373	26.394	-0.503	-13.590
08/08/2000	282	-7.218	0.735	19.608	-1.941	-9.602	-9.416	-8.877	33.561	-1.063	-20.334
11/08/2000	285	-6.362	2.860	16.495	-1.232	-7.747	-9.821	-3.464	33.150	-1.929	-17.741
15/08/2000	289	-6.190	-4.572	21.298	0.356	-11.177	-9.328	-8.914	33.274	1.572	-19.833
17/08/2000	291	-6.400	-4.021	23.747	-1.791	-12.461	-9.436	-0.588	23.160	3.669	-11.447
19/08/2000	293	-8.070	-1.660	21.927	2.029	-10.090	-9.315	-4.347	28.770	2.198	-14.956
21/08/2000	295	-7.255	-5.753	26.346	1.757	-13.712	-4.546	-13.500	31.425	-1.427	-22.806
23/08/2000	297	-7.722	-6.397	25.151	4.028	-14.869	-4.625	-15.466	33.750	-1.962	-24.871
25/08/2000	299	-5.336	-7.207	23.369	1.287	-12.840	-6.436	-7.882	33.368	-6.623	-21.022
29/08/2000	303	-3.166	-9.834	25.132	-1.327	-14.912	-5.634	-12.445	33.950	0.307	-21.296
31/08/2000	305	-4.570	-6.406	22.836	0.727	-11.333	-7.651	-1.083	15.825	7.499	-10.634
02/09/2000	307										
04/09/2000	309	3.996	-3.112	26.960	-6.672	-16.854	-8.299	-22.032	41.979	3.488	-33.494
06/09/2000	311										
08/09/2000	313	7.430	-5.356	17.025	8.798	-13.333	-9.167	-18.309	38.931	4.243	-29.042
12/09/2000	317	-6.133	-9.645	27.471	1.517	-16.240	-8.135	-27.214	50.172	1.709	-37.330
14/09/2000	319	-7.327	-0.675	13.537	5.771	-8.008	-9.993	-12.094	33.720	3.971	-22.371
16/09/2000	321	7.594	2.391	15.661	0.348	-7.828	-10.146	-14.678	40.199	-0.076	-25.730
18/09/2000	323	-7.401	-2.866	20.860	1.340	-10.548	-10.233	-16.883	42.438	0.691	-27.995
20/09/2000	325	-7.750	-3.440	20.079	3.863	-11.605	-10.286	-17.355	38.885	5.876	-28.235
22/09/2000	327	5.041	8.013	17.435	7.088	-13.508	-8.929	-14.019	33.057	4.830	-23.924
27/09/2000	332	-5.055	-5.283	19.268	3.734	-10.982	-8.230	-27.524	51.349	2.760	-36.844
29/09/2000	334	0.205	-1.519	1.542	0.274	-2.110	-8.494	-24.727	46.263	2.770	-37.460
03/10/2000	338	-4.547	5.493	17.310	-9.739	-14.400	-5.973	-24.897	42.965	3.515	-31.568
05/10/2000	340	-4.413	10.906	24.658	-25.507	-21.963	-5.682	-34.279	56.835	0.576	-41.260
07/10/2000	342	-6.792	2.245	12.423	6.843	-6.841	-8.586	-20.023	41.052	3.724	-29.530
09/10/2000	344	0.346	-7.000	14.550	-2.320	-9.767	-5.193	-34.111	52.534	3.532	-42.999
11/10/2000	346	-4.546	10.833	29.669	2.413	-15.890	-13.494	-36.797	71.292	3.241	-52.178
13/10/2000	348	-2.655	-4.213	16.427	1.256	-7.342	-5.202	-30.566	47.928	3.593	-39.180
17/10/2000	352	-5.376	3.827	15.286	0.642	-5.478	-7.945	-24.491	49.507	-0.078	-35.114
20/10/2000	355	-5.054	1.426	15.071	2.245	-5.197	-7.652	-21.408	43.595	2.384	-31.316
24/10/2000	359	-3.433	1.898	16.339	-6.539	-10.182	-8.172	-24.136	48.875	0.352	-34.662
26/10/2000	361	-3.714	0.028	13.980	0.848	-4.038	-8.459	-22.895	46.506	3.317	-32.897
28/10/2000	363	5.086	-7.070	8.267	4.701	-7.127	-4.290	-18.782	29.303	7.862	-26.553
01/11/2000	367	-7.542	7.147	14.219	-0.693	-8.513	-18.338	-13.441	53.161	13.342	-31.779
03/11/2000	369										
07/11/2000	373	-1.308	-5.913	12.015	3.324	-7.619	0.133	-51.681	67.536	-2.118	-54.093
09/11/2000	375	-0.040	-5.670	12.792	-0.062	-6.901	-4.718	-33.943	53.173	3.381	-39.747
11/11/2000	377	-2.186	-0.788	14.035	-5.194	-8.969	-3.945	-22.728	38.818	0.906	-28.584
13/11/2000	379	-2.326	-2.733	16.003	-6.124	-10.182	-6.806	-18.871	40.057	1.423	-28.445
15/11/2000	381	-3.055	-1.878	16.310	-2.772	-7.421	-5.375	-20.113	36.845	3.160	-27.014
17/11/2000	383	-7.327	7.988	13.042	-1.307	-9.067	-6.492	-18.580	39.340	0.864	-26.624
21/11/2000	387						0.527	-30.085	40.840	-4.926	-35.367

Date	Day No.	Module A: Δ in NO_3 Anaerobic (mgN/l_{inf})	Module A: Δ in NO_3 Anoxic (mgN/l_{inf})	Module A: Δ in NO_3 Aerobic (mgN/l_{inf})	Module A: Δ in NO_3 SST (mgN/l_{inf})	Module A: NO_3 denitrified Σ-ves (mgN/l_{inf})	Module B: Δ in NO_3 Anaerobic (mgN/l_{inf})	Module B: Δ in NO_3 Anoxic (mgN/l_{inf})	Module B: Δ in NO_3 Aerobic (mgN/l_{inf})	Module B: Δ in NO_3 SST (mgN/l_{inf})	Module B: NO_3 denitrified Σ-ves (mgN/l_{inf})
23/11/2000	389	0.362	-0.340	0.326	-0.428	-0.802	-4.799	-22.054	37.998	3.566	-27.349
25/11/2000	391	0.134	-0.490	32.149	-31.490	-32.220	-6.556	19.557	-25.185	27.419	-31.771
27/11/2000	393	0.025	-0.938	0.035	1.563	-0.938	0.206	-9.861	10.591	3.450	-9.861
29/11/2000	395	0.048	-0.585	-0.047	1.067	0.668	-6.183	-12.755	28.118	5.360	-19.024
01/12/2000	397	1.351	-1.061	0.654	-0.930	-2.021	-7.516	-24.730	42.625	1.091	-32.408
06/12/2000	402	0.536	-1.877	0.648	0.754	-1.585	-9.513	-15.514	35.417	1.097	-25.171
08/12/2000	404	0.504	-1.560	2.911	-1.338	-2.899	-8.130	-18.145	35.402	2.339	-26.711
12/12/2000	408	0.636	-3.279	4.185	-0.715	-3.578	-11.087	-29.571	54.669	0.641	-41.623
14/12/2000	410	0.591	-2.446	1.717	0.714	-2.597	-9.788	-33.308	54.879	2.106	-43.406
08/01/2001	435	-2.013	-36.684	69.410	-22.117	-60.814	-1.998	-66.976	72.732	6.999	-69.106
10/01/2001	437	0.092	-1.005	0.040	1.077	-1.024	-3.874	-46.419	72.172	-11.305	-71.217
12/01/2001	439	0.759	-0.875	1.275	-0.990	-1.865	-0.980	-36.605	50.922	3.599	-46.875
16/01/2001	441	1.018	-3.805	2.994	0.716	-4.468	-8.498	-43.518	70.420	-1.073	-53.137
18/01/2001	445	0.043	-4.554	24.926	-19.390	-24.482	-12.241	-14.061	37.919	5.481	-34.113
20/01/2001	447	0.275	-4.356	0.566	4.844	-4.356	-2.431	-27.460	34.976	3.430	-37.954
22/01/2001	449	0.350	-0.639	2.809	-2.358	-2.997	0.123	-26.727	30.439	1.068	-26.818
24/01/2001	451	-0.202	-21.916	15.824	13.028	-22.119	-0.393	-31.653	40.178	-3.060	-35.106
26/01/2001	453	0.606	-5.035	10.385	-4.553	-9.967	-5.242	-34.261	57.684	-6.310	-45.904
30/01/2001	457	-0.301	-13.023	23.569	-5.274	-20.951	0.141	-22.391	26.827	1.138	-21.649
01/02/2001	459	-6.331	1.815	14.689	7.095	-6.590	-9.428	-24.190	43.313	12.140	-34.474
03/02/2001	461	-6.351	5.512	3.737	7.670	-6.675	-3.992	-32.287	50.532	3.505	-36.748
05/02/2001	463	-1.541	-4.947	20.200	1.051	-14.713	-7.329	-32.159	56.923	0.767	-49.013
07/02/2001	465	-3.420	0.845	13.594	-1.518	-5.085	-6.053	-29.536	38.235	3.461	-38.329
09/02/2001	467	-10.582	12.748	12.858	5.031	-11.108	-6.535	-47.897	69.997	4.219	-56.033
13/02/2001	471	-1.078	-2.082	6.048	2.774	-3.535	-3.529	-34.800	49.475	1.186	-39.380
15/02/2001	473	-4.847	-3.149	5.158	-1.406	-9.406	-12.343	1.358	41.919	-34.168	-46.526
17/02/2001	475	77.468	-82.343	127.985	-127.935	-210.320	-4.751	-1.797	0.813	5.398	-6.502
19/02/2001	477										
21/02/2001	479	-4.904	1.752	13.854	2.572	-5.162	-3.465	-41.132	62.193	-4.986	-50.875
23/02/2001	481	-3.440	-2.558	17.538	-1.238	-7.314	6.506	-39.407	63.636	0.215	-54.695
27/02/2001	485	-10.136	13.643	11.176	2.726	-11.469	-2.791	-45.916	61.369	5.112	-51.308
01/03/2001	487	-10.125	16.448	7.433	6.801	-10.307	-3.572	-38.523	57.390	0.133	-44.638
03/03/2001	489	-3.314	3.341	14.837	3.557	-7.208	-7.120	-30.589	56.191	2.273	-43.593
05/03/2001	491	-2.839	-1.164	9.358	3.975	-4.756	-6.907	-22.573	41.606	3.874	-42.865
07/03/2001	493	-3.059	0.121	13.753	-0.913	-4.781	-2.954	-27.658	38.550	5.670	-36.250
09/03/2001	495	-0.232	-2.858	12.906	-0.519	-3.032	-0.200	-5.557	3.861	7.068	-5.757
13/03/2001	499	-11.159	24.967	10.794	-6.461	-17.896	-0.232	-5.166	7.963	-1.591	-6.901
15/03/2001	501	-6.149	6.101	9.217	5.581	-6.263	-2.853	-26.709	42.703	-1.787	31.349
17/03/2001	503	-5.704	6.661	10.656	1.695	-6.300	-1.279	-23.104	30.135	2.773	-24.383
19/03/2001	505	-5.664	4.671	13.836	0.823	-5.879	-0.313	-16.855	21.919	0.095	-17.168
23/03/2001	509	-5.505	5.026	-13.164	28.210	19.041	0.430	-8.358	12.577	-1.627	-10.774
27/03/2001	513	-2.902	9.049	4.444	6.109	-8.789	-0.794	-39.431	56.039	-6.413	-46.638
29/03/2001	515	-9.653	13.336	10.109	6.895	-10.458	-7.751	-19.633	44.280	1.384	-32.625
03/04/2001	520	-9.119	11.720	11.600	0.019	-10.480	-3.925	-23.582	47.260	-4.235	-32.564
05/04/2001	522	7.700	7.263	13.886	3.288	-7.557	-4.168	-16.599	47.432	-2.350	-29.244
09/04/2001	526	-6.333	10.975	4.925	1.957	-6.490	-8.499	-5.991	31.083	-1.613	-58.338
17/04/2001	534	3.617	-3.729	0.585	0.362	-4.156	0.230	71.791	29.140	-1.549	-23.380
19/04/2001	536	-2.004	-3.478	11.349	6.628	-5.822	-0.084	-28.471	43.669	-8.490	-37.129
21/04/2001	538	-5.636	4.327	9.375	6.237	-6.238	0.713	-40.872	56.685	-6.833	[illegible]
23/04/2001	540	0.713	-1.574	5.917	-0.661	-4.271	0.220	-21.179	29.050	-2.558	-24.343
25/04/2001	542	2.153	-2.001	2.278	-2.418	-4.419	-0.021	-4.421	5.986	-0.028	-5.008
02/05/2001	549	1.682	-1.600	-0.045	0.430	-2.306	0.358	-32.148	44.981	-1.726	-34.075
04/05/2001	551	-9.474	11.709	14.654	1.972	-9.466	0.139	-33.082	46.578	-1.551	-34.640
08/05/2001	555	-2.434	0.877	13.196	2.441	-2.434	-1.313	-47.110	69.170	-0.257	-48.680
10/05/2001	557	-0.431	-6.510	10.367	2.434	-6.940	3.465	-9.178	-12.825	44.447	-25.467
12/05/2001	559	-9.015	19.542	14.492	17.149	-28.164	-0.783	-31.040	50.139	-10.626	-41.949
14/05/2001	561	0.477	-5.402	8.302	9.093	-5.402	0.358	-13.816	-0.150	23.897	-13.965
16/05/2001	563	-8.351	9.673	13.134	3.763	-9.149	-0.774	-37.767	51.713	4.115	-39.578
18/05/2001	565	-7.257	10.063	8.904	3.528	-9.504	-5.429	-15.730	35.110	2.933	-22.158
22/05/2001	569	7.693	8.582	9.697	6.134	-7.691	-5.178	-25.771	41.913	2.317	-26.955
24/05/2001	571	-4.566	3.280	12.527	2.829	-4.566	-3.045	-25.195	42.100	2.130	-28.240
28/05/2001	575	-6.504	10.171	6.631	4.492	-6.504	-4.609	-27.632	48.793	1.287	-32.220
30/05/2001	577	-9.398	14.146	12.591	-2.178	-12.124	-6.620	-19.716	44.948	0.010	-27.827
01/06/2001	579	-7.147	14.987	17.127	-17.218	-24.365	-8.898	-25.165	54.152	1.122	-38.211
07/06/2001	585	-8.274	11.228	10.043	1.962	-8.543	-5.736	-38.889	63.950	-1.834	-50.406
09/06/2001	587	-0.053	-11.932	-0.307	21.818	-12.387	-1.730	-25.500	24.632	15.642	-29.901
11/06/2001	589	-8.114	14.481	15.076	-9.780	-18.302	0.147	-1.846	1.243	1.396	-1.926
Overall		-3.523	-1.470	14.930	[illegible]	-13.105	-5.770	-22.817	40.136	2.335	-32.644

APPENDIX E

Bi-DAILY "SITE" PHOSPHORUS MASS BALANCE

Table E1 : "Site" bi-daily Phosphorus Mass Balance.

MITCHELL'S PLAIN WWTP - PILOT PLANT : Bi-DAILY - PHOSPHORUS MASS BALANCE													
Date	Day No.	Module A Influent flow Q_I (l/d)	Module B Influent flow Q_I (l/d)	Module A Effluent flow Q_E (l/d)	Module B Effluent flow Q_E (l/d)	Influent Total P P_{ti} (mgP/l)	Module A TP in Waste P_{tw} (mgP/l)	Module B TP in Waste P_{tw} (mgP/l)	Module A Effluent TP P_{te} (mgP/l)	Module B Effluent TP P_{te} (mgP/l)	Module A %P Recovery (%)	Module B %P Recovery (%)
12/06/2000	225	1592006.40	2066053.20	1504423.40	1933416.20	12.16			0.32	2.34		
19/06/2000	232	1450137.60	2280614.40	1362554.60	2147947.40	12.40			0.32	4.09		
21/06/2000	234	1574812.80	2158617.60	1487229.80	2025950.60	12.95			0.31	1.21		
25/06/2000	236	1323993.60	2120688.00	1235410.60	1988021.00	11.10			0.37	3.19		
27/06/2000	240	1619308.80	2409177.60	1531725.80	2276510.60	15.11			0.40	8.69		
29/06/2000	242	1153785.60	2136672.00	1066202.60	2004005.00	12.30			0.45	2.34		
04/07/2000	247	1185667.20	2066774.40	1098084.20	1934107.40	14.83			0.29	1.15		
06/07/2000	249	1268265.60	1617235.20	1180682.60	1484568.20	13.61			0.35	2.10		
08/07/2000	251	2034806.40	2421792.00	1947223.40	2289125.00	13.87			12.55	4.10		
10/07/2000	253	1278806.40	2205705.60	1191223.40	2073038.60	12.36			0.40	3.02		
12/07/2000	255	1042848.00	2282947.20	955265.00	2150280.20	15.21			0.60	2.80		
14/07/2000	257	2009836.00	2445984.00	1922253.00	2313317.00							
18/07/2000	261	1493683.20	2427494.40	1406100.20	2294827.40	13.63			0.20	4.70		
20/07/2000	263	1407369.60	2221862.40	1319786.60	2089195.40	10.88			0.40	1.60		
22/07/2000	265	1380412.80	2150323.20	1292829.80	2017656.20							
24/07/2000	267	1321660.80	2057443.20	1234077.80	1924776.20	13.88			3.15	8.45		
26/07/2000	269	2119737.60	2500070.40	2032154.60	2367403.40	15.00			4.20	8.80		
28/07/2000	271	2000764.80	2363040.00	1913181.80	2230373.00	13.70			1.60	2.30		
01/08/2000	275	1653436.80	2248992.00	1565853.80	2116325.00	15.00			0.40	0.40		
03/08/2000	277	1236711.20	2212876.80	1148628.20	2080209.80	10.50			0.40	0.40		
05/08/2000	279	1391385.60	2340489.60	1303802.60	2207822.60	13.70			0.20	0.70		
08/08/2000	282	1118620.80	2055196.80	1031037.80	1922529.80	13.80	257.00	212.00	0.20	0.70	**144.88**	**103.91**
11/08/2000	285	1483920.00	2349648.00	1396337.00	2216981.00	12.60	294.00	205.00	0.10	0.70	**138.46**	**97.11**
15/08/2000	289	1469836.80	2328134.40	1382253.80	2195467.40	12.70	283.00	221.00	0.60	3.50	**137.22**	**125.15**
17/08/2000	291	1646784.00	2354745.60	1559201.00	2222078.60	13.20	273.00	195.00	1.50	6.40	**120.75**	**128.98**
19/08/2000	293	1589760.00	2389392.00	1502177.00	2256725.00	13.00	242.00	184.00	0.30	5.30	**104.74**	**117.09**
21/08/2000	295	1671753.60	2520288.00	1584170.60	2387621.00	12.20	233.00	157.00	2.20	5.30	**117.14**	**108.90**
23/08/2000	297	1577404.80	2413584.00	1489821.80	2280917.00	12.70	253.00	239.00	2.60	1.60	**129.95**	**115.35**
25/08/2000	299	1481328.00	2517782.40	1393745.00	2385115.40	13.60	274.00	194.00	0.40	0.70	**121.89**	**80.04**
29/08/2000	303	1737590.40	2499206.40	1650007.40	2366539.40	12.50	225.00	167.00	0.20	0.50	**92.25**	**74.71**
31/08/2000	305	1446595.20	2367446.40	1359012.20	2234779.40	12.60	202.00	220.00	0.30	0.60	**99.30**	**102.34**
02/09/2000	307	1414730.88	2207226.24	1327147.88	2074559.24							
04/09/2000	309	1582908.48	2210258.88	1495325.48	2077591.88	12.80	201.00	206.00	0.30	5.40	**89.10**	**136.26**
06/09/2000	311	1117307.52	2115054.72	1029724.52	1982387.72							
08/09/2000	313	1399066.56	2275758.72	1311483.56	2143091.72	14.56	175.30	159.50	0.29	1.98	**77.24**	**76.67**
12/09/2000	317	1483876.80	2319045.12	1396293.80	2186378.12	13.53	192.00	173.00	0.26	4.46	**85.57**	**104.23**
14/09/2000	319					10.59	202.10	190.50	0.29	3.19		
16/09/2000	321					13.34	337.30	241.50	1.40	10.74		
18/09/2000	323					11.32	214.40	201.20	4.99	13.49		
20/09/2050	325	1033741.44	1899996.48	946158.44	1767329.48	14.08	176.70	169.60				
22/09/2000	327	862462.08	1715869.44	774879.08	1583202.44	13.47	187.30	174.70	6.23	6.77	**183.14**	**160.35**
27/09/2000	332	1519283.52	2068156.80	1431700.52	1935489.80	13.38	177.60	158.50				
29/09/2000	334	1667269.44	2317749.12	1579686.44	2185082.12	12.59	161.00	168.40				
03/10/2000	338	1127563.20	1892237.76	1039980.20	1759570.76	13.30	178.00	194.00	0.30	1.40	**106.04**	**112.06**
05/10/2000	340	1473456.96	1885368.96	1385873.96	1752701.96	14.40	165.00	189.00	0.40	3.30	**89.33**	**143.57**
07/10/2000	342	1841633.28	2322760.32	1754050.28	2190093.32	13.17	194.40	191.60	0.39	4.27	**73.02**	**113.66**
09/10/2000	344	1509935.04	2159040.96	1422352.04	2026373.96	13.62	196.40	210.20	0.22	2.55	**85.16**	**112.40**
11/10/2000	346	1587435.84	2049183.36	1499852.84	1916516.36	13.78	190.50	218.70	0.18	2.47	**77.51**	**119.51**
13/10/2000	348	1643604.48	2240974.08	1556021.48	2108307.08	12.30	170.00	176.00	0.10	2.60	**74.42**	**103.63**
17/10/2000	352	1444227.84	2126969.28	1356644.84	1994302.28	13.00	181.00	196.00	0.30	1.50	**86.60**	**104.86**
20/10/2000	355	1813173.12	2174342.40	1725590.12	2041675.40	12.70	189.00	187.00	0.90	0.80	**78.63**	**95.76**
24/10/2000	359	1675883.52	2269771.20	1588300.52	2137104.20	13.30	173.00	179.00	0.30	1.10	**75.82**	**93.48**
26/10/2000	361	1686329.28	2218302.72	1598746.28	2085635.72	14.30	172.00	178.00	0.50	1.00	**65.78**	**81.02**
28/10/2000	363	1567926.72	2030503.68	1480343.72	1897836.68	14.30	197.00	144.00	0.50	0.80	**80.25**	**71.02**
01/11/2000	367	1396595.52	1734220.80	1309012.52	1601553.80	13.20	157.00	181.00	0.20	1.20	**76.01**	**113.29**
03/11/2000	369	1218602.88	1962601.92	1131019.88	1829934.92	13.50		246.00		2.00		**156.99**
07/11/2000	373	1661273.28	2296866.24	1573690.28	2164199.24	13.10	137.00	244.00	0.30	0.80	**62.04**	**112.70**
09/11/2000	375					12.00	164.00	289.00	0.30	1.20		
11/11/2000	377					12.40	116.00	249.00	0.40	0.80		
13/11/2000	379					13.30	170.00	174.00	0.10	2.60		
15/11/2000	381					13.50	119.00	211.00	0.30	0.80		
17/11/2000	383	1696662.72	2358720.00	1609079.72	2226053.00	13.90	72.00	271.00	3.90	0.90	**53.35**	**115.77**
21/11/2000	387	817136.64	2355125.76	729553.64	2222458.76	13.00		289.00		2.10		**140.47**
23/11/2000	389	1679572.80	2306802.24	1591989.80	2174135.24	11.20	132.00	339.00	2.70	2.90	**83.56**	**196.72**
25/11/2000	391	1860554.88	2328963.84	1772971.88	2196296.84	12.70	187.00	295.00	2.70	3.30	**89.57**	**155.92**

Date	Day No.	Module A Influent flow Q_I (l/d)	Module B Influent flow Q_I (l/d)	Module A Effluent flow Q_E (l/d)	Module B Effluent flow Q_E (l/d)	Influent Total P P_{Ti} (mgP/l)	Module A TP in Waste P_{W} (mgP/l)	Module B TP in Waste P_{W} (mgP/l)	Module A Effluent TP P_E (mgP/l)	Module B Effluent TP P_E (mgP/l)	Module A %P Recovery (%)	Module B %P Recovery (%)
27/11/2000	393	1659674.88	2242503.36	1572091.88	2109836.36	12.90	187.00	297.00	2.70	1.10	96.32	144.22
29/11/2000	395	662117.76	1027797.12	574534.76	895130.12	12.90	143.00	153.00	0.80		121.25	
01/12/2000	397	476599.68	1079593.92	389016.68	946926.92	13.80	131.00		3.30		193.96	
06/12/2000	402	719831.96	858263.04	632249.96	725596.04	13.60	35.00	251.00	2.20		90.25	
08/12/2000	404	809084.16	1163350.08	721501.16	1030683.08	12.70	93.00	262.00	1.00		86.29	
12/12/2000	408	1275860.16	1533340.80	1188277.16	1400673.80	12.90	113.00	233.00	0.80		65.91	
14/12/2000	410	1053000.00	1586450.88	965417.00	1453783.88	12.70	329.00	270.00	9.60		98.82	
08/01/2001	435	466767.36	1053190.08	379184.36	920523.08	13.70	191.00	227.00	0.50		264.56	
10/01/2001	437	2099822.40	2352974.40	2012239.40	2220307.40	12.20	345.00	285.00	2.70		70.78	
12/01/2001	439	1839611.52	2354045.76	1752028.52	2221378.76	12.10	138.00	281.00	3.30	0.40	80.27	134.00
16/01/2001	443	1778034.24	2241336.96	1690451.24	2108669.96	13.80	188.00	180.00	0.50	0.50	70.55	80.61
18/01/2001	445	1682156.16	2243635.20	1594573.16	2110968.20	12.50	244.00	103.00	7.00	2.00	154.72	63.78
20/01/2001	447	1850160.96	2238693.12	1762577.96	2106026.12	12.30	338.00	54.00	0.60	1.80	134.73	39.78
22/01/2001	449	1221626.88	2250979.20	1134043.88	2118312.20	13.60	343.00	55.00	1.20	1.80	189.01	36.29
24/01/2001	451	1723947.84	2268086.40	1636364.84	2135419.40	11.30	322.00	115.00	0.30	0.70	144.73	64.22
26/01/2001	453	1984098.24	2118147.84	1896515.24	1985480.84	13.30	263.00	114.00	0.20	0.30	95.58	60.54
30/01/2001	457	1982638.08	2308167.36	1895055.08	2175500.36	12.00	221.00	214.00	0.20	0.30	82.95	104.86
01/02/2001	459	1745271.36	2276190.72	1657688.36	2143523.72	11.60	46.00	65.00	0.20	0.70	21.84	38.34
03/02/2001	461	1771433.28	2323926.72	1683850.28	2191259.72	11.70	136.00	276.00	0.20	0.40	59.10	137.89
05/02/2001	463	2053166.40	2356801.92	1965583.40	2224134.92	13.70	199.00	133.00	5.20	1.90	98.30	67.74
07/02/2001	465	1934038.08	2346701.76	1846455.08	2214034.76	11.40	257.00	174.00	0.40	0.50	105.44	90.43
09/02/2001	467	2067068.16	2238969.28	1979485.16	2156302.28	13.00	179.00	286.00	4.60	1.60	92.23	139.10
13/02/2001	471	1763242.56	2332568.96	1675659.56	2200901.96	13.00	41.00	291.00	6.80	1.00	65.28	134.51
15/02/2001	473	1933994.88	2025000.00	1846411.88	1892333.00	12.10	46.00	26.00	10.30	7.40	98.49	71.22
17/02/2001	475	2007599.04	2320021.44	1920016.04	2187354.44	12.80	275.00	87.00	4.70	12.60	128.84	131.68
19/02/2001	477	1418627.52	1917578.88	1331044.52	1784911.88							
21/02/2001	479	1966887.36	2269330.56	1879304.36	2136663.56	11.60	233.00	158.00	0.40	2.10	93.50	96.67
23/02/2001	481	2221300.80	2337837.12	2133717.80	2205170.12	12.70	272.00	116.00	2.50	4.10	103.35	82.28
27/02/2001	485	2224860.48	2241129.60	2137277.48	2108462.60	10.80	115.00	269.00	3.40	0.60	116.63	152.67
01/03/2001	487	1920386.88	2344481.28	1832803.88	2211814.28	12.50	47.00	292.00	6.30	5.90	65.26	176.72
03/03/2001	489	1961081.28	2346338.88	1873498.28	2213671.88	13.50	224.00	170.00	6.60	11.40	120.81	150.87
05/03/2001	491	1755959.04	2320980.48	1668376.04	2188313.48	13.20	287.00	90.00	4.30	6.10	139.40	82.54
07/03/2001	493	1769947.20	2347012.80	1682364.20	2214345.80	11.80	52.00	300.00	3.40	7.20	49.19	169.30
09/03/2001	495	1726392.96	2306283.84	1638809.96	2173616.84	12.60	187.00	164.00	3.10	5.20	98.65	113.77
13/03/2001	499	1737357.12	2294524.80	1649774.12	2161857.80	13.30	113.00	23.00	11.00	1.50	121.37	20.61
15/03/2001	501	1599531.84	2298464.64	1511948.84	2165797.64	12.20	313.00	81.00	4.20	0.90	173.02	45.27
17/03/2001	503	1675330.56	2317766.40	1587747.56	2185099.40	13.00	395.00	62.00	7.80	3.40	191.58	51.96
19/03/2001	505	1694433.60	2265114.24	1606850.60	2132447.24	12.60	312.00	50.00	6.60	5.30	177.66	62.84
23/03/2001	509	1526713.92	2108531.52	1439130.92	1975864.52	12.20	335.00	38.00	9.00	2.30	227.06	37.26
27/03/2001	513	1648520.64	2308979.52	1560937.64	2176312.52	13.00	78.00	262.00	12.40	3.30	105.85	139.72
29/03/2001	515	1607601.60	2299337.28	1520018.60	2166670.28	12.30	153.00	169.00	8.70	9.60	134.65	152.92
03/04/2001	520	1585025.28	2192702.40	1497442.28	2060035.40	11.40	178.00	58.00	6.30	1.60	138.49	43.97
05/04/2001	522	1666440.00	2189877.12	1578857.00	2057210.12	12.60	156.00	67.00	0.40	6.40	68.08	62.91
09/04/2001	526	1283748.48	1706762.88	1196165.48	1574095.88	11.50	184.00	57.00	8.40	9.30	161.01	113.11
17/04/2001	534	1814322.24	2190222.72	1726739.24	2057555.72	13.10	135.00	56.00	2.70	1.70	61.99	38.08
19/04/2001	536	1568859.84	2100055.68	1481276.84	1967388.68	10.60	257.00	56.00	0.40	0.60	138.91	38.68
21/04/2001	538	1789732.80	2067465.60	1702149.80	1934798.60	11.80	186.00	68.00	0.40	0.50	80.36	40.94
23/04/2001	540	1968338.88	2234018.88	1880755.88	2101351.88	10.90	192.00	66.00	0.10	0.50	79.25	40.77
25/04/2001	542	1897387.20	2155973.76	1809804.20	2023306.76	10.20	121.00	58.00	2.70	0.50	80.01	39.59
02/05/2001	549	1723403.52	2258228.16	1635820.52	2125561.16	14.00	222.00	80.00	0.50	0.70	83.98	38.28
04/05/2001	551	2014873.92	2293712.64	1927290.92	2161045.64	12.20	211.00	92.00	2.70	0.60	96.35	48.25
08/05/2001	555	1869877.44	2257994.88	1782294.44	2125327.88	11.50	219.00	122.00	0.10	1.10	90.03	71.33
10/05/2001	557	1938306.24	2290040.64	1850723.24	2157373.64	11.90	219.00	123.00	0.20	1.20	84.76	69.38
12/05/2001	559	1821035.52	2280579.84	1733452.52	2147912.84	14.30	205.00	131.00	3.30	1.30	104.23	60.64
14/05/2001	561	1841209.92	2222242.56	1753626.92	2089575.56	12.40	181.00	130.00	3.10	1.30	93.24	72.45
16/05/2001	563	2132939.52	2293945.92	2045356.52	2161278.92	12.70	159.00	135.00	0.40	3.00	54.43	83.72
18/05/2001	565	1847715.84	2276337.60	1760132.84	2143670.60	13.10	162.00	149.00	0.20	2.80	60.07	86.42
22/05/2001	569	1727663.04	2600182.08	1640080.04	2467515.08	11.90	152.00	164.00	1.30	1.20	75.12	79.80
24/05/2001	571	2025691.20	2236377.60	1938108.20	2103710.60	13.10	179.00	155.00	1.90	4.20	68.57	100.35
28/05/2001	575	2058929.28	2306370.24	1971346.28	2173703.24	12.70	52.00	174.00	8.10	3.80	78.48	107.01
30/05/2001	577	1878629.76	2266790.40	1791046.76	2134123.40	10.70	257.00	178.90	1.50	1.90	81.77	114.57
01/06/2001	579	1669757.76	2223624.96	1582174.76	2090957.96	10.40	172.00	151.00	4.10	2.10	124.10	105.61
07/06/2001	585	1956692.16	2298525.12	1869109.16	2165858.12	11.60	152.00	150.00	1.50	3.00	71.00	99.01
09/06/2001	587	1907409.60	2254901.76	1819826.60	2122234.76	14.00	143.00	141.00	5.80	5.20	60.43	98.25
11/06/2001	589	1920965.76	1335009.60	1833382.76	1202342.60	12.40	138.00	107.00	2.60		70.75	
Overall		1605442.93	2166012.60	1517859.93	2033345.60	12.73	186.25	171.90	2.31	2.93	102.6395	96.6778

Table E2 : "Site" bi-daily Soluble P Mass Balance.

MITCHELL'S PLAIN PILOT PLANT : Sol. P MASS BALANCE over REACTORS & SST											
		Module A					Module B				
Date	Day No.	Δ in P_s in Anaerobic (mgP/l_{inf})	Δ in P_s in Anoxic (mgP/l_{inf})	Δ in P_s in Aerobic (mgP/l_{inf})	Δ in P_s in SST (mgP/l_{inf})	P removal ΔP (mgP/l_{inf})	Δ in P_s in Anaerobic (mgP/l_{inf})	Δ in P_s in Anoxic (mgP/l_{inf})	Δ in P_s in Aerobic (mgP/l_{inf})	Δ in P_s in SST (mgP/l_{inf})	P removal ΔP (mgP/l_{inf})
12/06/2000	225	28.200	-10.506	-29.593	-0.171	-13.07[illegible]	44.595	22.893	-81.987	4.399	-10.100
19/06/2000	232	29.974	-5.568	-35.826	-0.780	-12.200	45.440	11.771	-68.868	3.269	-8.408
21/06/2000	234	22.955	17.949	-18.128	0.172	-12.750	15.883	4.307	-35.125	3.025	-11.910
23/06/2000	236	14.766	-17.177	-8.244	-0.395	-11.000	19.090	17.638	-48.397	3.610	-8.059
27/06/2000	240	20.676	-11.229	-24.674	-0.253	-14.884	27.468	6.093	-45.650	5.079	-7.010
29/06/2000	242	2.499	-9.787	-5.098	0.276	-12.110	18.800	6.880	-43.336	6.496	-10.160
04/07/2000	247	-16.673	11.980	-9.779	0.032	-14.590	12.427	-2.387	-25.576	1.557	-13.979
06/07/2000	249	8.485	-10.193	-11.600	0.000	-13.308	22.915	-9.548	-26.787	1.719	-11.701
08/07/2000	251	41.617	-12.896	-50.878	99.388	2.770	27.238	-0.531	-39.087	2.510	-9.870
10/07/2000	253	77.428	-26.971	-12.364	-0.303	-33.700	27.798	-0.752	-39.579	2.873	-9.660
12/07/2000	255	53.995	-20.302	-49.424	[illegible]	-14.611	20.394	-1.170	-34.930	2.997	-12.709
14/07/2000	257	-	-	-	-	-	-	-	-	-	-
18/07/2000	261	16.055	-20.455	-8.755	-0.275	1.430	21.906	3.482	-37.930	3.312	-9.230
20/07/2000	263	7.304	-11.823	-6.501	0.540	-10.480	-6.607	8.500	-13.641	2.171	-9.577
22/07/2000	265	-	-	-	-	-	-	-	-	-	-
24/07/2000	267	20.055	-12.469	-24.179	5.583	-10.980	13.534	7.833	-30.528	3.280	-5.885
26/07/2000	269	22.970	-14.876	-11.083	-6.011	-9.000	24.312	3.176	-33.516	1.428	-4.600
28/07/2000	271	19.662	19.042	-36.144	-14.760	-12.200	35.788	18.774	-51.455	-14.658	-11.551
01/08/2000	275	32.727	-6.318	-41.109	0.000	-14.700	48.673	10.056	-73.213	-0.216	-14.700
03/08/2000	277	26.339	-20.536	-16.103	0.000	-10.300	25.581	-4.149	-31.950	0.218	-10.300
05/08/2000	279	24.102	-21.953	-15.176	-0.574	-13.605	29.259	-2.481	-40.389	0.211	-13.400
08/08/2000	282	10.543	-14.307	-9.836	0.000	-13.600	15.416	6.728	-35.996	0.453	-13.399
11/08/2000	285	14.457	-16.431	-10.508	-0.028	-12.510	15.760	-6.302	-22.289	0.632	-12.199
15/08/2000	289	30.205	-14.576	-27.729	0.000	-12.100	25.836	-1.539	-32.428	-1.270	-9.401
17/08/2000	291	35.267	-21.530	-28.212	2.576	-11.899	26.942	3.437	-40.102	2.222	-7.201
19/08/2000	293	21.593	-14.537	-19.065	0.791	-12.800	14.141	-2.738	-20.756	1.253	-8.100
21/08/2000	295	31.158	-14.467	-27.559	0.767	-10.101	39.933	25.649	-75.987	3.454	-6.901
23/08/2000	297	12.334	-57.411	-29.985	4.762	-10.300	41.350	9.315	-64.320	2.100	-11.599
25/08/2000	299	37.362	-16.818	-30.601	-3.243	-13.300	41.021	5.461	-59.781	0.000	-13.299
29/08/2000	303	42.420	-22.558	-31.262	0.000	-12.400	33.907	-7.517	-38.985	0.395	-12.200
31/08/2000	305	19.971	-12.959	-19.317	0.000	-12.300	23.651	-0.857	-35.399	0.405	-12.200
02/09/2000	307	-	-	-	-	-	-	-	-	-	-
04/09/2000	309	32.638	-15.419	-30.471	0.752	-12.500	37.714	-4.652	-48.773	8.111	-7.600
06/09/2000	311	-	-				-	-	-		-
08/09/2000	313	22.162	-8.453	-28.252	[illegible]	-14.280	27.397	1.133	-39.958	-1.287	-12.720
12/09/2000	317	31.712	-15.877	-29.418	0.362	-13.320	28.984	2.050	-40.017	-0.727	-9.710
14/09/2000	319	1.045	-5.471	-6.170	0.326	-10.370	8.497	-0.829	-15.690	0.392	-7.030
16/09/2000	321	3.620	-3.800	-8.314	-5.455	-13.950	13.000	-2.941	-10.166	-4.923	-5.030
18/09/2000	323	24.773	-10.070	-17.907	-3.047	-6.250	26.976	-3.371	-23.270	0.895	1.230
20/09/2000	325	16.591	-32.091	13.769	2.671	0.940	20.052	-77.022	61.642	10.880	15.550
22/09/2000	327	18.384	-4.984	-21.330	0.640	-7.290	25.828	-1.143	-33.788	4.084	-5.020
27/09/2000	332	10.354	-31.688	28.590	-2.257	5.000	11.023	-50.019	45.365	3.832	10.200
29/09/2000	334	34.999	26.758	-61.845	3.649	3.561	47.084	8.489	-63.934	1.231	-7.130
03/10/2000	338	35.852	-30.507	-18.345	0.000	-13.000	44.871	-7.801	-50.468	0.599	-12.800
05/10/2000	340	22.871	-21.237	-12.086	-0.647	-11.100	41.486	-10.128	-42.057	0.399	-10.300
07/10/2000	342	38.555	-23.881	-27.237	-0.367	-12.930	44.143	1.742	-50.815	-4.449	-9.380
09/10/2000	344	44.385	-28.991	-28.230	-0.604	-13.440	50.245	7.137	-70.507	1.975	-11.150
11/10/2000	346	39.391	-31.615	-21.172	-0.194	-13.600	32.676	0.907	-46.510	1.417	-11.510
13/10/2000	348	42.715	-34.844	-19.640	-0.432	-12.200	46.728	-5.549	-48.984	-1.995	-9.800
17/10/2000	352	34.903	-27.631	-19.208	-0.863	-12.800	48.214	2.637	-61.354	-1.197	-11.700
20/10/2000	355	24.511	-15.161	-22.079	0.928	-11.800	33.988	-5.467	-41.067	1.496	-11.050
24/10/2000	359	38.562	-27.569	-21.798	-1.295	-12.100	48.013	-4.791	-54.921	0.399	-11.300
26/10/2000	361	37.211	-31.372	-19.748	0.108	-13.800	38.473	-0.600	-52.151	0.879	-13.399
28/10/2000	363	38.248	-18.811	-33.237	0.000	-13.800	41.928	-5.954	-49.974	0.399	-13.600
01/11/2000	367	29.505	-32.605	-9.900	0.000	-13.000	-9.169	-6.721	26.531	6.671	17.362
03/11/2000	369		-	-	-	-	-	-	-	-	-
07/11/2000	373	45.337	-35.862	-19.125	-2.250	-11.900	-18.027	125.148	-118.989	0.568	-11.500
09/11/2000	375	48.050	-37.800	-21.600	-0.450	-11.800	65.275	36.369	-113.581	0.737	-11.200
11/11/2000	377	45.285	-35.810	-19.125	-0.450	-12.100	0.578	32.662	-44.621	0.737	-11.800
13/11/2000	379	43.865	-32.890	-23.400	-0.675	-13.100	49.905	-14.480	-48.678	0.553	-12.790
15/11/2000	381	42.154	-34.429	-19.800	-1.125	-13.200	49.060	-1.326	-61.253	0.718	-12.800
17/11/2000	383	-4.756	-6.731	-11.475	3.150	-10.300	45.714	-8.720	-50.931	0.737	-13.200
21/11/2000	387	-	-	-	-	-	26.456	68.572	-108.623	2.395	-11.200
23/11/2000	389	-27.116	51.566	-68.400	60.750	16.800	1.641	58.255	-63.101	-5.895	-9.100

Date	Day No.	Module A: Δ in P_s in Anaerobic (mgP/l_{inf})	Module A: Δ in P_s in Anoxic (mgP/l_{inf})	Module A: Δ in P_s in Aerobic (mgP/l_{inf})	Module A: Δ in P_s in SST (mgP/l_{inf})	Module A: P removal ΔP (mgP/l_{inf})	Module B: Δ in P_s in Anaerobic (mgP/l_{inf})	Module B: Δ in P_s in Anoxic (mgP/l_{inf})	Module B: Δ in P_s in Aerobic (mgP/l_{inf})	Module B: Δ in P_s in SST (mgP/l_{inf})	Module B: P removal ΔP (mgP/l_{inf})
25/11/2000	391	-1.624	-2.226	-30.150	38.700	4.700	39.894	-41.843	4.507	-5.158	-2.600
27/11/2000	393	-3.082	15.170	-24.008	-0.270	-12.190	66.436	8.627	-87.890	0.717	-12.100
29/11/2000	395	21.841	-23.316	-11.250	0.225	-12.500	34.444	-9.017	-29.747	4.421	0.100
01/12/2000	397	1.799	-16.361	-5.708	8.969	-11.300	18.021	2.714	-35.684	2.349	-12.600
06/12/2000	402	9.331	-16.115	-7.746	1.631	-12.900	15.437	2.575	-22.303	-1.409	-5.700
08/12/2000	404	9.602	-19.848	-3.262	0.408	-12.100	23.316	-1.010	-23.790	2.584	1.100
12/12/2000	408	25.361	-17.904	-20.185	0.408	-12.500	40.405	3.124	-49.066	5.637	0.100
14/12/2000	410	23.332	-17.486	-17.939	-0.408	-12.500	46.800	7.115	-62.447	4.932	-3.600
08/01/2001	435	-	-	-	-	-13.400		-	-	-	-1.100
10/01/2001	437	50.901	15.122	-36.345	-24.179	5.300	66.636	31.329	-109.999	10.534	-1.500
12/01/2001	439	45.262	-20.933	-42.107	7.978	-9.800	51.233	29.475	-91.103	-1.404	-11.800
16/01/2001	443	47.780	-16.757	-42.551	-1.775	-13.300	48.455	-15.068	-47.239	0.351	-15.500
18/01/2001	445	52.177	-49.256	-38.561	30.140	-5.500	34.646	1.500	-44.839	-2.107	-10.500
20/01/2001	447	38.290	-11.932	-39.005	0.856	-11.850	24.814	-32.473	-5.399	2.458	-10.600
22/01/2001	449	60.578	-18.109	-57.177	2.216	-12.500	9.035	25.249	-48.588	1.464	-12.000
24/01/2001	451	39.648	-17.705	-31.913	-1.330	-11.300	28.544	10.440	-51.288	1.404	-10.900
26/01/2001	453	46.245	-13.135	-45.210	-0.000	-12.100	33.650	13.736	-59.386	0.000	-12.000
30/01/2001	457	46.715	-18.280	-39.448	-0.886	-11.900	56.720	32.779	-101.901	0.702	-11.700
01/02/2001	459	19.433	-17.716	-12.262	-0.855	-11.400	30.750	-4.993	-37.157	0.000	-11.400
03/02/2001	461	4.374	-5.844	-9.695	-0.285	-11.500	24.971	13.261	-49.733	0.000	-11.500
05/02/2001	463	27.215	13.017	-45.910	-3.422	-9.100	37.604	10.589	-58.307	-1.685	-11.800
07/02/2001	465	23.721	-21.438	-22.247	-1.141	-1.100	39.989	13.015	-62.860	-1.124	-11.000
09/02/2001	467	27.011	-22.109	-12.262	-1.141	-8.500	37.588	23.126	-90.890	-1.124	-11.500
13/02/2001	471	0.230	-1.967	-5.988	1.426	-6.300	48.061	6.481	-63.452	-3.090	-12.000
15/02/2001	473	4.778	2.237	12.547	3.117	-2.400	40.246	-3.026	-44.588	3.933	-5.300
17/02/2001	475	35.789	-19.465	-23.668	-0.855	-8.200	20.417	-2.023	-21.722	3.528	-0.800
19/02/2001	477	-	-	-	-	-	-	-	-	-	-
21/02/2001	479	25.819	-23.147	-33.687	0.285	-11.300	40.164	3.758	-57.735	4.213	-9.600
23/02/2001	481	37.453	-19.523	-26.234	-1.996	-10.300	27.174	12.625	-49.161	0.562	-8.800
27/02/2001	485	35.197	-19.668	-9.125	1.996	8.400	66.776	6.012	-70.883	-1.404	0.500
01/03/2001	487	2.316	-4.119	-5.711	0.914	-6.600	36.184	12.402	-53.917	-1.269	-6.600
03/03/2001	489	37.667	-28.805	-27.184	11.422	-6.900	40.356	-4.774	-40.919	2.557	-2.800
05/03/2001	491	34.091	-28.114	-16.904	1.877	-9.100	19.346	5.600	-36.587	4.440	-7.200
07/03/2001	493	47.891	-36.974	-18.046	-1.371	-8.500	10.525	6.529	-26.477	0.423	-9.000
09/03/2001	495	50.351	-44.975	-11.879	-1.198	-9.700	17.447	7.010	-33.698	1.861	-7.420
13/03/2001	499	12.378	-20.660	2.284	3.198	-2.800	0.109	9.126	-16.368	0.634	-6.500
15/03/2001	501	24.605	-19.327	-11.422	-2.056	-8.200	12.159	8.907	-32.254	-0.211	-11.400
17/03/2001	503	34.794	-29.786	-10.280	-0.228	-5.500	11.879	4.522	-25.013	-1.269	-9.900
19/03/2001	505	30.848	-24.814	-14.163	1.827	-6.300	2.418	23.850	-34.180	0.211	-7.700
23/03/2001	509	27.061	-24.950	-8.681	2.970	3.600	-0.936	18.293	-25.514	1.057	-7.100
27/03/2001	513	3.022	-3.793	-1.371	2.741	-1.400	50.335	16.472	-76.062	-0.846	-10.100
29/03/2001	515	9.203	-7.192	-8.452	2.741	-3.700	29.332	2.763	-36.587	0.211	-4.300
03/04/2001	520	20.879	-32.776	-6.072	12.369	-5.600	11.359	2.417	-25.167	1.291	-10.100
05/04/2001	522	10.962	-12.568	-10.120	-0.675	-12.400	11.358	-1.492	-18.985	-1.076	10.200
09/04/2001	526	5.620	-5.548	-2.924	-2.249	-5.100	8.869	-4.084	-10.155	-0.430	-5.800
17/04/2001	534	7.600	3.137	2.474	-9.708	33.000	4.178	15.585	-31.348	-0.215	-11.800
19/04/2001	536	27.085	-35.787	-3.373	-0.225	-10.300	13.851	-1.964	-22.517	0.430	-10.200
21/04/2001	538	7.549	-13.651	-4.948	-0.450	-11.500	12.053	-0.142	-23.842	0.430	-11.500
23/04/2001	540	47.155	-39.514	-18.216	0.225	-10.800	14.757	10.844	-36.646	0.645	-10.400
25/04/2001	542	8.419	15.909	-3.148	0.000	21.200	28.538	22.480	-60.488	-0.430	-9.900
02/05/2001	549	45.047	-39.425	-19.654	0.432	-13.600	14.844	52.217	-80.761	0.000	-13.700
04/05/2001	551	13.274	-16.354	-8.207	0.907	-10.380	19.084	31.122	-62.440	0.234	-12.000
08/05/2001	555	25.201	-26.882	-9.503	-0.216	-11.400	31.153	1.018	-43.372	0.000	-11.200
10/05/2001	557	40.717	-37.615	-14.687	-0.216	-11.800	23.514	9.653	-44.867	0.000	-11.700
12/05/2001	559	22.989	32.289	-10.367	10.367	9.300	33.387	30.183	-77.770	0.000	-14.000
14/05/2001	561	44.259	-21.578	-35.658	3.477	-9.500	24.982	45.842	-82.256	-0.468	-11.900
16/05/2001	563	33.975	-33.982	-13.175	-0.216	-12.400	43.086	2.802	-56.084	-1.404	-11.600
18/05/2001	565	21.275	-23.906	-10.151	-0.216	-13.000	40.540	-21.286	-32.155	0.000	-12.900
22/05/2001	569	26.754	-30.758	-8.835	2.160	-10.700	47.999	-24.504	-36.268	1.872	-10.900
24/05/2001	571	33.684	-30.249	-15.983	0.648	-11.900	41.356	-11.901	-42.624	0.468	-12.700
28/05/2001	575	10.078	-9.446	-4.968	-0.864	-5.200	46.129	-13.776	-44.119	-0.234	-12.000
30/05/2001	577	17.504	-21.189	-7.775	2.160	-9.500	38.490	-11.289	-38.137	0.936	-10.000
01/06/2001	579	14.838	-32.977	-6.354	7.887	-6.600	23.625	1.434	-32.994	1.303	-9.500
07/06/2001	585	23.275	-19.234	-13.803	-0.428	-10.200	39.398	13.455	-62.988	0.434	-9.700
09/06/2001	587	40.500	-32.010	-5.696	-11.393	-8.600	42.482	5.442	-46.991	0.651	-9.300
11/06/2001	589	28.305	-32.927	-9.850	4.382	-10.100	13.537	46.373	-35.993	-7.817	16.100
Overall		25.877	-17.630	-18.888	1.541	-9.100	29.403	5.783	-44.768	0.808	-8.774

APPENDIX F

Bi-DAILY "SITE" CALCULATED vs MEASURED P REMOVAL

Table F-1 : "Site" bi-daily calculated versus measured P removal - determination of [illegible] and [illegible]

MITCHELL'S PLAIN PILOT PLANT : BI-DAILY PHOSPHORUS REMOVAL

Table F2 : [illegible]

MITCHELL'S PLAIN PILOT PLANT : BIOLOGICAL PHOSPHORUS REMOVAL

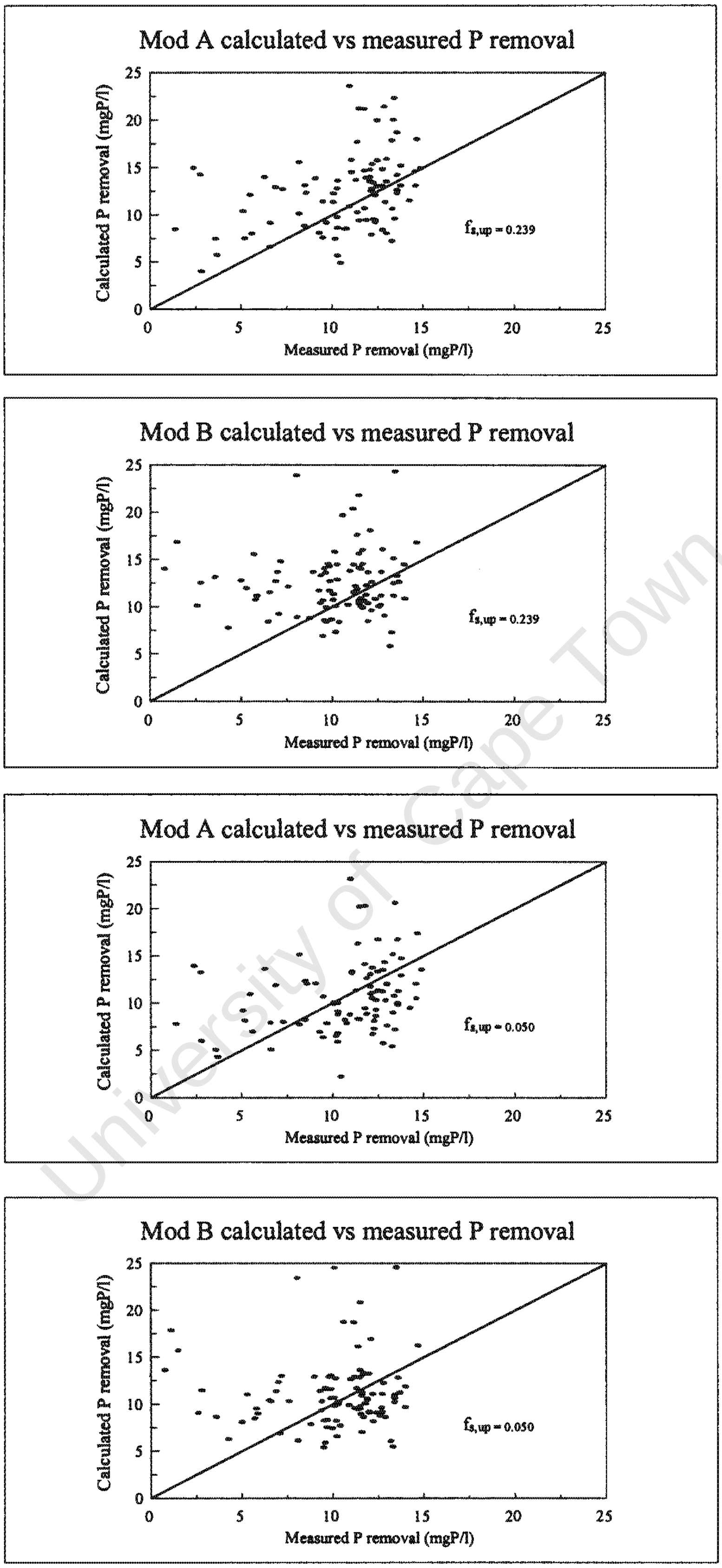
[illegible]

Table F3 : "Site" bi-daily calculated versus measured P removal - determination of $f_{av,OHO}$, $f_{av,PAO}$ and $f_{XBG,P}$ for a fixed $f_{S,up}$ of 0.05

MITCHELL'S PLAIN PILOT PLANT : BI-DAILY PHOSPHORUS REMOVAL

Date	Day No.	Module A P removal $\Delta P_{measured}$ (mgP/l)	Module B P removal $\Delta P_{measured}$ (mgP/l)	Influent COD S_{ti} (mgCOD/l)	Influent RBCOD S_{bsi} (mgCOD/l)	Influent unbio. sol. f_{us}	Influent unbio. part f_{up}	Module A total P removal/litre $\Delta P_{predicted}$ (mgP/litre)	Module B total P removal/litre $\Delta P_{predicted}$ (mgP/litre)	Average active OHO/VSS $f_{av,OHO}$	Average active PAO/VSS $f_{av,PAO}$	Average PAO P content $f_{XBG,P}$
12/06/2000	225	12.02	18.300	750.0	404.0	0.077	0.050	25.028	24.497	0.266	0.339	0.132
19/06/2000	232	12.2	8.410	788.0	442.0	0.061	0.050	28.504	28.545	0.251	0.362	0.104
21/06/2000	234	12.75	11.910	565.0	304.0	0.046	0.050	11.207	10.405	0.306	0.179	0.453
23/06/2000	236	11	8.060	669.0	397.0	0.023	0.050	23.129	23.448	0.266	0.345	0.132
27/06/2000	240	14.88	7.210	596.0	239.0	0.037	0.050	13.540	12.310	0.350	0.207	0.304
29/06/2000	242	12.11	10.160	573.0	242.0	0.054	0.050	11.705	12.716	0.347	0.207	0.336
04/07/2000	247	14.59	13.960	661.0	236.0	0.045	0.050	12.028	11.891	0.372	0.167	0.483
06/07/2000	249	13.3	11.700	624.0	269.0	0.056	0.050	15.171	13.334	0.355	0.225	0.321
08/07/2000	251	2.77	9.870	598.0	205.0	0.079	0.050	13.206	10.628	0.355	0.195	0.144
10/07/2000	253	12.16	9.660	589.0	234.0	0.065	0.050	10.516	11.579	0.364	0.179	0.374
12/07/2000	255	14.61	12.710	570.0	219.0	0.058	0.050	10.489	11.068	0.363	0.180	0.318
14/07/2000	257			521.0	274.0	0.063						
18/07/2000	261	13.43	9.530	467.0	187.0	0.060	0.050	7.212	8.368	0.382	0.151	0.645
20/07/2000	263	10.48	9.580	418.0	161.0	0.093	0.050	2.224	5.898	0.432	0.063	1.574
22/07/2000	265			391.0	204.0	0.056	0.050	5.734	8.167	0.378	0.160	
24/07/2000	267	10.98	5.880	600.0	207.0	0.068	0.050	8.735	8.980	0.394	0.128	0.352
26/07/2000	269	9	4.600	565.0	192.0	0.037						
28/07/2000	271	13.2	11.550	403.0	186.0	0.077	0.050	11.074	8.947	0.352	0.199	0.473
01/08/2000	275	14.7	14.700	845.0	261.5	0.035	0.050	17.389	16.240	0.363	0.186	0.316
03/08/2000	277	10.3	10.300	581.0	195.0	0.074	0.050	9.118	9.987	0.379	0.152	0.423
05/08/2000	279	13.6	13.400	591.0	204.0	0.054	0.050	9.995	10.217	0.379	0.156	0.562
08/08/2000	282	13.6	13.450	505.0	223.0	0.050	0.050	9.792	10.680	0.355	0.194	0.541
11/08/2000	285	12.51	12.290	404.0	-	0.087						
15/08/2000	289	12.1	9.400	535.0	217.0	0.058	0.050	10.979	10.796	0.357	0.192	0.385
17/08/2000	291	11.9	7.200	586.0	-							
19/08/2000	293	12.8	8.100	452.0	144.0	0.042	0.050	5.741	6.191	0.412	0.105	0.858
21/08/2000	295	10.1	6.900	515.0	200.0	0.045	0.050	10.040	11.372	0.371	0.173	0.272
23/08/2000	297	10.3	11.600	519.0	207.0	0.066	0.050	9.956	11.740	0.352	0.199	0.396
25/08/2000	299	13.3	13.300	533.0	514.0	0.054	0.050	5.415	5.473	0.434	0.067	1.534
29/08/2000	303	12.4	12.400	541.0	186.0	0.065	0.050	10.292	9.068	0.372	0.168	0.529
31/08/2000	305	12.3	12.200	587.0	169.0	0.068	0.050	8.098	8.181	0.403	0.118	0.666
02/09/2000	307			578.0	201.0	0.076	0.050	12.302	12.291	0.343	0.211	
04/09/2000	309	12.5	7.600	579.0	211.0	0.062	0.050	11.230	10.326	0.352	0.197	0.346
06/09/2000	311			563.0	241.0	0.055	0.050	14.397	14.868	0.321	0.250	
08/09/2000	313	14.28	12.720	485.0	197.0	0.076	0.050	9.475	9.136	0.359	0.187	0.609
12/09/2000	317	12.32	9.710	686.0	162.0	0.060	0.050	8.999	8.290	0.413	0.100	0.596
14/09/2000	319	10.37	7.630	500.0	201.0	0.072						
16/09/2000	321	13.95	5.030	-	-							
18/09/2000	323	11.32		551.0	204.0	0.073						
20/09/2000	325			535.0	203.0	0.079	0.050	8.651	8.551	0.387	0.142	
22/09/2000	327	7.29	3.020	512.0	198.0	0.068	0.050	8.011	8.088	0.383	0.143	0.248
27/09/2000	332			590.0	194.0	0.080	0.050	9.716	8.579	0.389	0.136	
29/09/2000	334		7.130	-	154.0	0.083						
03/10/2000	338	13	12.800	631.0	236.0	0.073	0.050	12.048	12.252	0.357	0.187	0.412
05/10/2000	340	11.1	10.300	570.0	215.0	0.065	0.050	13.185	10.248	0.351	0.200	0.337
07/10/2000	342	12.93	9.360	644.0	181.0	0.053	0.050	10.260	9.302	0.395	0.132	0.461
09/10/2000	344	13.44	11.550	647.0	319.0	0.084	0.050	20.621	18.696	0.281	0.314	0.213
11/10/2000	346	13.6	11.510	571.0	293.0	0.058	0.050	16.699	13.613	0.305	0.274	0.301
13/10/2000	348	12.2	9.800	550.0	235.0	0.091	0.050	13.736	12.889	0.330	0.249	0.298
17/10/2000	352	12.8	11.200	628.0	247.0	0.070	0.050	13.501	13.195	0.345	0.210	0.339
20/10/2000	355	11.8		610.0	245.0	0.082	0.050	14.124	12.816	0.338	0.222	0.320
24/10/2000	359	12.1	11.300	590.0	226.0	0.085	0.050	13.060	11.691	0.345	0.210	0.353
26/10/2000	361	13.8	13.400	682.0	211.0	0.066	0.050	12.876	10.967	0.375	0.163	0.455
28/10/2000	363	13.8	11.600	664.0	228.0	0.071	0.050	14.686	12.755	0.349	0.203	0.379
01/11/2000	367	13	12.200	663.0	229.0	0.062	0.050	11.971	11.057	0.374	0.161	0.431
03/11/2000	369		11.600	555.0	138.0	0.096	0.050	8.128	7.022	0.396	0.120	0.699
07/11/2000	373	11.9	13.500	537.0	215.0	0.086	0.050	12.635	12.847	0.325	0.242	0.341
09/11/2000	375	11.8	11.200	556.0	241.0	0.083						
11/11/2000	377	12.1	11.800	528.0	289.0	0.070						
13/11/2000	379	13.7	12.900	771.0	207.0	0.065						
15/11/2000	381	13.2	12.800	731.0	265.0	0.059						
17/11/2000	383	10.3	13.200	580.0	122.0	0.053	0.050	5.908	6.040	0.433	0.068	1.141
21/11/2000	387		11.200	674.0	205.0	0.082	0.050	11.557	12.856	0.352	0.193	0.338
23/11/2000	389		9.100	960.0	444.0	0.064	0.050	31.984	30.067	0.275	0.328	0.085

Date	Day No.	Module A P removal $\Delta P_{measured}$ (mgP/l)	Module B P removal $\Delta P_{measured}$ (mgP/l)	Influent COD S_{ti} (mgCOD/l)	Influent RBCOD S_{bsi} (mgCOD/l)	Influent unbio. sol. f_{us}	Influent unbio. part. f_{up}	Module A total P removal/l_{inf} $\Delta P_{predicted}$ (mgP/l_{inf})	Module B total P removal/l_{inf} $\Delta P_{predicted}$ (mgP/l_{inf})	Average active OHO/VSS $f_{av,OHO}$	Average active PAO/VSS $f_{av,PAO}$	Average PAO P content f_{XBGP}
25/11/2000	391		2.600	603.0	171.0	0.066	0.050	10.997	9.070	0.382	0.152	
27/11/2000	393		12.100	627.0	268.0	0.096	0.050	17.242	16.911	0.298	0.284	0.247
29/11/2000	395	12.5	-0.100	683.0	244.0	0.114	0.050	13.308	9.501	0.362	0.164	0.137
01/12/2000	397	11.3	12.600	563.0	163.0	0.156						
06/12/2000	402	12.9	5.700	657.0	256.0	0.125	0.050	14.319	8.493	0.355	0.174	0.285
08/12/2000	404	12.3	-1.100	546.0	137.0	0.145	0.050	7.271	4.063	0.410	0.082	0.372
12/12/2000	408	12.5	-0.100	621.0	269.0	0.076	0.050	16.749	12.538	0.326	0.238	0.106
14/12/2000	410	12.5	3.600	621.0	190.0	0.076	0.050	11.304	8.622	0.380	0.148	0.274
08/01/2001	435	13.4	1.100	774.0	312.0	0.090	0.050	10.730	17.884	0.353	0.181	0.127
10/01/2001	437		1.500	673.0	252.0	0.074	0.050	13.036	15.722	0.325	0.245	
12/01/2001	439	9.8	11.800	610.0	425.0	0.123	0.050	28.922	26.709	0.183	0.471	0.127
16/01/2001	443	13.3	13.500	706.0	421.0	0.096	0.050	29.048	24.569	0.233	0.392	0.167
18/01/2001	445	5.5	10.500	677.0	436.0	0.093	0.050	29.783	25.387	0.218	0.417	0.080
20/01/2001	447	11.8	10.600	574.0	310.0	0.099	0.050	20.284	18.775	0.255	0.355	0.195
22/01/2001	449	12.5	12.000	719.0	392.0	0.086	0.050	25.718	26.294	0.244	0.373	0.152
24/01/2001	451	11.3	10.900	-	-							
26/01/2001	453	12.1	12.000	-	-							
30/01/2001	457	11.9	11.700	692.0	405.0	0.067	0.050	27.075	27.236	0.232	0.398	0.136
01/02/2001	459	11.4	11.400	646.0	292.0	0.081	0.050	16.247	16.113	0.318	0.255	0.242
03/02/2001	461	11.5	11.500	629.0	341.0	0.083	0.050	20.215	20.830	0.269	0.336	0.187
05/02/2001	463	9.1	11.800	763.0	419.5	0.071	0.050	28.498	26.778	0.231	0.367	0.112
07/02/2001	465	11.1	11.000	655.0	221.0	0.064	0.050	13.304	12.649	0.359	0.191	0.305
09/02/2001	467	8.5	11.500	711.0	169.5	0.065	0.050	8.198	9.765	0.415	0.100	0.454
13/02/2001	471	6.3	12.000	660.0	218.5	0.083	0.050	13.583	13.205	0.341	0.201	0.222
15/02/2001	473	2.4	5.300	607.0	209.5	0.101	0.050	13.938	10.971	0.361	0.181	0.024
17/02/2001	475	8.2	0.800	615.0	231.5	0.094	0.050	15.156	13.624	0.327	0.239	0.053
19/02/2001	477			-	-							
21/02/2001	479	11.3	9.600	560.0	204.0	0.070	0.050	11.322	11.699	0.353	0.201	0.334
23/02/2001	481	10.3	5.800	603.0	146.0	0.058	0.050	8.783	7.842	0.407	0.114	0.471
27/02/2001	485		-0.500	598.0	168.5	0.114	0.050	3.811	9.735	0.389	0.135	
01/03/2001	487	6.6	6.600	657.0	173.5	0.101	0.050	7.898	10.271	0.398	0.122	0.217
03/03/2001	489	6.9	2.800	715.0	207.5	0.094	0.050	11.906	11.489	0.379	0.164	0.061
05/03/2001	491	9.1	7.200	599.0	236.5	0.084	0.050	12.070	12.979	0.346	0.208	0.207
07/03/2001	493	8.5	9.000	663.0	207.0	0.092	0.050	12.333	12.888	0.359	0.187	0.224
09/03/2001	495	9.7	12.600	644.0	136.5	0.121	0.050	7.875	8.734	0.400	0.114	0.590
13/03/2001	499	2.8	6.500	667.0	165.5	0.120	0.050	6.031	10.407	0.406	0.105	0.103
15/03/2001	501	8.2	11.400	577.0	163.0	0.092	0.050	7.712	9.420	0.390	0.134	0.463
17/03/2001	503	5.5	9.900	643.0	206.0	0.101	0.050	10.894	13.037	0.359	0.184	0.197
19/03/2001	505	6.3	7.700	577.0	131.5	0.117						
23/03/2001	509	3.6	7.100	500.0	120.0	0.142	0.050	5.069	6.886	0.403	0.102	0.313
27/03/2001	513	1.4	10.100	615.0	170.5	0.104	0.050	7.772	10.656	0.387	0.138	0.167
29/03/2001	515	3.7	4.300	612.0	131.5	0.163	0.050	4.280	6.262	0.430	0.057	
03/04/2001	520	5.6	10.100	638.0	169.5	0.123	0.050	7.020	9.796	0.397	0.117	0.340
05/04/2001	522	12.4	10.200	610.0	143.5	0.109	0.050	8.636	6.583	0.406	0.105	0.657
09/04/2001	526	5.1	5.300	724.0	204.5	0.099	0.050	9.198	9.530	0.401	0.111	0.121
17/04/2001	534	-33	11.800	701.0	154.0	0.120	0.050	10.189	10.061	0.387	0.134	0.480
19/04/2001	536	10.3	10.200	553.0	138.5	0.122	0.050	6.820	8.226	0.393	0.123	0.595
21/04/2001	538	11.5	11.500	617.0	166.5	0.115	0.050	8.288	9.501	0.388	0.134	0.548
23/04/2001	540	10.8	10.400	614.0	119.0	0.096	0.050	7.859	7.704	0.407	0.106	0.609
25/04/2001	542	-21.2	9.900	545.0	193.0	0.136	0.050	11.835	11.587	0.329	0.228	0.310
02/05/2001	549	13.6	13.700	683.0	173.5	0.118	0.050	11.220	11.217	0.372	0.160	0.496
04/05/2001	551	12.2	12.000	583.0	150.0	0.117	0.050	6.730	9.205	0.396	0.123	0.686
08/05/2001	555	11.4	11.200	577.0	166.0	0.113	0.050	8.311	9.575	0.381	0.147	0.526
10/05/2001	557	11.8	11.700	558.0	156.0	0.108	0.050	9.465	8.623	0.376	0.155	0.543
12/05/2001	559	9.3	14.000	610.0	157.0	0.133	0.050	6.910	9.684	0.392	0.125	0.616
14/05/2001	561	9.5	11.900	618.0	169.0	0.123	0.050	10.688	10.559	0.365	0.171	0.384
16/05/2001	563	12.4	11.600	647.0	174.0	0.118	0.050	9.246	10.894	0.380	0.148	0.486
18/05/2001	565	13	12.900	598.0	164.0	0.127	0.050	7.619	8.634	0.393	0.124	0.731
22/05/2001	569	10.7	10.900	628.0	174.5	0.108	0.050	8.191	9.883	0.391	0.131	0.493
24/05/2001	571	11.9	12.700	632.0	165.0	0.133	0.050	8.843	9.592	0.384	0.139	0.569
28/05/2001	575	5.2	12.000	657.0	159.5	0.120	0.050	8.139	9.091	0.399	0.116	0.379
30/05/2001	577	9.5	10.000	571.0	153.0	0.133	0.050	6.360	7.414	0.405	0.104	0.646
01/06/2001	579	6.6	9.500	514.0	131.0	0.144	0.050	5.117	5.380	0.418	0.079	0.769
07/06/2001	585	10.2	9.700	606.0	143.5	0.130	0.050	6.535	7.523	0.410	0.096	0.655
09/06/2001	587	8.6	9.300	693.0	183.5	0.119	0.050	12.019	11.388	0.368	0.160	0.255
11/06/2001	589	10.1		710.0	185.0	0.120	0.050	9.860	10.832	0.384	0.137	0.366
Average								12.149	12.021	0.359	0.185	0.396



Figures F.1 & F.2 and F3 & F.4 : "Site" bi-daily calculated vs measured P removal for $f_{s,up}$ =0.239 and $f_{s,up}$ =0.050 for Modules A & B respectively.

APPENDIX G

DAILY "UCT" CALCULATED vs MEASURED P REMOVAL

Table G1 : "UCT" daily calculated versus measured P removal - determination of $f_{S,up}$, $f_{av,OHO}$, $f_{av,PAO}$ and $f_{XBG,P}$.

Date	Day No.	Influent Total P P_{ti} (mgP/l)	Lab Unit effluent TP P_{te} (mgP/l)	Lab Unit P removal $\Delta P_{measured}$ (mgP/l)	Influent COD S_{ti} (mgCOD/l)	*Influent RBCOD S_{bsi} (mgCOD/l)	Influent unbio. sol. f_{us}	Influent unbio. part. f_{up}	Lab Unit influent flow Q_i (l/d)	Lab Unit VSS X_v (mgVSS/l)	Lab Unit r-recycle rate r	Lab Unit sludge age R_s (d)	Lab Unit NO_3 in r-recycle NO_{3r} (mgN/l)	UCT Lab RBCOD for conversion S'_{bsi} (mgCOD/l)	Lab Unit OHO active mass/l_{inf} MX_{BH}/Q_i (mgVASS/l/d)	RBCOD at end of anaerobic S_{bse} (mgCOD/l)	SCFA Lab Unit sequestered MS_{seq} (mgCOD/d)	Lab Unit OHO substrate mass $MS_{b,H}$ (mgCOD/d)	Lab Unit PAO bio. active mass $MX_{B,G}$ (mgVASS)	Lab Unit PAO endogen. mass $MX_{E,G}$ (mgVESS)	Lab Unit OHO bio. active mass $MX_{B,H}$ (mgVASS)	Lab Unit OHO endogen. mass $MX_{E,H}$ (mgVESS)	Lab Unit inert mass MX_I (mgVISS)	Lab Unit volatile solids MX_v (mgVSS)	Lab Unit PAO P removal/l_{inf} ΔP_G (mgP/l_{inf})	Lab Unit OHO P removal/l_{inf} ΔP_H (mgP/l_{inf})	Lab Unit inert P removal/l_{inf} ΔP_I (mgP/l_{inf})	Lab Unit total P removal/l_{inf} $\Delta P_{predicted}$ (mgP/l_{inf})	Lab Unit total P removal/l_{inf} $\Delta P_{predicted}$ for $f_{XBG,P}$ (mgP/l_{inf})	Lab Unit active OHO/VSS $f_{av,OHO}$	Lab Unit active PAO/VSS $f_{av,PAO}$	Lab Unit PAO P content $f_{XBG,P}$
12/02/2001	470	14.1	5.6	8.47	598.4	203.9	0.0336	-0.031	24.0	1966	1.00	15.00	0.35	200.920	165.598	54.921	2185.9	12136.8	9221.7	1383.3	17809.4	12822.8	-4473.0	36764.2	9.849	2.553	-0.373	12.029	8.470	0.484	0.251	0.241
13/02/2001	471																															
14/02/2001	472	15.7	4.6	11.12	546.0	203.9	0.0332	-0.061	24.0	1656	1.00	15.00	0.75	197.480	167.189	53.743	2159.9	11308.1	9111.9	1366.8	16593.4	11947.2	-8052.1	30967.2	9.732	2.378	-0.671	11.439	11.120	0.536	0.294	0.367
15/02/2001	473																															
16/02/2001	474																															
17/02/2001	475																															
18/02/2001	476																															
19/02/2001	477	13.4	0.3	13.09	389.6	208.9	0.1134	0.128	24.0	1872	1.00	15.00	0.90	196.190	167.791	53.303	2150.0	4938.0	9070.4	1360.6	7245.9	5217.1	12112.5	35006.4	9.688	1.039	1.009	11.736	13.090	0.207	0.259	0.434
20/02/2001	478																															
21/02/2001	479																															
22/02/2001	480	14.4	3.3	11.13	459.8	203.9	0.1004	0.042	24.0	1796	1.00	15.00	0.95	195.760	167.993	53.157	2146.7	7313.8	9056.4	1358.5	10732.2	7727.2	4710.8	33585.2	9.673	1.538	0.393	11.604	11.130	0.320	0.270	0.361
23/02/2001	481	17.3	6.2	11.12	564.3	203.9	0.0605	-0.019	24.0	1878	1.00	15.00	1.25	193.180	169.209	52.282	2126.8	10852.7	8972.5	1345.9	15925.2	11466.1	-2591.1	35118.6	9.583	2.283	-0.216	11.650	11.120	0.453	0.255	0.359
24/02/2001	482	17.3	3.6	13.74	554.2	203.9	0.1522	-0.003	24.0	1760	1.00	15.00	2.25	184.580	173.358	49.395	2059.0	9263.2	8686.3	1302.9	13592.7	9786.8	-456.7	32912.0	9.277	1.948	-0.038	11.188	13.740	0.413	0.264	0.486
25/02/2001	483	17.0	3.3	13.74	600.4	203.9	0.1271	0.015	24.0	2046	1.00	15.00	1.50	191.030	170.233	51.555	3110.1	10256.2	8901.9	1335.3	15049.8	10835.9	2137.4	38260.2	9.508	2.157	0.178	11.843	13.740	0.393	0.233	0.457
26/02/2001	484	15.7	3.6	12.11	506.0	203.9	0.0859	0.043	24.0	1974	1.00	15.00	1.20	193.610	169.006	52.427	2130.1	8450.5	8986.5	1348.0	12400.2	8928.2	5250.9	36913.8	9.598	1.777	0.438	11.813	12.110	0.336	0.243	0.392
27/02/2001	485	15.7	7.9	7.86	566.3	203.9	0.0532	-0.031	24.0	1828	1.00	15.00	1.40	191.890	169.823	51.845	2116.8	11176.3	8930.2	1339.5	16400.0	11808.0	-4294.2	34183.6	9.538	2.351	-0.358	11.531	7.860	0.480	0.261	0.232
28/02/2001	486	12.8	3.8	8.94	538.1	203.9	0.0746	-0.025	24.0	1758	1.00	15.00	0.12	202.898	164.694	55.602	2200.7	10069.9	9284.1	1392.6	14776.4	10639.0	-3217.5	32874.6	9.916	2.118	-0.268	11.766	8.940	0.449	0.282	0.270
01/03/2001	487	12.8	2.6	10.22	556.2	203.9	0.0830	-0.010	24.0	1870	1.00	15.00	8.35	200.920	165.598	54.921	2185.9	10189.2	9221.7	1383.3	14951.5	10765.1	-1352.5	34969.0	9.849	2.143	-0.113	11.880	10.220	0.428	0.264	0.315
02/03/2001	488	14.1	5.8	8.31	552.2	203.9	0.1018	0.006	24.0	1912	1.00	15.00	0.26	201.694	165.243	55.187	2191.7	9631.2	9246.2	1386.9	14132.8	10175.6	812.9	35754.4	9.875	2.026	0.068	11.969	8.310	0.395	0.259	0.238
03/03/2001	489																															
04/03/2001	490	14.7	3.2	11.5	544.2	203.9	0.0664	-0.007	24.0	1882	1.00	15.00	0.24	201.866	165.165	53.246	2193.0	10090.3	9251.6	1387.7	14806.4	10660.6	-912.9	35193.4	9.881	2.122	-0.076	11.927	11.500	0.421	0.263	0.363
05/03/2001	491	14.1	3.8	10.22	626.2	203.9	0.0822	-0.029	24.0	1958	1.00	15.00	0.27	201.608	165.283	55.158	2191.0	12039.1	9243.4	1386.5	17666.0	12719.5	-4400.9	36614.6	9.873	2.532	-0.367	12.038	10.220	0.482	0.252	0.309
06/03/2001	492	13.7	6.4	7.35	535.6	203.9	0.0538	0.033	24.0	2088	1.00	15.00	0.26	201.694	166.243	55.187	2191.7	9541.1	9246.2	1386.9	14000.5	10080.4	4331.6	39045.6	9.875	2.007	0.361	12.243	7.350	0.359	0.237	0.189
07/03/2001	493	14.7	6.7	7.99	572.7	203.9	0.0719	-0.014	24.0	1918	1.00	15.00	0.24	201.866	165.165	55.246	2193.0	10751.9	9251.6	1387.7	15777.2	11359.6	-1909.5	35866.6	9.881	2.261	-0.159	11.983	7.990	0.440	0.258	0.225
08/03/2001	494	15.3	7.0	8.31	541.8	203.9	0.0380	0.018	24.0	2058	1.00	15.00	0.24	201.866	165.165	55.246	2193.0	10076.0	9251.6	1387.7	14785.4	10645.5	2414.4	38484.6	9.881	2.119	0.201	12.202	8.310	0.384	0.240	0.229
09/03/2001	495																															
10/03/2001	496	12.1	5.6	6.49	502.6	203.9	0.0820	0.053	24.0	2026	1.00	15.00	0.46	199.974	166.033	54.596	2178.8	8252.7	9191.7	1378.7	12109.9	8719.1	6486.8	37886.2	9.817	1.736	0.541	12.094	6.490	0.320	0.243	0.161
11/03/2001	497	12.6	8.0	4.55	498.5	203.9	0.1157	0.069	24.0	2030	1.00	15.00	0.36	199.114	166.430	54.302	2172.3	7587.8	9164.3	1374.6	11134.3	8016.7	8271.0	37961.0	9.788	1.596	0.689	12.073	4.550	0.293	0.241	0.084
12/03/2001	498	12.6	8.7	3.9	467.6	134.7	0.0573	0.103	24.0	2045	1.00	15.00	0.33	131.891	123.667	40.719	1210.9	8216.2	5108.3	766.2	12056.4	8680.6	11629.9	38241.5	5.456	1.728	0.969	8.153	3.900	0.315	0.134	0.080
13/03/2001	499	13.2	8.4	4.76	587.1	134.7	0.1087	0.037	24.0	2060	1.00	15.00	0.07	134.127	122.756	41.527	1225.8	10807.1	5171.1	775.7	15858.3	11418.0	5299.0	38522.0	5.523	2.273	0.442	8.238	4.760	0.412	0.134	0.138
14/03/2001	500																															
15/03/2001	501																															
16/03/2001	502	13.6	8.7	4.98	422.3	134.7	0.1024	0.116	24.0	1852	1.00	15.00	0.43	131.031	124.020	40.409	1205.1	6719.3	5084.0	762.6	9859.8	7099.1	11827.0	34632.4	5.430	1.413	0.986	7.829	4.980	0.285	0.147	0.178
17/03/2001	503	13.4	9.7	3.67	414.1	134.7	0.0647	0.150	24.0	2004	1.00	15.00	0.65	129.139	124.801	39.730	1192.3	6616.0	5030.0	754.5	9708.3	6990.0	14992.0	37474.8	5.372	1.392	1.249	8.013	3.670	0.259	0.134	0.069
18/03/2001	504																															
19/03/2001	505	13.6	10.8	2.81	416.1	134.7	0.0594	0.138	24.0	1976	1.00	15.00	0.50	130.429	124.267	40.193	1201.0	6811.1	5066.9	760.0	9994.5	7196.1	13933.7	36951.2	5.412	1.433	1.161	8.005	2.810	0.270	0.137	0.011
20/03/2001	506	15.2	11.9	3.25	518.1	134.7	0.0781	0.029	24.0	1844	1.00	15.00	0.31	132.063	123.596	40.781	1212.0	9891.1	5113.2	767.0	14514.1	10450.2	3638.4	34482.8	5.461	2.080	0.303	7.845	3.250	0.421	0.148	0.057
21/03/2001	507																															
22/03/2001	508	14.8	8.4	6.38	469.6	134.7	0.0776	0.086	24.0	1946	1.00	15.00	0.55	129.999	124.445	40.038	1198.1	8223.4	5054.6	758.2	12066.9	8688.2	9822.3	36390.2	5.399	1.730	0.819	7.947	6.380	0.332	0.139	0.268
23/03/2001	509	13.3	5.8	7.53	558.6	134.7	0.0688	0.062	24.0	2172	1.00	15.00	0.42	131.117	123.984	40.440	1205.7	10444.8	5086.4	763.0	15326.7	11035.2	8405.2	40616.4	5.433	2.197	0.700	8.330	7.530	0.377	0.125	0.323
24/03/2001	510	13.3	5.8	7.53	534.3	134.7	0.0909	0.063	24.0	2052	1.00	15.00	0.40	131.289	123.913	40.502	1206.8	9639.6	5091.3	763.7	14145.1	10184.5	8187.9	38372.4	5.438	2.027	0.682	8.148	7.530	0.369	0.133	0.336
25/03/2001	511	14.2	7.5	6.66	744.8	134.7	0.0435	-0.039	24.0	2178	1.00	15.00	0.45	130.859	124.090	40.348	1203.9	16586.4	5079.1	761.9	24338.8	17523.9	-6975.0	40728.6	5.425	3.489	-0.581	8.332	6.660	0.598	0.125	0.261
26/03/2001	512	14.8	7.8	6.95	676.0	134.7	0.0599	-0.008	24.0	2154	1.00	15.00	0.45	130.859	124.090	40.348	1203.9	14183.2	5079.1	761.9	20812.3	14984.9	-1358.4	40279.8	5.425	2.983	-0.113	8.295	6.950	0.517	0.126	0.285
27/03/2001	513	13.1	8.4	6.65	740.8	134.7	0.0738	0.010	24.0	2448	1.00	15.00	0.30	132.149	123.561	40.812	1212.6	15070.3	5115.6	767.3	22114.0	15922.1	1858.6	45777.6	5.464	3.170	0.155	8.788	6.650	0.483	0.112	0.230
28/03/2001	514	15.1	9.3	5.8	643.6	134.7	0.0629	0.075	24.0	2576	1.00	15.00	0.30	132.149	123.561	40.812	1212.6	12097.5	5115.6	767.3	17751.8	12781.3	11755.1	48171.2	5.464	2.544	0.980	8.988	5.800	0.369	0.106	0.156
29/03/2001	515																															
30/03/2001	516																															
31/03/2001	517																															
01/04/2001	518	15.0	9.4	5.62	688.2	134.7	0.8647	-0.091	24.0	2214	1.00	15.00	2.05	117.099	129.945	35.463	1108.2	14360.7	4675.1	701.3	21072.8	15172.4	-219.8	41401.8	4.993	3.020	-0.018	7.995	5.620	0.509	0.113	0.197
02/04/2001	519																															
03/04/2001	520																															
04/04/2001	521	13.4	7.2	6.25	464.9	134.7	0.1078	0.148	24.0	2150	1.00	15.00	1.80	119.249	129.005	36.217	1123.5	7184.4	4740.0	711.0	10542.4	7590.5	16621.1	40205.0	5.063	1.511	1.385	7.959	6.250	0.262	0.118	0.250
05/04/2001	522																															
06/04/2001	523																															
07/04/2001	524																															
08/04/2001	525																															
09/04/2001	526																															
10/04/2001	527																															
11/04/2001	528	14.4	7.8	6.56	442.9	134.7	0.0860	0.130	24.0	1964	1.00	15.00	7.05	74.099	150.890	21.099	765.6	7571.1	3229.9	484.5	11109.8	7999.0	13903.6	36726.8	3.450	1.592	1.159	6.201	6.560	0.302	0.088	0.420
12/04/2001	529	14.1	9.1	5	489.0	134.7	0.0984	0.108	24.0	2036	1.00	15.00	7.20	72.809	151.584	20.691	754.2	8555.8	3182.0	477.3	12554.8	9039.4	12819.7	38073.2	3.399	1.800	1.068	6.266	3.000	0.330	0.084	0.237
13/04/2001	530	13.8	10.3	3.43	466.1	134.7	0.1032	0.114	24.0	1944	1.00	15.00	9.35	54.319	161.992	14.992	584.0	8168.1	2463.9	369.6	11985.9	8629.8	12903.7	36352.8	2.632	1.718	1.075	5.425	3.430	0.330	0.068	0.089
14/04/2001	531																															
15/04/2001	532	13.8	10.0	2.81	416.8	134.7	0.0577	0.181	24.0	2098	1.00	15.00	7.20	72.809	151.584	20.691	754.2	6862.8	3182.0	477.3	10070.5	7250.7	18252.1	39232.6	3.399	1.443	1.521	6.363	2.810	0.257	0.081	-0.022
16/04/2001	533																															
17/04/2001	534	13.8	10.0	3.75	432.9	134.7	0.0509	0.121	24.0	1922	1.00	15.00	8.45	62.059	157.531	17.342	657.0	7942.8	2771.6	415.7	11655.3	8391.8	12706.9	35941.4	2.960	1.671	1.059	5.690	3.750	0.324	0.077	0.128
18/04/2001	535	13.8	11.3	2.5	392.8	134.7	0.1531	0.219	24.0	1994	1.00	15.00	8.45	62.059	157.531	17.342	657.0	5262.9	2771.6	415.7	7722.7	5560.4	20817.3	37287.8	2.960	1.107	1.735	5.802	2.500	0.207	0.074	-0.049
19/04/2001	536	15.0	9.4	5.63	515.0	134.7	0.0739	0.046	24.0	1914	1.00	15.00	1.65	130.539	128.445	36.672	1132.7	9750.2	4778.6	716.8	14307.3	10301.3	5687.8	35791.8	5.104	2.051	0.474	7.629	3.630	0.400	0.134	0.229
20/04/2001	537	13.2	7.9	5.29	511.0	134.7	0.1137	0.089	24.0	2056	1.00	15.00	0.60	129.569	124.623	39.884	1195.2	8585.9	5042.3	756.3	12598.9	9071.2	10978.4	38447.2	5.385	1.806	0.915	8.106	5.290	0.328	0.131	0.179
21/04/2001	538																															
22/04/2001	539	12.9	6.0	6.94	503.0	134.7	0.0478	0.067	24.0	2026	1.00	15.00	0.85	127.419	125.518	39.114	1180.6	9504.1	4980.6	747.1	13946.2	10041.3	8171.0	37886.2	5.320	1.999	0.681	7.999	6.940	0.368	0.131	0.303
23/04/2001	540	12.8	6.0	6.94	493.0	134.7	0.0732	0.160	24.0	2392	1.00	15.00	1.20	124.409	126.787	38.041	1159.8	7907.9	4893.0	734.0	11604.0	8354.9	19144.6	44730.4	5.226	1.663	1.595	8.485	6.940	0.299	0.109	0.366
24/04/2001	541	13.2	6.3	6.94	543.4	134.7	0.1078	0.090	24.0	2194	1.00	15.00	0.85	127.419	125.518	39.114	1180.6	9275.9	4980.6	747.1	13611.4	9800.2	11888.5	41027.8	5.320	1.951	0.991	8.261	6.940	0.332	0.121	0.285
25/04/2001	542																															
26/04/2001	543	13.2	7.6	5.62	559.5	134.7	0.1047	0.077	24.0	2186	1.00	15.00	0.95	126.559	125.879	38.807	1174.7	9817.1	4955.7	743.4	14405.5	10371.9	10401.7	40878.2	5.293	2.065	0.867	8.225	3.620	0.352	0.121	0.191
27/04/2001	544	13.2	8.3	4.96	531.3	134.7	0.1141	0.080	24.0	2084	1.00	15.00	0.65	129.139	124.801	39.730	1192.3	9087.2	5030.0	754.5	13334.5	9600.8	10251.0	38970.8	5.372	1.911	0.854	8.138	4.960	0.342	0.129	0.153
28/04/2001	545	12.6	6.3	6.27	535.3	134.7	0.1283	0.097	24.0	2160	1.00	15.00	1.20	124.409	126.787	38.041	1159.8	8792.4	4893.0	734.0	12901.9	9289.4	12573.7	40392.0	5.226	1.849	1.048	8.123	6.270	0.319	0.131	0.244
29/04/2001	546																															
30/04/2001	547																															
01/05/2001	548	11.6	8.3	3.3	537.3	134.7	0.0789	0.012	24.0	1796	1.00	15.00	3.05	108.499	133.805	32.478	1045.0	10677.2	4408.8	661.3	15467.7	11280.7	1566.7	33585.2	4.709	2.246	0.131	7.085	3.300	0.467	0.131	0.071
02/05/2001	549	12.2	9.3	2.97	456.5	134.7	0.1284	0.087	24.0	1818	1.00	15.00	1.20	124.409	126.787	38.041	1159.8	7439.0	4893.0	734.0	10916.0	7839.5	9594.2	33996.6	5.226	1.565	0.800	7.590	2.970	0.321	0.144	0.040
03/05/2001	550	11.9	6.9	4.95	434.3	134.7	0.1442	0.097	24.0	1758	1.00	15.00	1.10	125.269	126.422	38.347	1165.8	8745.3	4918.2	737.7	9895.1	7124.5	10199.1	32874.6	5.253	1.418	0.850	7.521	4.950	0.301	0.150	0.192

Date	Day No.	Influent Total P P_{ti} (mgP/l)	Lab Unit effluent TP P_{te} (mgP/l)	Lab Unit P removal $\Delta P_{measured}$ (mgP/l)	Influent COD S_{ti} (mgCOD/l)	*Influent RBCOD S_{bsi} (mgCOD/l)	Influent unbio. sol. f_{us}	Influent unbio. part. f_{up}	Lab Unit influent flow Q_i (l/d)	Lab Unit VSS X_v (mgVSS/l)	Lab Unit r-recycle rate r	Lab Unit sludge age R_s (d)	Lab Unit NO_3 in r-recycle NO_{3r} (mgN/l)	UCT Lab rbcod for conversion S_{bsi} (mgCOD/l)	Lab Unit OHO active mass/l_{inf} MX_{BH}/Q_i (mgVASS/l/d)	RBCOD at end of anaerobic S_{bsa} (mgCOD/l)	SCFA Lab Unit sequestered MS_{seq} (mgCOD/d)	Lab Unit OHO substrate mass $MS_{bs,H}$ (mgCOD/d)	Lab Unit PAO bio. active mass $MX_{B,G}$ (mgVASS)	Lab Unit PAO endogen. mass $MX_{E,G}$ (mgVESS)	Lab Unit OHO bio. active mass $MX_{B,H}$ (mgVASS)	Lab Unit OHO endogen. mass $MX_{E,H}$ (mgVESS)	Lab Unit inert mass MX_I (mgVISS)	Lab Unit volatile solids MX_v (mgVSS)	Lab Unit PAO P removal/l_{inf} ΔP_G (mgP/l_{inf})	Lab Unit OHO P removal/l_{inf} ΔP_H (mgP/l_{inf})	Lab Unit inert P removal/l_{inf} ΔP_I (mgP/l_{inf})	Lab Unit total P removal/l_{inf} $\Delta P_{predicted}$ (mgP/l_{inf})	Lab Unit total P removal/l_{inf} $\Delta P_{predicted}$ for $f_{XBG,P}$ (mgP/l_{inf})	Lab Unit active OHO/VSS $f_{av,OHO}$	Lab Unit active PAO/VSS $f_{av,PAO}$	Lab Unit PAO P content $f_{XBG,P}$
04/05/2001	551	11.2	5.6	5.57	519.1	134.7	0.0973	0.046	24.0	1900	1.00	15.00	0.48	130.601	124.197	40.255	1202.2	9470.7	5071.7	760.8	13897.2	10006.0	5794.3	35530.0	5.417	1.992	0.483	7.892	5.570	0.391	0.143	0.215
05/05/2001	552																															
06/05/2001	553																															
07/05/2001	554	11.5	9.0	2.48	456.5	134.7	0.0796	0.153	24.0	2188	1.00	15.00	0.58	129.741	124.552	39.946	1196.4	7210.7	5047.2	757.1	10580.9	7618.2	16912.1	40915.6	5.391	1.517	1.409	8.317	2.480	0.259	0.123	-0.036
08/05/2001	555	11.5	9.3	2.17	575.7	134.7	0.0736	0.023	24.0	2006	1.00	15.00	0.47	130.687	124.161	40.286	1202.8	11277.9	5074.2	761.1	16549.1	11915.4	3212.5	37512.2	5.420	2.372	0.268	8.059	2.170	0.441	0.135	-0.038
09/05/2001	556	11.2	5.3	5.88	575.7	134.7	0.0771	0.019	24.0	1978	1.00	15.00	0.39	131.375	123.878	40.533	1207.4	11280.0	5093.7	764.1	16552.1	11917.5	2661.2	36988.6	5.440	2.372	0.222	8.035	5.880	0.447	0.138	0.228
10/05/2001	557	11.8	5.3	6.5	519.1	134.7	0.0817	0.052	24.0	1956	1.00	15.00	0.58	129.741	124.552	39.946	1196.4	9594.9	5047.2	757.1	14079.6	10137.2	6556.3	36577.2	5.391	2.018	0.546	7.955	6.500	0.385	0.138	0.276
11/05/2001	558	11.2	6.8	4.34	397.2	134.7	0.1218	0.203	24.0	2056	1.00	15.00	1.20	124.409	126.787	38.041	1159.8	5277.2	4893.0	734.0	7743.7	5575.5	19501.0	38447.2	5.226	1.110	1.625	7.961	4.340	0.201	0.127	0.114
12/05/2001	559	11.2	7.1	4.03	532.2	134.7	0.1212	0.025	24.0	1778	1.00	15.00	2.30	114.949	130.896	34.711	1092.6	9818.4	4609.5	691.4	14407.5	10373.4	3166.8	33248.6	4.923	2.065	0.264	7.252	4.030	0.433	0.139	0.128
13/05/2001	560																															
14/05/2001	561																															
15/05/2001	562																															
16/05/2001	563	11.5	4.0	7.43	678.2	134.7	0.0605	-0.096	24.0	1580	1.00	15.00	0.65	129.139	124.801	39.730	1192.3	15664.5	5030.0	754.5	22985.9	16549.8	-15774.3	29546.0	5.372	3.295	-1.315	7.352	7.430	0.778	0.170	0.386
17/05/2001	564	11.5	4.7	6.81	643.7	134.7	0.1107	-0.069	24.0	1568	1.00	15.00	0.81	127.763	125.374	39.237	1182.9	13626.4	4990.5	748.6	19995.2	14396.5	-10809.2	29321.6	5.330	2.866	-0.901	7.295	6.810	0.682	0.170	0.345
18/05/2001	565	11.5	5.0	6.5	557.3	134.7	0.0581	-0.047	24.0	1592	1.00	15.00	0.94	126.645	125.842	38.838	1175.3	12051.2	4958.2	743.7	17683.8	12732.4	-6347.7	29770.4	5.296	2.535	-0.529	7.301	6.500	0.594	0.167	0.322
19/05/2001	566																															
20/05/2001	567	14.0	7.9	6.08	598.3	134.7	0.0758	-0.042	24.0	1686	1.00	15.00	2.25	115.379	130.705	34.861	1095.7	12772.6	4622.7	693.4	18742.5	13494.6	-6824.9	31528.2	4.937	2.686	-0.502	7.122	6.080	0.594	0.147	0.299
21/05/2001	568	12.1	7.0	5.16	500.0	134.7	0.0847	0.037	24.0	1800	1.00	15.00	1.95	117.959	129.568	35.764	1114.3	9427.3	4701.1	705.2	13833.5	9960.2	4460.0	33660.0	5.021	1.983	0.372	7.376	5.160	0.411	0.140	0.210
22/05/2001	569	12.1	5.5	6.67	440.6	134.7	0.1111	0.071	24.0	1702	1.00	15.00	3.35	105.919	134.994	31.593	1025.6	7619.0	4326.8	649.0	11180.1	8049.7	7621.8	31827.4	4.621	1.602	0.635	6.859	6.670	0.351	0.136	0.364
23/05/2001	570	13.1	4.0	9.11	465.1	134.7	0.1053	0.064	24.0	1760	1.00	15.00	4.00	100.329	137.619	29.692	982.7	8288.9	4145.6	621.8	12163.1	8757.5	7224.0	32912.0	4.428	1.743	0.602	6.773	9.110	0.370	0.126	0.583
24/05/2001	571	13.1	9.1	3.95	436.6	134.7	0.0607	-0.131	24.0	876	1.00	15.00	6.40	79.689	147.926	22.885	814.1	10395.7	3434.4	515.2	15254.6	10983.3	-13806.2	16381.2	3.668	2.186	-1.151	4.704	3.950	0.931	0.210	0.301
25/05/2001	572																															
26/05/2001	573																															
27/05/2001	574	12.5	10.3	2.13	552.8	134.7	0.0886	0.005	24.0	1734	1.00	15.00	8.90	58.189	159.743	16.161	620.8	11411.6	2619.1	392.9	16745.3	12056.6	611.9	32425.8	2.797	2.400	0.051	5.248	2.130	0.516	0.081	-0.049
28/05/2001	575	14.0	13.1	0.91	477.4	139.2	0.1282	0.064	24.0	1804	1.00	15.00	0.25	137.022	126.303	41.961	1274.4	7978.2	5376.2	806.4	11707.2	8429.2	7415.8	33734.8	5.742	1.678	0.618	8.038	0.910	0.347	0.159	-0.097
29/05/2001	576	13.4	5.5	7.89	379.4	139.2	0.1129	0.125	24.0	1652	1.00	15.00	7.15	77.682	154.486	21.895	813.4	6126.4	3431.6	514.7	8989.9	6472.7	11483.5	30892.4	3.665	1.289	0.957	5.911	7.890	0.291	0.111	0.588
30/05/2001	577																															
31/05/2001	578	13.1	9.4	3.65	477.4	139.2	0.0812	0.017	24.0	1618	1.00	15.00	5.40	92.732	146.599	26.732	942.4	9386.3	3975.8	596.4	13773.3	9916.8	1994.3	30256.6	4.246	1.974	0.166	6.387	3.650	0.455	0.131	0.132
01/06/2001	579																															
02/06/2001	580																															
03/06/2001	581																															
04/06/2001	582																															
05/06/2001	583	13.7	8.5	5.16	561.8	139.2	0.1364	-0.169	24.0	790	1.00	15.00	2.80	115.092	135.831	34.243	1118.5	12801.0	4718.8	707.8	18784.0	13524.5	-22962.1	14773.0	5.040	2.692	-1.914	5.818	5.160	1.272	0.319	0.330
06/06/2001	584	13.7	8.5	5.16	614.5	139.2	0.0528	-0.199	24.0	849	1.00	15.00	1.65	124.982	131.412	37.682	1190.8	15707.1	5023.7	753.6	23048.5	16594.9	-29544.4	15876.3	5.366	3.304	-2.462	6.207	5.160	1.452	0.316	0.305
07/06/2001	585	12.5	6.0	6.58	496.9	139.2	0.0612	-0.005	24.0	1644	1.00	15.00	0.65	133.582	127.733	40.729	1251.0	9999.5	5277.6	791.6	14673.2	10564.7	-564.4	30742.8	5.637	2.103	-0.047	7.693	6.580	0.477	0.172	0.304
08/06/2001	586	10.7	5.3	5.33	480.6	139.2	0.0591	0.043	24.0	1826	1.00	15.00	0.00	139.172	125.421	42.736	1288.8	9069.1	5437.1	815.6	13307.9	9581.7	5004.0	34146.2	5.807	1.907	0.417	8.132	5.330	0.390	0.159	0.195
09/06/2001	587																															
10/06/2001	588	11.6	5.6	5.96	478.6	139.2	0.0890	0.021	24.0	1662	1.00	15.00	2.65	116.382	135.243	34.688	1128.1	9091.0	4759.4	713.9	13349.1	9604.9	2474.2	30892.4	5.083	1.912	0.206	7.202	5.960	0.432	0.154	0.286
11/06/2001	589	15.4	9.4	5.96	517.1	139.2	0.0863	0.034	24.0	1840	1.00	15.00	3.10	112.512	137.017	33.357	1099.1	9814.6	4636.9	695.5	14401.9	10369.3	4304.4	34408.0	4.952	2.064	0.359	7.375	5.960	0.419	0.135	0.270
12/06/2001	590	15.1	10.4	4.7	444.7	139.2	0.0917	0.076	24.0	1776	1.00	15.00	3.00	113.372	136.620	33.652	1105.6	7772.5	4664.3	699.6	11405.3	8211.8	8230.2	33211.2	4.982	1.635	0.686	7.302	4.700	0.343	0.140	0.179
13/06/2001	591	12.9	10.4	2.51	430.4	139.2	0.1043	0.099	24.0	1792	1.00	15.00	3.75	106.922	139.638	31.455	1056.3	7179.4	4456.1	668.4	10534.9	7585.1	10263.8	33510.4	4.759	1.510	0.855	7.125	2.510	0.314	0.133	0.007
14/06/2001	592	15.5	7.7	7.73	395.8	139.2	0.0412	0.078	24.0	1668	1.00	15.00	2.80	115.092	135.831	34.243	1118.5	7247.0	4718.8	707.8	10634.2	7656.6	7474.2	31191.6	5.040	1.524	0.623	7.187	7.730	0.341	0.151	0.421
15/06/2001	593	9.7	4.5	5.15	438.6	139.2	0.0930	0.058	24.0	1674	1.00	15.00	3.10	112.512	137.017	33.357	1099.1	7833.3	4636.9	695.5	11494.5	8276.0	6200.8	31303.8	4.952	1.648	0.517	7.117	5.150	0.367	0.148	0.227
16/06/2001	594	10.6	5.2	5.48	418.2	139.2	0.0780	0.087	24.0	1730	1.00	15.00	4.30	102.192	141.908	29.864	1019.1	7358.4	4299.5	644.9	10797.6	7774.3	8834.7	32351.0	4.592	1.548	0.736	6.876	5.480	0.334	0.133	0.263
17/06/2001	595	11.6	8.7	2.9	424.3	139.2	0.0865	0.065	24.0	1644	1.00	15.00	4.95	96.602	144.655	28.005	974.2	7667.4	4109.9	616.5	11251.1	8100.8	6664.4	30742.8	4.390	1.613	0.555	6.558	2.900	0.366	0.134	0.060
18/06/2001	596	11.3	6.1	5.15	428.0	139.2	0.0374	0.023	24.0	1548	1.00	15.00	5.30	94.452	145.731	27.296	956.6	8698.1	4035.7	605.4	12763.5	9189.7	2353.4	28947.6	4.310	1.829	0.196	6.336	5.150	0.441	0.139	0.274
19/06/2001	597	11.3	6.1	5.15	444.0	139.2	0.0901	0.046	24.0	1610	1.00	15.00	6.85	80.262	153.096	22.711	836.1	8372.0	3527.5	529.1	12285.1	8845.3	4920.1	30107.0	3.768	1.761	0.410	5.938	5.150	0.408	0.117	0.300
20/06/2001	598	11.6	5.8	5.8	490.0	139.2	0.0898	-0.018	24.0	1472	1.00	15.00	6.15	86.282	149.914	24.637	888.2	10021.7	3747.0	562.1	14705.8	10588.1	-2076.6	27536.4	4.002	2.108	-0.173	5.937	5.800	0.534	0.136	0.367
21/06/2001	599	11.3	6.1	5.15	430.0	139.2	0.0930	0.095	24.0	1770	1.00	15.00	6.20	85.852	150.138	24.498	884.5	7494.8	3731.6	559.7	10997.8	7918.4	9891.6	33099.0	3.986	1.576	0.824	6.386	5.150	0.332	0.113	0.261
22/06/2001	600	11.6	9.0	2.58	338.0	139.2	0.1243	0.173	24.0	1582	1.00	15.00	11.50	40.272	176.488	10.687	453.6	5249.0	1913.5	287.0	7702.4	5545.7	14134.9	29583.4	2.044	1.104	1.178	4.326	2.580	0.260	0.065	0.052
23/06/2001	601	20.8	10.7	10.06	342.0	139.2	0.1404	0.196	24.0	1760	1.00	15.00	0.50	134.872	127.194	41.190	1259.8	4186.8	5314.8	797.2	6143.6	4423.4	16233.0	32912.0	5.676	0.881	1.353	7.910	10.060	0.187	0.161	0.526
24/06/2001	602																															
25/06/2001	603	13.1	10.1	3.02	516.0	139.2	0.0891	0.008	24.0	1720	1.00	15.00	0.72	132.980	127.985	40.514	1246.8	9928.4	5260.1	789.0	14568.9	10489.6	1056.4	32164.0	5.618	2.088	0.088	7.794	3.020	0.453	0.164	0.053
26/06/2001	604																															
27/06/2001	605	15.4	11.4	4.02	530.0	139.2	0.0830	-0.026	24.0	1570	1.00	15.00	3.80	106.492	139.842	31.310	1052.9	10945.7	4442.0	666.3	16061.7	11564.4	-3375.4	29359.0	4.744	2.302	-0.281	6.765	4.020	0.547	0.151	0.158
28/06/2001	606	17.8	14.4	3.35	592.0	139.2	0.0878	-0.027	24.0	1740	1.00	15.00	1.85	123.262	132.166	37.079	1178.5	12167.0	4971.7	745.8	17853.7	12854.7	-3887.9	32538.0	5.310	2.559	-0.324	7.545	3.350	0.549	0.153	0.076
29/06/2001	607	16.4	14.4	2.01	596.0	139.2	0.1007	-0.000	24.0	1884	1.00	15.00	1.45	126.702	130.664	38.288	1203.0	11665.9	5075.3	761.3	17118.4	12325.2	-49.4	35230.8	5.421	2.454	-0.004	7.870	2.010	0.486	0.144	-0.036
30/06/2001	608	16.1	12.8	3.35	644.0	139.2	0.0963	-0.069	24.0	1616	1.00	15.00	0.00	139.172	125.421	42.736	1288.8	13741.7	5437.1	815.6	20164.4	14518.4	-10716.3	30219.2	5.807	2.890	-0.893	7.804	3.350	0.667	0.180	0.085
01/07/2001	609	15.4	11.7	3.69	632.0	139.2	0.0737	-0.066	24.0	1642	1.00	15.00	1.50	126.272	130.850	38.136	1200.0	13847.7	5062.4	759.4	20320.0	14630.4	-10066.8	30705.4	5.407	2.913	-0.839	7.481	3.690	0.662	0.165	0.110
02/07/2001	610																															
03/07/2001	611	15.4	11.7	3.69	602.0	139.2	0.0764	-0.097	24.0	1384	1.00	15.00	1.25	128.422	129.922	38.895	1215.2	13534.1	5126.5	769.0	19859.8	14299.1	-14173.5	25880.8	5.475	2.847	-1.181	7.141	3.690	0.767	0.198	0.138
04/07/2001	612	16.8	8.7	8.06	600.0	139.2	0.1133	-0.089	24.0	1354	1.00	15.00	1.45	126.702	130.664	38.288	1203.0	12848.4	5075.3	761.3	18853.7	13574.6	-12945.1	25319.8	5.421	2.702	-1.079	7.044	8.060	0.745	0.200	0.452
05/07/2001	613	16.8	8.1	8.73	664.0	139.2	0.0783	-0.112	24.0	1412	1.00	15.00	1.10	129.712	129.370	39.352	1224.2	15251.2	5164.6	774.7	22379.4	16113.2	-18027.5	26404.4	5.516	3.208	-1.502	7.222	8.730	0.848	0.196	0.485
06/07/2001	614	12.8	8.2	4.58	548.0	139.2	0.0949	-0.082	24.0	1324	1.00	15.00	0.85	131.862	128.457	40.115	1239.1	11745.3	5227.6	784.1	17234.9	12409.1	-10897.0	24758.8	5.583	2.470	-0.908	7.146	4.580	0.696	0.211	0.203
07/07/2001	615	12.4	8.8	3.6	468.0	139.2	0.0812	0.003	24.0	1560	1.00	15.00	1.20	128.852	129.738	39.047	1218.2	9063.5	5139.2	770.9	13299.7	9575.8	386.4	29172.0	5.489	1.906	0.032	7.427	3.600	0.456	0.176	0.112
08/07/2001	616																															
09/07/2001	617	14.4	9.5	4.91	584.0	139.2	0.0959	-0.102	24.8	1284	1.00	15.00	1.05	130.142	129.186	39.504	1227.2	12876.8	5177.3	776.6	18895.2	13604.6	-14442.9	24010.8	5.530	2.708	-1.204	7.034	4.910	0.787	0.216	0.232
10/07/2001	618	15.1	7.5	7.53	536.0	139.2	0.1679	-0.015	24.0	1516	1.00	15.00	1.30	127.992	130.107	38.743	1212.1	9688.7	5113.7	767.1	14217.0	10236.3	-1984.9	28349.2	5.462	2.038	-0.165	7.334	7.530	0.501	0.180	0.394
11/07/2001	619	12.8	6.5	6.23	580.0	139.2	0.0966	-0.087	24.0	1360	1.00	15.00	1.40	127.132	130.478	38.439	1206.1	12875.4	5088.1	763.2	18453.0	13286.2	-12158.6	25432.0	5.434	2.645	-1.013	7.066	6.230	0.726	0.200	0.321
12/07/2001	620	15.1	9.8	5.24	552.0	139.2	0.0833	-0.035	24.0	1600	1.00	15.00	1.60	125.412	131.224	37.833	1193.9	11414.2	5036.6	755.5	16749.1	12059.3	-4680.6	29920.0	5.379	2.401	-0.390	7.390	5.240	0.560	0.168	0.226
13/07/2001	621																															
14/07/2001	622																															
15/07/2001	623																															
16/07/2001	624																															
17/07/2001	625	15.1	7.5	7.53	572.0	139.2	0.0664	-0.034	24.0	1682	1.00	15.00	2.60	116.812	135.048	34.836	1131.3	12151.0	4772.8	715.9	17830.3	12837.8	-4703.4	31453.4	5.098	2.556	-0.392	7.261	7.530	0.567	0.152	0.400
18/07/2001	626	15.1	8.5	6.55	626.0	139.2	0.0927	-0.059	24.0	1630	1.00	15.00	1.90	122.832	132.355	36.929	1175.4	13337.4	4958.6	743.8	19571.2	14091.3	-8883.9	30481.0	5.296	2.805	-0.740	7.361	6.550	0.642	0.163	0.321
19/07/2001	627	15.8	9.2	6.58	622.0	139.2	0.0579	-0.069	24.0	1620	1.00	15.00	2.85	114.662	136.028	34.095	1115.3	13979.9	4705.2	705.8	20514.0	14770.1	-10401.1	30294.0	5.025	2.940	-0.867	7.099	6.580	0.677	0.155	0.340
20/07/2001	628																															
21/07/2001	629	15.6	9.9	5.68	564.0	139.2	0.0887	0.015	24.0	1884	1.00	15.00	3.40	109.932	138.218	32.477	1079.5	11047.3	4554.1	683.1	16210.5	11671.6	2111.5	35230.8	4.864	2.324	0.176	7.363	5.680	0.460	0.129	0.247
22/07/2001	630																															
23/07/2001	631																															
24/07/2001	632	15.8	8.2	7.57	570.0	139.2	0.0702	0.042	24.0	2080	1.00	15.00	3.65	187.782	139.230	31.746	1062.9	11086.1	4484.2	672.6	16267.7	11712.7	5758.7	38896.0	4.789	2.332	0.480	7.601	7.570	0.418	0.115	0.378
Average		13.2	7.4	5.83	503.7	143.3	0.0859	0.029	24.0	1750.1			2.1															7.953	5.933	0.405	0.157	0.223

APPENDIX H

MONTHLY FILAMENT IDENTIFICATIONS

Table H1 : Filament identifications for Modules A & B and lab-scale system.

Sample Date	Filamentous Organisms	Rank			Abundance		
		Large-Scale Pilot Plant		Lab-Scale	Large-Scale Pilot Plant		Lab-Scale
		Module A	Module B	UCT System	Module A	Module B	UCT System
02/11/1999	*M. parvicella*	2	2	N/A	1	1	N/A
	type 1851	1	1	N/A	2	2	N/A
22/11/1999	type 1851	1	1	N/A	2	2	N/A
	N. limicola	2	2	N/A	1	1	N/A
20/12/1999	*M. parvicella*	-	2	N/A	-	1	N/A
	type 1851	1	1	N/A	2	2	N/A
19/01/2000	*M. parvicella*	2	2	N/A	2	2	N/A
	type 1851	1	1	N/A	3	1	N/A
	Nocardia sp.	-	3	N/A	-	3	N/A
23/03/2000	*M. parvicella*	1	1	N/A	2	2	N/A
	type 0092	2	2	N/A	1	1	N/A
20/07/2000	*M. parvicella*	2	2	N/A	2	1	N/A
	type 1851	3	3	N/A	1	1	N/A
	type 0092	1	1	N/A	3	3	N/A
31/08/2000	*M. parvicella*	2	2	1	2	2	4
	type 1851	-	3	2	-	1	2
	type 0092	1	1	-	3	3	-
28/09/2000	*M. parvicella*	2	2	1	2	3	3
	type 1851	3	1	-	2	3	-
	type 0092	1	3	-	3	2	-
20/10/2000	*M. parvicella*	1	2	1	3	2	3
	type 1851	3	3	-	2	1	-
	type 0092	2	1	-	2	3	-
	H. hydrossis	-	-	2	-	-	2
23/11/2000	*M. parvicella*	1	1	1	4	3	3
	type 0092	2	2	-	2	2	-
14/12/2000	*M. parvicella*	2	1	1	2	3	4
	type 0092	1	2	-	3	2	-
23/01/2001	*M. parvicella*	1	1	N/A	3	3	N/A
	type 1851	4	3	N/A	1	2	N/A
	type 0092	2	-	N/A	2	-	N/A
	type 1701	3	2	N/A	1	2	N/A
01/03/2001	*M. parvicella*	2	2	1	2	2	3
	type 0092	1	1	2	3	3	2
21/03/2001	*M. parvicella*	1	1	1	3	3	3
	type 0092	2	1	2	3	3	3
	type 1701	-	3	-	-	1	-
19/04/2001	*M. parvicella*	1	1	1	3	3	4
	type 1851	-	3	2	-	1	1
	type 0092	2	2	-	3	2	-
25/05/2001	*M. parvicella*	1	1	1	3	3	4
	type 0092	2	2	2	2	2	2
20/06/2001	*M. parvicella*	-	N/A	1	-	N/A	3
	type 1851	1	N/A	2	2	N/A	2
	type 0092	2	N/A	-	1	N/A	-
23/07/2001	*M. parvicella*	N/A	N/A	1	N/A	N/A	3
	type 0092	N/A	N/A	2	N/A	N/A	2

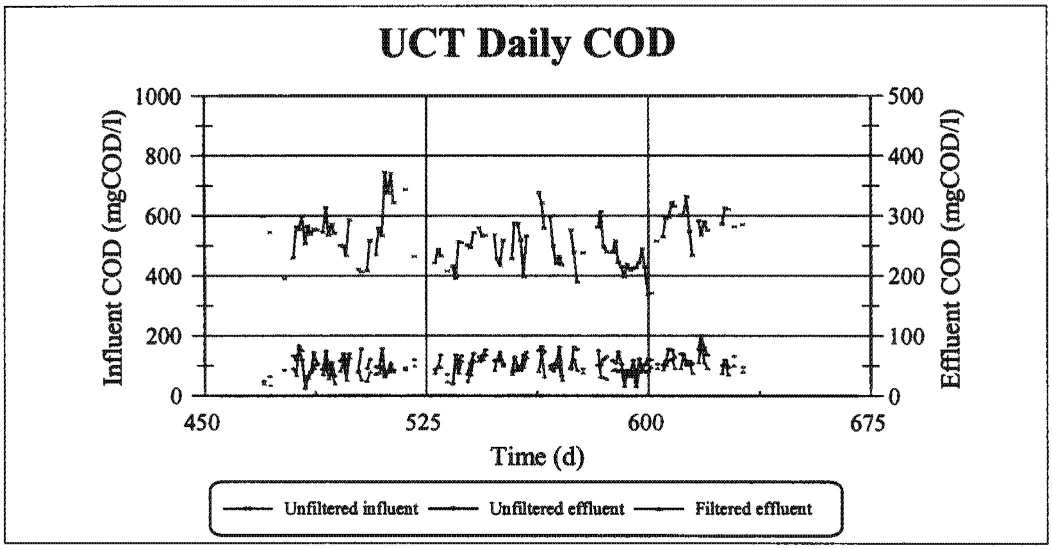
APPENDIX I

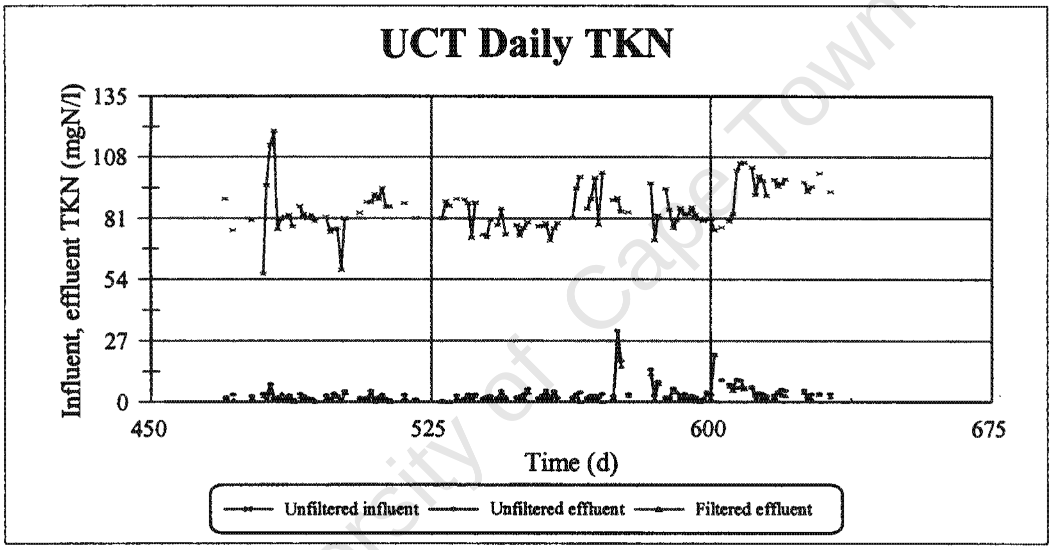
DAILY "UCT" RESULTS

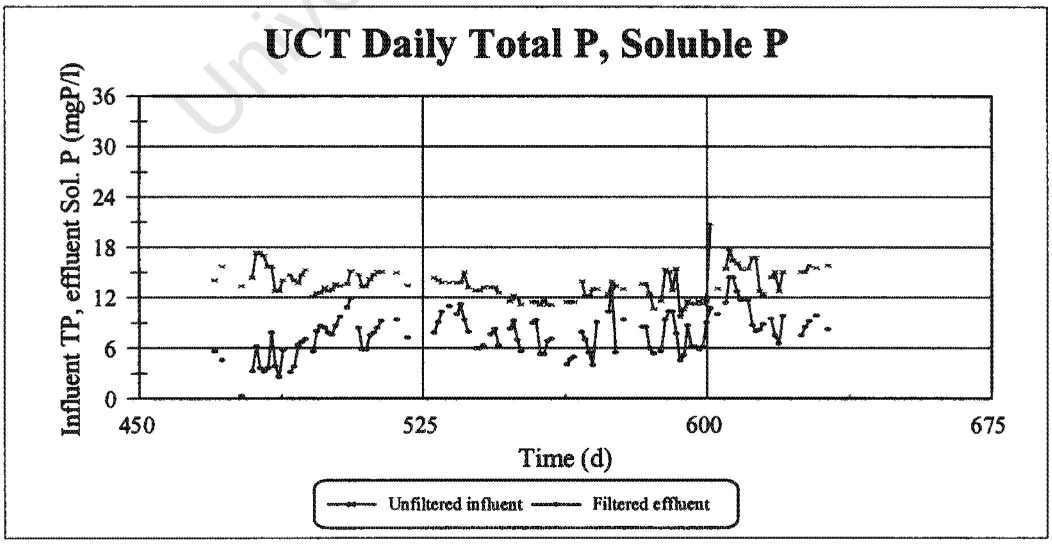
Table I1: Daily "UCT" data.

Date	Day No.	COD Influent (mgCOD/l)	COD Reactor (mgCOD/l)	COD Unf Effl (mgCOD/l)	COD Filt Effl (mgCOD/l)	TKN Influent (mgN/l)	TKN Reactor (mgN/l)	TKN Unf Effl (mgN/l)	TKN Filt Effl (mgN/l)	FSA Influent (mgN/l)	FSA Filt Effl (mgN/l)	$NO_3 + NO_2$ Anaerobic (mgN/l)	$NO_3 + NO_2$ Anoxic (mgN/l)	$NO_3 + NO_2$ Aerobic (mgN/l)	$NO_3 + NO_2$ Filt Effl (mgN/l)	Total P Influent (mgP/l)	Total P Anaerobic (mgP/l)	Total P Anoxic (mgP/l)	Total P Aerobic (mgP/l)	Total P Filt Effl (mgP/l)	DSVI Aerobic (ml/g)	OUR Aerobic (mgO/l.h)	MLSS Anoxic (mgTSS/l)	MLSS Aerobic (mgTSS/l)	MLVSS Anoxic (mgVSS/l)	MLVSS Aerobic (mgVSS/l)
12/02/2001	470	598.4	2670.6	24.1	20.1	89.5	179.9	2.1	2.0	69.4	0.0	0.15	0.35	32.80	33.20	14.1	17.6	16.4	5.2	5.6	142.31	26.78	1914	2108	1680	1966
13/02/2001	471																									
14/02/2001	472	546.0	2449.8	32.1	18.1	75.7	158.2	3.2	1.0	61.6	0.4	0.13	0.75	31.40	33.20	15.7	18.3	13.1	3.3	4.6	154.16	27.05	2064	1946	1772	1656
15/02/2001	473																									
16/02/2001	474																									
17/02/2001	475																									
18/02/2001	476																									
19/02/2001	477	389.6	2530.1	44.2	44.2	80.1	189.0	2.5	1.4	59.6	0.8	0.20	0.90	29.00	30.40	13.4	20.3	10.5	0.7	0.3	165.59	25.4	2292	2174	200	1872
20/02/2001	478																									
21/02/2001	479																									
22/02/2001	480	459.8	2469.8	66.3	46.2	56.3	175.7	3.5	2.5	54.9	1.5	0.09	0.95	30.80	33.20	14.4	24.2	22.3	2.3	3.3	175.12	20.63	2022	2170	1734	1796
23/02/2001	481	564.3	2650.6	60.2	34.1	95.5	191.1	3.5	0.7	80.9	0.0	0.09	1.25	38.00	36.00	17.3	27.5	22.6	7.9	6.2	166.67	20.94	2120	2280	1826	1878
24/02/2001	482	554.2	2630.5	78.3	84.3	113.3	200.1	7.8	5.2	59.4	1.7	0.06	2.25	40.00	40.00	17.3	26.5	22.6	7.9	3.6	179.58		2514	2116	2154	1760
25/02/2001	483	600.4	2951.8	60.2	76.3	119.7	193.2	1.8	1.5	68.3	1.8	0.09	1.50	40.00	40.00	17.0	27.8	18.3	3.9	3.3	162.34	44.8	2402	2464	2160	2046
26/02/2001	484	506.0	2369.4	12.1		76.0	179.9	2.0	1.4	65.5	1.1	0.04	1.20	33.60	40.00	15.7	28.5	19.6	3.9	3.6	154.10	34.57	2300	2466	1880	1974
27/02/2001	485	566.3	2590.3	32.1	30.1	80.6	179.2	1.1	3.8	68.0	2.2	0.04	1.40	31.00	33.60	15.7	32.4	25.5	14.4	7.9	166.67	34	2330	2280	1820	1828
28/02/2001	486	538.1	2510.0	40.2	40.2	81.5	197.4	0.7	2.1	64.7	1.8	0.28	0.12	11.20	32.20	12.8	28.1	24.9	4.5	3.8	155.69	39	2486	2248	2110	1758
01/03/2001	487	556.2	2630.5	72.3	46.2	82.5	173.6	2.8	0.7	70.8	0.7	0.14	0.35	12.40	32.80	12.8	33.6	24.6	4.5	2.6	178.57	40.6	2322	2240	2012	1870
02/03/2001	488	552.2	2530.1	52.2	56.2	77.3	183.4	1.0	0.0	47.2	0.8	0.12	0.26	15.60	30.80	14.1	29.4	23.7	6.4	5.8	176.37	48.1	2306	2268	1994	1912
03/03/2001	489																									
04/03/2001	490	544.2	2630.5	44.2	36.1	86.2	196.0	3.5	2.4	54.6	1.3	0.13	0.24	18.80	32.00	14.7	27.5	19.2	3.8	3.2	167.55	48	2424	2268	2110	1882
05/03/2001	491	626.2	2801.6	74.2	51.5	82.7	165.2	2.5	1.8	60.8	0.5	0.10	0.27	22.40	33.20	14.1	28.8	17.9	6.1	3.8	158.07	50.1	2486	2404	2058	1958
06/03/2001	492	535.6	2863.4	45.3	28.8	81.1	172.2	0.3	1.7	54.9	1.1	0.10	0.26	23.60	31.20	13.7	29.4	18.9	7.0	6.4	162.87		2336	2456	1954	2088
07/03/2001	493	572.7	2987.0	55.6	41.2	82.3	209.3	1.3	1.0	63.0	0.5	0.10	0.24	24.80	32.80	14.7	28.1	19.2	7.4	6.7	179.03		2424	2346	2030	1918
08/03/2001	494	541.8	2472.0	33.0	20.6	79.5	203.0	0.1	0.0	62.4	0.1	0.11	0.24	27.60	32.00	15.3	25.9	16.0	7.4	7.0	161.81	47.5	2602	2472	2190	2058
09/03/2001	495																									
10/03/2001	496	502.6	2904.6	57.7	41.2							0.19	0.46	12.20	30.40	12.1	18.2	13.4	6.9	5.6	165.98	46.6	2574	2410	2208	2026
11/03/2001	497	498.5	3048.8	70.0	57.7	81.6	181.3	2.8	1.4	48.2	1.0	0.20	0.56	15.20	31.40	12.6	17.1	12.8	8.4	8.0	179.01	49.5	2558	2402	2358	2030
12/03/2001	498	467.6	2914.9	51.5	26.8	74.8	176.4	0.9	1.3		0.0	0.15	0.33	18.20	32.80	12.6	18.2	14.5	8.7	8.7	171.26	48.2	2598	2394		
13/03/2001	499	587.1	3543.2	70.0	63.8	76.2	191.8	3.8	2.4	54.3	1.3	0.06	0.07	18.20	30.20	13.2	17.5	12.6	8.4	8.4	171.29	42.4	2566	2452	2176	2060
14/03/2001	500					76.7	203.0	2.4		61.6	0.0	0.05	0.09	21.80	31.40	12.8	16.9	12.8	7.8	7.8	175.00	45.3	2496	2430	2116	2030
15/03/2001	501					58.2	151.2	0.0			0.0	0.10	0.06	26.40	32.80	13.0	15.6	11.5	8.2	7.6	183.79	42.5	2544	2394	2200	2048
16/03/2001	502	422.3	2698.6	39.1	43.3	80.9	231.7	4.6	4.1	60.2	0.8	0.05	0.43	26.00	33.00	13.6	21.0	10.0	8.7	8.7	182.48		2298	2192	1938	1852
17/03/2001	503	414.1	3007.6	78.3	26.8							0.05	0.65	27.00	32.20	13.4	18.4	11.0	10.0	9.7	166.39	43.2	2496	2404	2108	2004
18/03/2001	504																									
19/03/2001	505	416.1	2925.2	45.3	24.7							0.10	0.50	26.80	32.60	13.6	14.7	11.9	10.8	10.8	171.53	41.3	2348	2332	2010	1976
20/03/2001	506	518.1	2833.6	60.7	40.5	83.4	175.0	1.8	1.8	63.3	0.2	0.07	0.31	32.20	35.00	15.2	21.0	16.4	12.1	11.9	193.01	45	2314	2176	2030	1844
21/03/2001	507																									
22/03/2001	508	469.6	2833.6	48.6	36.4	88.2	189.7	1.8	1.4	73.9	0.0	0.30	0.55	15.60	33.00	14.8	23.5	17.1	6.4	5.4	191.97	54.2	2518	2292	2170	1946
23/03/2001	509	558.6	2894.3	46.6	38.5	87.9	226.1	4.8	2.9	73.4	2.0	0.16	0.42	18.80	33.00	13.3	22.6	16.2	6.7	5.8	181.96		2616	2528	2282	2172
24/03/2001	510	534.3	2894.3	78.9	48.6	91.7	211.4	0.0	0.0	58.5	0.0	0.10	0.40	22.40	32.80	13.3	18.0	11.3	7.5	5.8	192.63	54.4	2488	2388	2160	2052
25/03/2001	511	744.8	3036.0	34.4	32.4	89.5	219.8	2.0	2.0	64.7	1.3	0.15	0.45	27.20	32.00	14.2	23.7	16.2	8.7	7.5	197.67	43.2	2634	2580	2250	2178
26/03/2001	512	676.0	2833.6	40.5	40.5	94.4	207.2	3.1	2.1	78.7	0.4	0.18	0.45	29.60	32.60	14.8	23.7	18.2	8.4	7.8	224.90	44.9	2636	2490	2326	2154
27/03/2001	513	740.8	3440.8	44.5	54.7	86.0	210.7	1.3	1.3	67.8	0.0	0.10	0.30	30.40	31.60	15.1	25.5	20.3	9.6	8.4	195.12	47.8	3074	2870	2690	2448
28/03/2001	514	643.6	3683.7	42.5	40.5	86.2	222.6	0.7	0.1	67.8	0.8	0.08	0.30	26.00	31.40	15.1	24.0	15.6	9.3	9.3	181.00	47.5	3026	3094	2592	2576
29/03/2001	515																									
30/03/2001	516																									
31/03/2001	517																									
01/04/2001	518	688.2	2874.1	46.6	44.5	87.6	189.7	3.1	1.5	65.2	0.1	0.27	2.05	30.20	34.00	15.0	23.8	17.2	12.5	9.4	217.90	43.4	2574	2570	2238	2214
02/04/2001	519																									
03/04/2001	520																									
04/04/2001	521	464.9	3206.4	60.1	50.1	81.2	195.3	1.1	1.3	69.4	1.2	0.14	1.80	32.20	34.60	13.4	21.3	14.4	7.5	7.2	252.24	47.6	2616	2458	2320	2150
05/04/2001	522																									
06/04/2001	523																									
07/04/2001	524																									
08/04/2001	525																									
09/04/2001	526																									
10/04/2001	527																									
11/04/2001	528	442.9	3426.8	44.1	38.1	00.8	131.6	0.4	0.0	65.8	0.0	0.58	7.05	35.40	36.00	14.4	20.6	8.1	7.8	7.8	248.45	44.7	2286	2254	1832	1964
12/04/2001	529	489.0	3126.2	48.1	48.1	89.2	196.7	0.0	0.0	67.2	0.0	0.85	7.20	34.20	38.40	14.1	19.7	10.6	9.4	9.1	313.86	42.8	2450	2294	2186	2036
13/04/2001	530	466.1	3286.6	68.1	48.1	86.4	189.0	0.0	0.0	53.8	0.0	1.95	9.35	37.00	42.00	13.8	20.9	11.9	10.9	10.3	337.59	41.35	2048	2192	1902	1944
14/04/2001	531																									
15/04/2001	532	416.8	3046.1	36.1	24.1	89.6	206.5	2.8	1.7	49.3	0.0	0.43	7.20	37.40	41.80	13.8	11.9	11.3	10.9	10.9	550.77	33.75	2400	2324	2140	2098
16/04/2001	533																									
17/04/2001	534	432.9	2825.6	20.0	22.0	89.2	201.6	1.4	1.0	79.0	0.1	1.57	8.45	37.20	46.30	13.8	20.0	11.6	11.3	10.0	374.53	30.9	2152	2136	1950	1922
18/04/2001	535	392.8	2685.4	68.1	68.1	87.5	191.1	3.2	2.8	66.4	1.8	2.40	8.45	39.80	42.80	13.8	14.4	12.5	11.3	11.3	306.35	29.4	2268	2174	2068	1994
19/04/2001	536	515.0	2885.8	56.1	30.1	72.2	172.2	2.9	2.0	52.9	0.0	0.43	1.65	31.40	40.60	15.0	17.8	11.6	9.7	9.4	352.95	32.2	2214	2170	1970	1914
20/04/2001	537	511.0	3507.0	66.1	58.1	87.8	212.8	3.2	2.5	69.4	0.4	0.22	0.60	41.00	42.40	13.2	13.2	11.2	7.9	7.9	320.47	32.3	2362	2286	2140	2056
21/04/2001	538																									
22/04/2001	539	503.0	3206.4	36.1	24.1	73.8	208.6	1.5	0.8	48.7	0.0	0.29	0.85	42.80	43.00	12.9	13.6	9.6	6.3	6.0	353.00	28.5	2404	2264	2180	2026
23/04/2001	540	493.0	2845.7	54.1	36.1	72.5	202.3	2.1	1.0		0.0	0.13	1.20	41.83	47.00	12.9	14.5	9.6	6.0	6.0	298.21	27.9	2462	2680	2212	2392
24/04/2001	541	543.4	3534.0	70.7	58.6	80.4	203.7	2.5	1.3	62.1	0.0	0.17	0.85	41.00	46.00	13.2	9.9	10.6	6.9	6.3	332.46	28.7	2404	2454	2162	2194
25/04/2001	542																									
26/04/2001	543	559.5	3131.0	64.6	58.6	78.0	189.7	1.7	1.5	65.0	0.0	0.08	0.95	41.60	46.00	13.2	15.2	11.9	8.9	7.6	334.67	28.6	2312	2388	2152	2186
27/04/2001	544	531.3	3131.0	66.7	68.6	85.4	211.4	4.8	2.2	60.2	0.0	0.10	0.65	40.00	42.80	13.2	16.5	11.9	8.6	8.3	355.77	29.5	2380	2340	2176	2084
28/04/2001	545	535.3	2989.6	76.8	68.7	73.8	190.8	2.0	2.0	38.9	0.0	0.13	1.20	42.00	44.00	12.6	15.6	10.2	5.6	6.3	317.54	28.4	2278	2412	2080	2160
29/04/2001	546																									
30/04/2001	547																									
01/05/2001	548	537.3	2807.8	58.6	42.4	78.0	173.6	2.0	1.0	58.2	0.3	0.10	3.05	40.60	42.20	11.6	18.8	11.2	8.3	8.3	379.16		1978	2020	1776	1796
02/05/2001	549	456.5	2706.8	60.6	58.6	73.2	183.4	2.4	1.4	64.1	0.0	0.28	1.20	40.00	41.20	12.2	16.5	12.6	9.9	9.3	319.27	22.1	2020	2086	1762	1818
03/05/2001	550	434.3	2706.8	72.7	62.6	76.7	190.4	3.2	1.5	60.2	0.6	0.06	1.10	41.00	43.80	11.9	16.2	10.9	6.6	6.9	344.82	31.7	2106	2028	1850	1758
04/05/2001	551	519.1	2666.4	52.5	50.5	79.2	199.5	5.7	4.2	57.4	3.8	0.22	0.48	20.20	33.20	11.2	15.5	11.8	5.6	5.6	308.63	27.2	2084	2104	1904	1900
05/05/2001	552																									
06/05/2001	553																									
07/05/2001	554	456.5	2484.6	40.4	36.4	77.4	207.2	1.7	1.0	61.0	0.5	0.25	0.58	28.60	40.00	11.5	14.9	10.5	9.3	9.0	307.82	33.2	2460	2380	2288	2188
08/05/2001	555	575.7	3211.8	64.6	42.4	77.6	215.6	2.8	1.8	61.6	0.2	0.15	0.47	30.00	39.20	11.5	13.3	9.6	9.3	9.3	296.26	32.5	2394	2248	2128	2006
09/05/2001	556	575.7	2787.6	48.5	44.4	79.0	198.1	5.0	2.2	59.1	0.4	0.13	0.39	32.60	38.20	11.2	10.5	7.1	5.0	5.3	315.28	35.3	2266	2218	2008	1978
10/05/2001	557	519.1	3090.6	46.5	42.4	71.1	184.1	1.3	1.1	59.9	0.0	0.15	0.58	36.60	39.80	11.8	11.8	8.1	5.6	5.3	365.93		3300	2184	2038	1956
11/05/2001	558	397.2	3306.2	68.5	48.4	76.6	221.2	4.6	3.4	59.9	1.5	0.10	1.20	37.40	33.80	11.2	12.7	8.7	6.8	6.8	383.10		2130	2260	1930	2056
12/05/2001	559	532.2	3145.0	72.6	64.5	78.8	189.7	2.0	0.4	49.0	0.0	0.26	2.30	42.30	38.00	11.2	10.8	8.7	7.1	7.1	429.46		2102	2016	1856	1778
13/05/2001	560																									
14/05/2001	561																									
15/05/2001	562																									
16/05/2001	563	678.2	2980.8	75.6	41.0	81.2	168.0	2.2	2.1	70.6	0.0	0.11	0.65	40.10	42.00	11.5	17.0	11.8	6.8	4.0	424.56		1464	1804	1320	1580
17/05/2001	564	643.7	3067.2	82.1	71.3	94.2	186.9	3.2	2.5	70.5	0.0	0.25	0.81	43.20	43.10	11.5	14.3	9.0	5.0	4.7	405.20		1876	1808	1666	1568
18/05/2001	565	557.3	2916.0	73.4	32.4	99.4	173.6	4.3	0.0	80.4	0.0	0.17	0.94	45.50	45.40	11.5	16.4	9.9	5.9	5.0	423.62		1926	1808	1710	1592
19/05/2001	566																									
20/05/2001	567	598.3	3261.6	49.7	45.4	85.3	184.8	1.8	1.8	54.6	0.6	0.25	2.25	42.00	57.70	14.0	11.2	9.1	8.2	7.9	359.22		1940	1854	1792	1686
21/05/2001	568	500.0	3003.8	52.4	42.3	89.6	149.8	2.7	1.7	83.7	0.5	0.23	1.95	45.00	59.60	12.1	15.8	10.6	7.0	7.0	315.72		2032	2004	1856	1800
22/05/2001	569	440.6	2346.0	55.1	49.0	98.8	206.5	2.7	2.1	76.4	0.7	0.27	3.35	40.20	50.75	12.1	17.3	10.0	6.4	5.5	363.08		1972	1926	1804	1702
23/05/2001	570	465.1	2509.2	81.6	49.0	78.1	140.7	2.2	0.4	67.5	0.0	0.24	4.00	45.20	45.00	13.1	15.8	8.8	4.6	4.0	332.67		1950	2002	1712	1760
24/05/2001	571	436.6	2427.6	32.6	26.5	101.1	193.9	3.5	0.0	73.4	0.0	0.28	6.40	50.30	59.70	13.1	15.5	10.0	4.9	9.1	362.67		1038	2020	913	876
25/05/2001	572																									

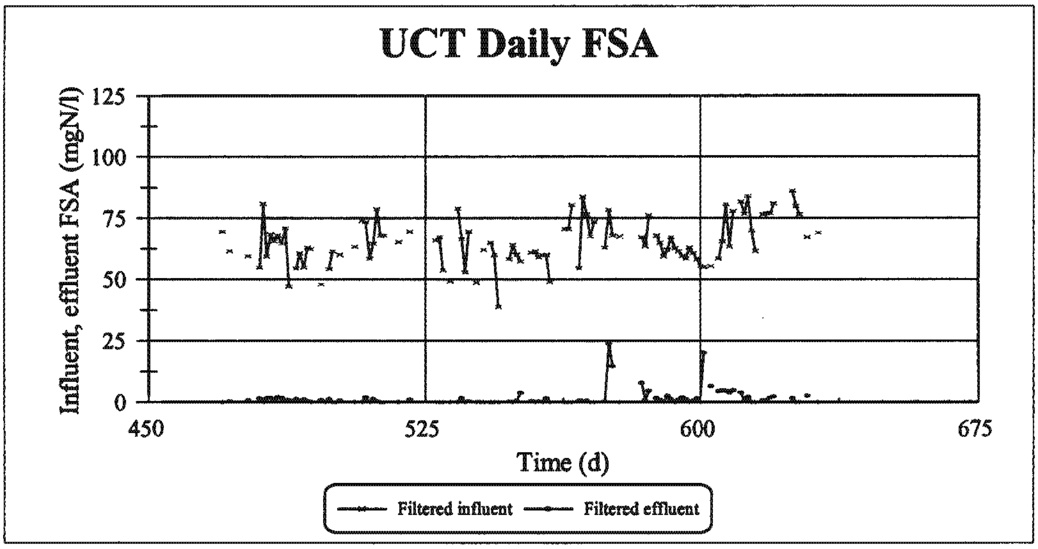
Date	Day No.	COD				TKN				FSA		$NO_3 + NO_2$				Total P					DSVI	OUR	MLSS		MLVSS	
		Influent (mgCOD/l)	Reactor (mgCOD/l)	Unf Effl (mgCOD/l)	Filt Effl (mgCOD/l)	Influent (mgN/l)	Reactor (mgN/l)	Unf Effl (mgN/l)	Filt Effl (mgN/l)	Influent (mgN/l)	Filt Effl (mgN/l)	Anaerobic (mgN/l)	Anoxic (mgN/l)	Aerobic (mgN/l)	Filt Effl (mgN/l)	Influent (mgP/l)	Anaerobic (mgP/l)	Anoxic (mgP/l)	Aerobic (mgP/l)	Filt Effl (mgP/l)	Aerobic (ml/g)	Aerobic (mgO/l.h)	Anoxic (mgTSS/l)	Aerobic (mgTSS/l)	Anoxic (mgVSS/l)	Aerobic (mgVSS/l)
26/05/2001	573																									
27/05/2001	574	552.8	2488.8	44.8	49.0	89.0	181.3	2.5	1.5	63.0	0.4	0.32	8.90	47.50	59.40	12.5	16.1	14.0	14.3	10.3	345.08	26.9	1900	1930	1688	1734
28/05/2001	575	477.4	2876.4	81.6	61.2	90.2	239.4	31.4	26.2	78.4	24.1	0.21	0.25	4.00	26.50	14.0	22.8	23.1	18.5	13.1	314.15		1800	1928	1692	1804
29/05/2001	576	379.4	2570.4	77.5	42.8	84.0	204.4	18.2	15.8	67.8	14.7	0.21	7.15	50.00	50.75	13.4	7.9	6.7	6.4	5.5	304.68		1900	1858	1716	1652
30/05/2001	577																									
31/05/2001	578	477.4	2672.4	44.8	38.8	83.6	196.0	3.4	2.8	67.5	0.0	0.15	5.40	53.50	59.30	13.1	16.1	11.2	9.1	9.4	324.00		1874	1850	1674	1618
01/06/2001	579																									
02/06/2001	580																									
03/06/2001	581																									
04/06/2001	582																									
05/06/2001	583	561.8	2372.8	50.7	76.6							0.15	2.80	57.70	50.50	13.7	15.5	11.8	9.4	8.5	275.29		1866	1754	851	790
06/06/2001	584	614.5	2474.2	50.7	32.5	96.6		14.4	12.3	67.2	8.0	0.10	1.65	54.50	28.75	13.7	15.2	12.8	6.4	8.5	254.48		1946	1832	902	849
07/06/2001	585	496.9	2210.5	60.8	30.4	71.4	182.7	2.8	1.0	63.6	1.0	0.14	0.65	30.00	36.40	12.5	14.7	9.7	4.4	6.0	256.41		2026	1872	1792	1644
08/06/2001	586	480.6	2656.7	64.9	28.4	82.2	185.5	9.0	8.1	76.2	4.8	0.16	0.00	17.20	24.00	10.7	17.6	18.5	6.6	5.3	224.83		2234	2046	2032	1826
09/06/2001	587																									
10/06/2001	588	478.6	2839.2	58.8	42.6	94.1	198.1	2.2	2.2	67.8	1.7	0.21	2.65	42.00	44.40	11.6	17.3	10.7	7.2	5.6	286.32		1946	1886	1754	1652
11/06/2001	589	517.1	2900.0	54.8	44.6	84.8	212.8	2.2	1.4	65.0	0.9	0.34	3.10	40.80	40.40	15.4	16.6	11.6	11.3	9.4	260.62		2216	2072	1976	1840
12/06/2001	590	444.7	2652.0	73.4	40.8	76.7	197.4	6.0	5.5	59.4	0.3	0.14	3.00	36.40	36.40	15.1	16.6	11.6	10.4	10.4	232.32		2150	1980	1950	1776
13/06/2001	591	430.4	2346.0	53.1	44.9	79.9	158.2		4.5	62.2	2.7	0.17	3.75	42.00	36.00	12.9	16.0	11.3	10.4	10.4	210.00		2134	2000	1928	1792
14/06/2001	592	395.8	2284.8	28.6	16.3	85.5	175.7	2.0	1.7	67.2	1.4	0.18	2.80	38.00	37.60	15.5	14.8	8.7	5.5	7.7	209.56	35.8	1996	1890	1778	1668
15/06/2001	593	438.6	2346.0	42.8	40.8	82.6	164.5	3.5	2.0	62.7	0.0	0.16	3.10	38.40	37.60	9.7	15.5	9.0	4.5	4.5	192.51	33.2	1968	1870	1770	1674
16/06/2001	594	418.2	2509.2	40.8	32.6	83.0	210.0	0.8	0.7	61.6	1.1	0.16	4.30	40.40	38.00	10.6	16.8	10.0	5.8	5.2	192.70		2052	1972	1832	1730
17/06/2001	595	424.3	2346.0	59.2	36.7	86.0	162.4	2.7	2.4	59.6	2.0	0.19	4.95	39.60	40.00	11.6	11.0	10.3	6.4	8.7	184.98	35.1	1992	1838	1802	1644
18/06/2001	596	428.0	2120.0	22.0	16.0	82.6	149.8	2.1	1.7	58.5	1.3	0.23	5.20	40.40	40.00	11.3	15.1	10.0	6.1	6.1	213.13	34.7	1888	1736	1642	1548
19/06/2001	597	444.0	2340.0	62.0	40.0	80.8	137.9	0.0	0.0	63.0	0.0	0.24	6.85	41.60	44.00	11.3	7.4	7.1	7.4	6.1	160.58	33.5	1774	1806	1582	1610
20/06/2001	598	490.0	2520.0	48.0	44.0	79.8	164.5	1.3	1.0	60.8	0.6	0.23	6.15	42.40	43.20	11.6	15.5	9.7	5.8	5.8	128.34	38	1916	1948	1750	1472
21/06/2001	599	430.0	2400.0	52.0	40.0	80.6	179.2	4.2	3.6	58.2	1.5	0.24	6.20	41.60	41.60	11.3	13.9	10.6	7.1	6.1	126.83	38.4	1908	2050	1696	1770
22/06/2001	600	338.0	2340.0	62.0	42.0	80.8		3.1	1.5	55.4	0.0	1.71	11.50	44.80	46.00	11.6	12.6	10.6	10.3	9.0	145.74		1798	1784	1614	1582
23/06/2001	601	342.0	2460.0	60.0	48.0	75.7	166.6	21.0	20.9	55.2	20.2	0.15	0.50	36.80	16.40	20.8	23.2	20.5	17.5	10.7	166.32		1962	1924	1796	1760
24/06/2001	602																									
25/06/2001	603	516.0	2080.0	54.0	46.0	77.0	128.8	9.7		55.4	6.6	0.73	0.72	33.60	36.40	13.1	10.1	11.4	10.4	10.1	126.32		1852	1900	1686	1720
26/06/2001	604																									
27/06/2001	605	530.0	2220.0	52.0	44.0	79.5	175.0	7.7	7.0	58.5	4.5	0.22	3.80	32.80	32.00	15.4	13.1	12.1	11.7	11.4	145.90		1782	1782	1584	1570
28/06/2001	606	592.0	2400.0	58.0	52.0	82.9	193.2	6.4	5.2	65.5	4.9	0.07	1.85	36.00	32.00	17.8	14.8	14.1	13.4	14.4	146.90		1948	1906	1770	1740
29/06/2001	607	596.0	2620.0	78.0	60.0	102.1	212.8	9.8	6.4	80.6	4.8	0.09	1.45	36.40	34.00	16.4	15.8	15.4	14.8	14.4	136.85		1702	2046	1578	1884
30/06/2001	608	644.0	2380.0	76.0	62.0	105.3	161.7	9.5	6.7	63.3	4.0	0.07	0.00	36.00	38.00	16.1	14.8	14.4	13.1	12.8	141.72		1520	1764	1412	1616
01/07/2001	609	632.0	2480.0	64.0	46.6	105.7	212.1	6.4	5.9	77.8	4.8	0.14	1.50	33.60	38.00	15.4	14.8	13.1	12.1	11.7	132.89		1446	1806	1314	1642
02/07/2001	610																									
03/07/2001	611	602.0	2120.0	70.0	46.0	103.6	149.1	6.7	6.6	81.8	3.9	0.18	1.25	36.10	40.00	15.4	15.8	13.1	11.7	11.7	131.06		1288	1526	1192	1384
04/07/2001	612	600.0	2000.0	70.0	68.0	91.3	119.0	2.9	0.4	76.7	0.4	0.19	1.45	36.40	36.80	16.8	14.8	12.8	10.1	8.7	168.54		1332	1424	1242	1354
05/07/2001	613	664.0	1840.0	56.0	52.0	99.8	176.4	3.9	3.5	84.0	2.2	0.16	1.10	36.40	40.00	16.8	13.1	11.4	9.7	8.1	183.24		1518	1528	1418	1412
06/07/2001	614	548.0	1960.0	58.0	52.0	97.7	128.1	3.5	2.0	70.0	0.0	0.25	0.85	35.20	33.60	12.8	14.7	11.8	8.2	8.2	156.25		1780	1664	1508	1324
07/07/2001	615	468.0	1980.0	54.0	38.0	91.0	149.1	2.5	1.7	61.6	0.0	0.24	1.20	36.40	34.80	12.4	14.7	11.5	8.6	8.8	148.40		1746	1752	1582	1560
08/07/2001	616																									
09/07/2001	617	584.0	1580.0	78.0	56.0	98.0	151.9	2.9	2.2	76.4	0.8	0.10	1.05	34.80	33.20	14.4	16.1	13.1	8.8	9.5	203.19		1556	1378	1440	1284
10/07/2001	618	536.0	2440.0	180.0	90.0	95.1	172.9	4.5	4.2	77.0	0.6	0.10	1.30	34.40	33.60	15.1	15.4	12.4	7.5	7.5	171.04	35.95	1626	1754	1442	1516
11/07/2001	619	580.0	2100.0	80.0	56.0	96.5	150.5	5.5	3.1	77.0	1.8	0.21	1.40	34.80	36.40	12.8	15.7	11.8	7.5	6.5	180.18	38.2	1576	1554	1378	1360
12/07/2001	620	552.0	2080.0	68.0	46.0	98.4	155.4	5.0	2.9	00.9	2.4	0.13	1.60	34.40	39.20	15.1	16.1	11.8	7.9	9.8	138.27	36.9	1628	1808	1460	1600
13/07/2001	621																									
14/07/2001	622																									
15/07/2001	623																									
16/07/2001	624																									
17/07/2001	625	572.0	2300.0	50.0	38.0	97.2	181.3	5.2	4.3	86.2	1.7	0.13	2.60	34.40	40.80	15.1	17.4	12.1	9.2	7.5	149.41		1720	1874	1526	1682
18/07/2001	626	626.0	2700.0	60.0	58.0	92.7	193.2	2.1	1.5	79.8	0.0	0.10	1.90	33.20	38.80	15.1	17.0	12.8	9.5	8.5	158.56		1642	1892	1446	1630
19/07/2001	627	622.0	2680.0	48.0	36.0	95.1	195.3	3.4	1.4	76.4	0.0	0.23	2.85	29.60	38.00	15.8	15.5	12.5	9.6	9.2	175.82		1498	1852	1352	1620
20/07/2001	628																									
21/07/2001	629	564.0	2780.0	66.0	50.0	100.9	214.2	3.8	3.2	67.2	2.5	0.32	3.40	34.00	36.00	15.6	16.5	12.5	10.2	9.9	173.38		1694	2134	1504	1884
22/07/2001	630																									
23/07/2001	631																									
24/07/2001	632	570.0	3060.0	48.0	40.0	92.7	204.4	3.5	2.4	68.9	0.0	0.22	3.65	34.00	34.80	15.8	13.5	10.2	8.2	8.2	169.35		2088	2362	1854	2080
Average		508.2	2653.0	55.3	44.1	83.1	182.1	3.7	2.7	63.4	1.6	0.2	2.1	33.3	37.4	13.3	17.5	12.9	8.0	7.5	228.1	35.7	2070.5	2073.5	1787.7	1784.2

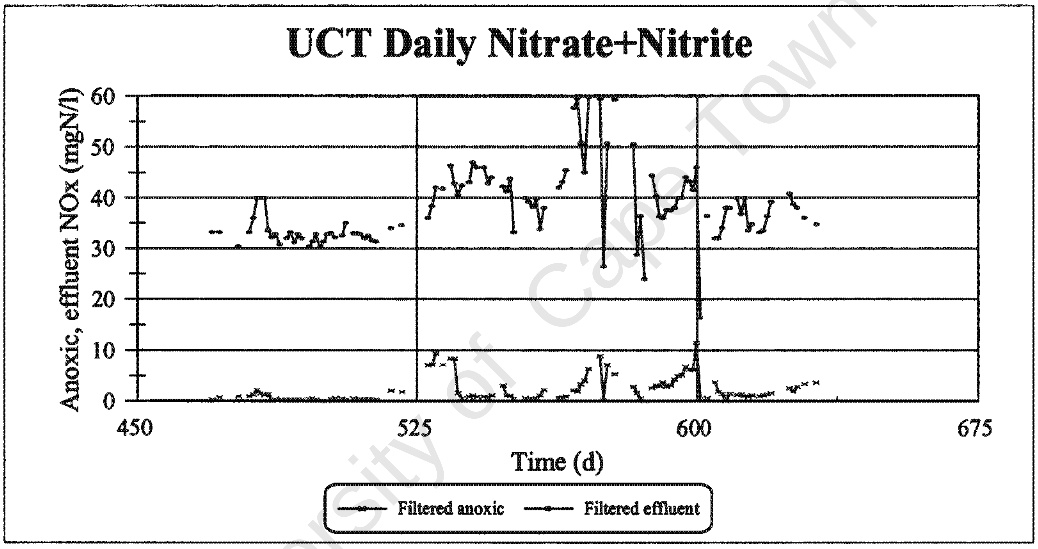


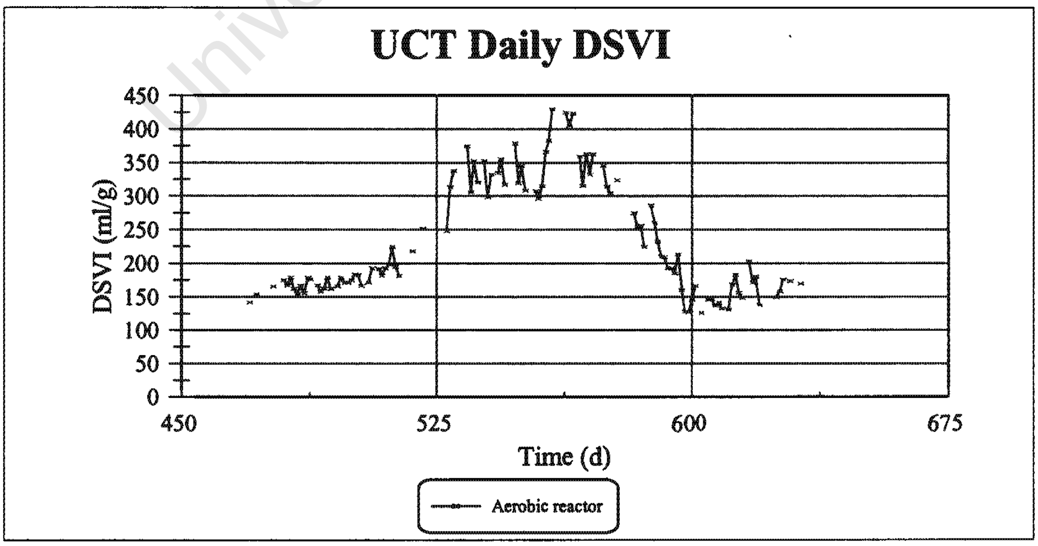




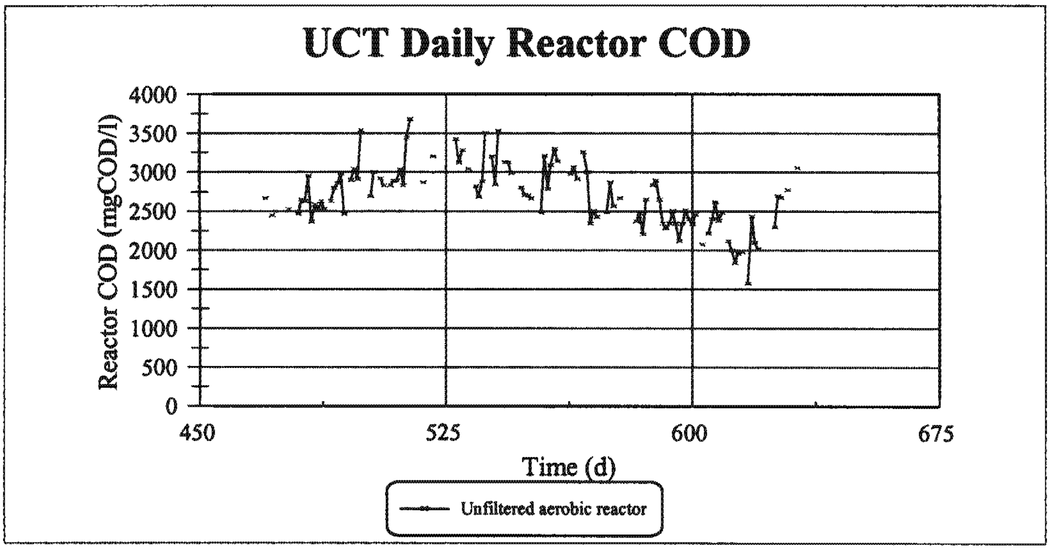
Figures I.1, I.2 and I.3 : "UCT" daily unfiltered influent and unfiltered/filtered effluent COD, TKN and Total P respectively.

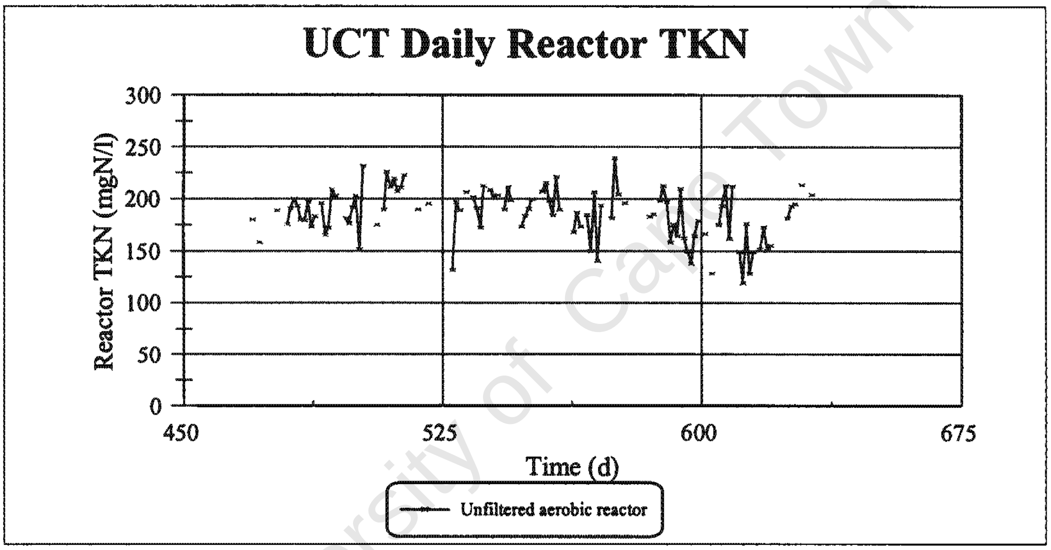


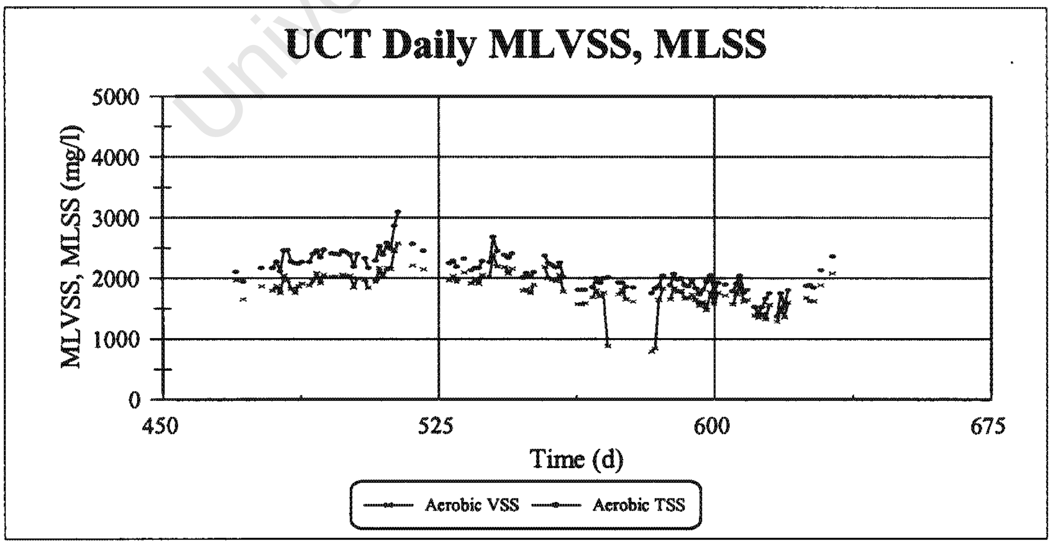




Figures I.4, I.5 and I.6 : "UCT" daily filtered influent and effluent FSA, anoxic and effluent NO_x and reactor DSVI respectively.



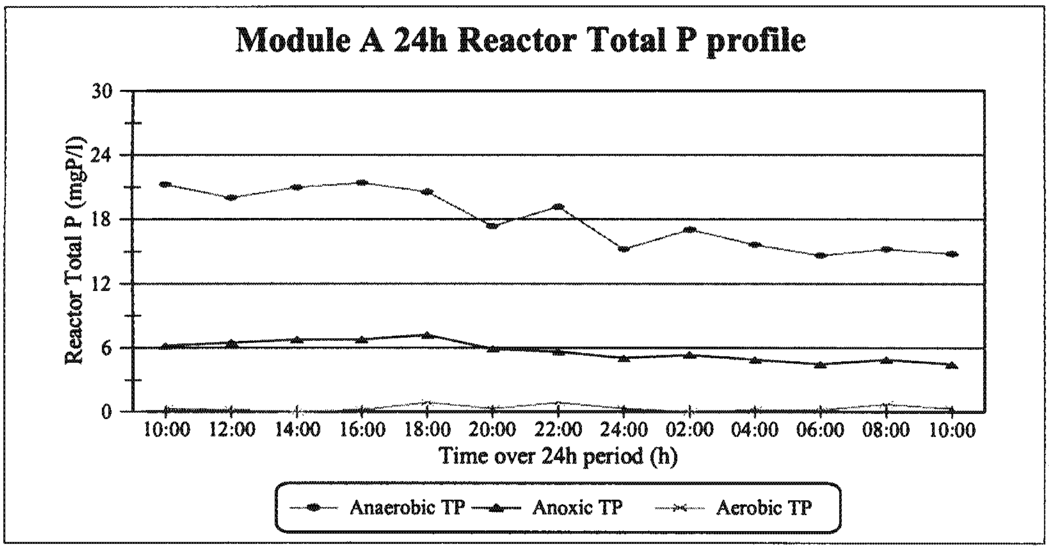


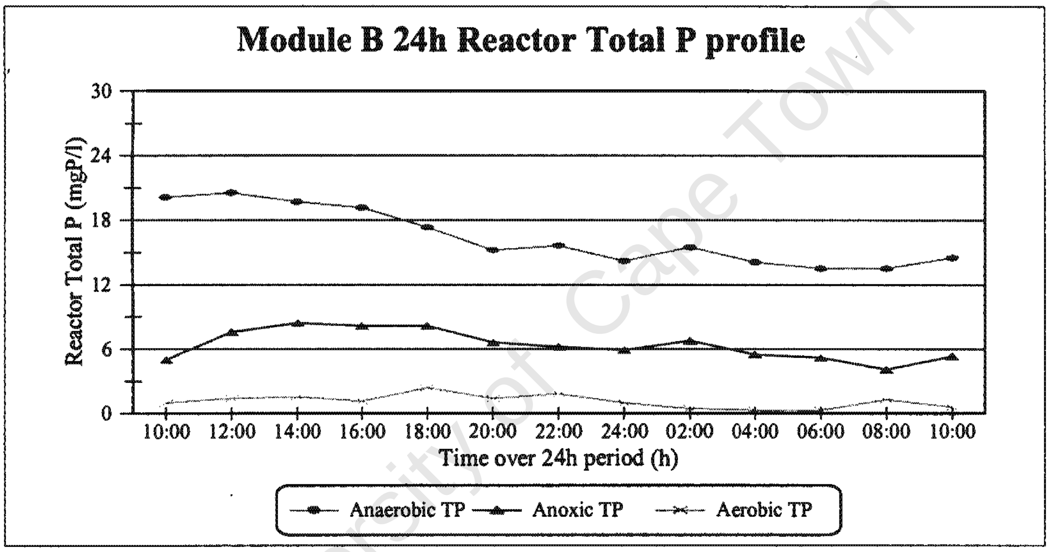


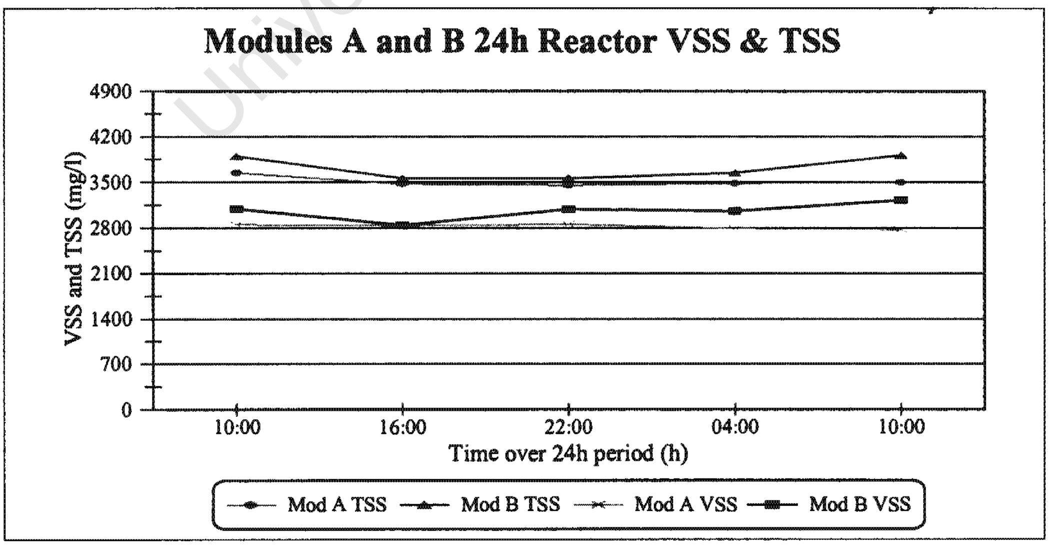
Figures I.7, I.8 and I.9 : "UCT" daily unfiltered reactor COD, TKN and VSS/TSS respectively.

APPENDIX J

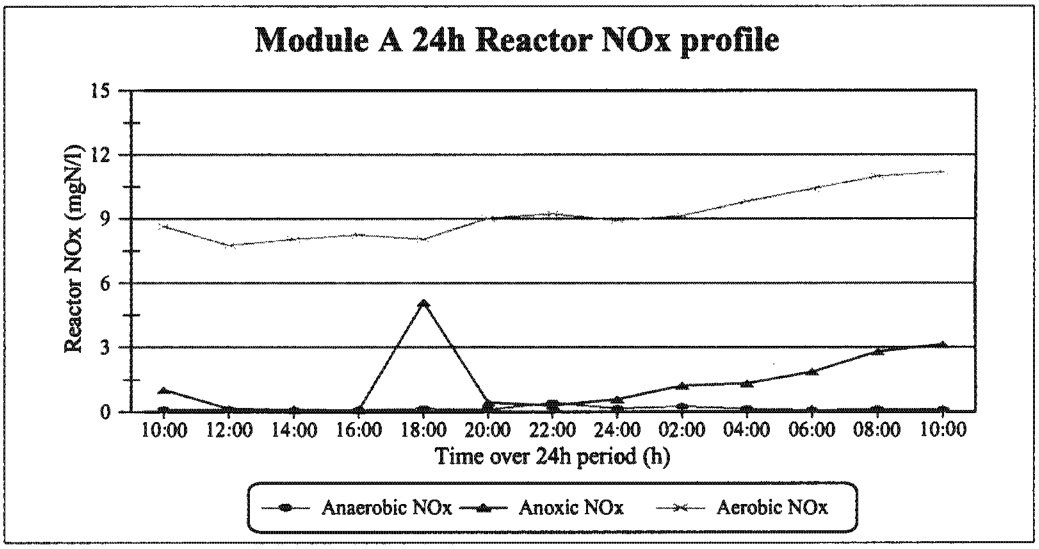
24 HR REACTOR CONCENTRATION PROFILES

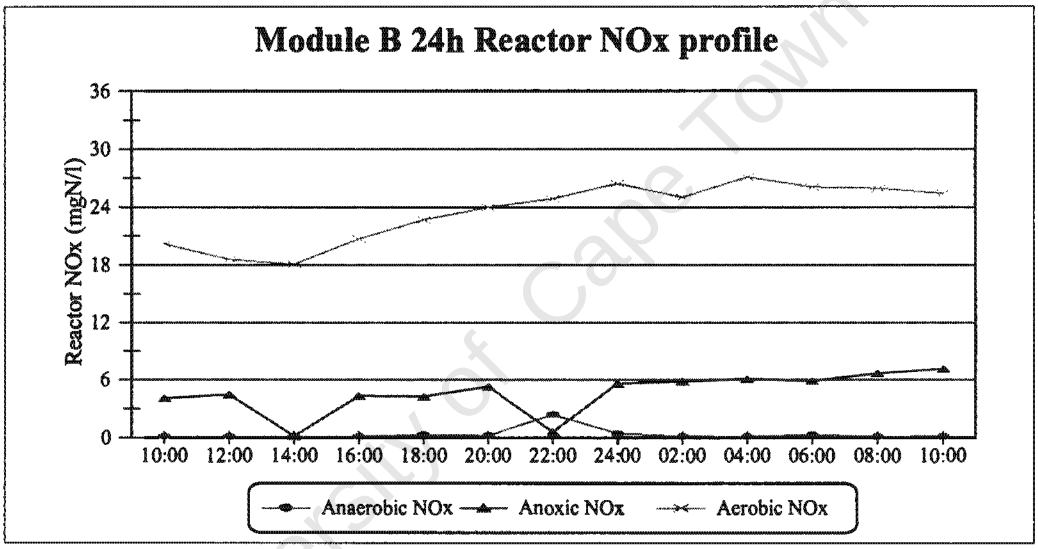


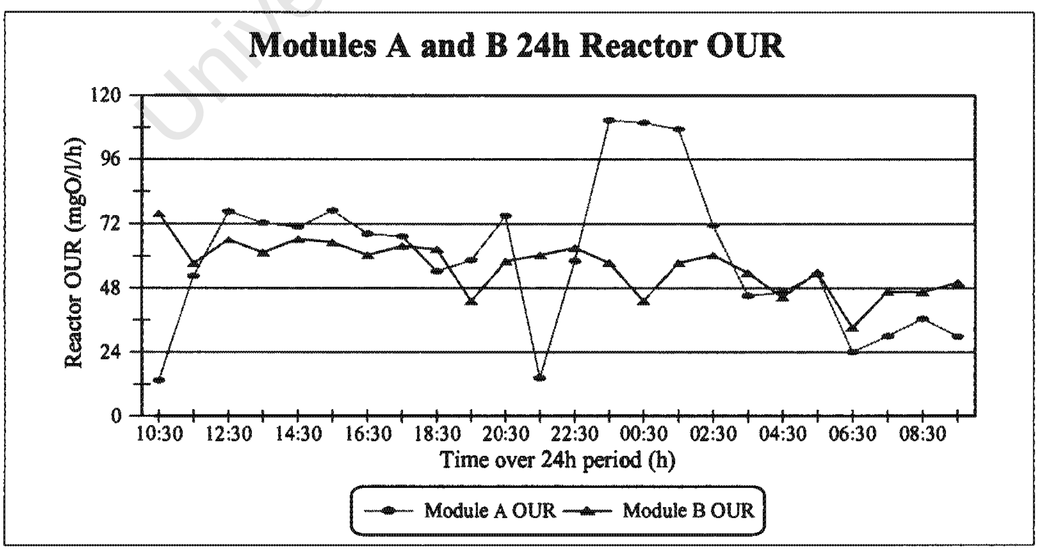




Figures J.1, J.2 and J.3 : 24h test no. 2 reactor profiles for Module A TP, Module B TP and Modules A & B VSS/TSS respectively.







Figures J.4, J.5 and J.6 : 24h test no. 2 reactor profiles for Module A NO_x, Module B NO_x and Modules A & B OUR respectively.

APPENDIX K

BIOWIN and *UCTPHO* SIMULATION RESULTS

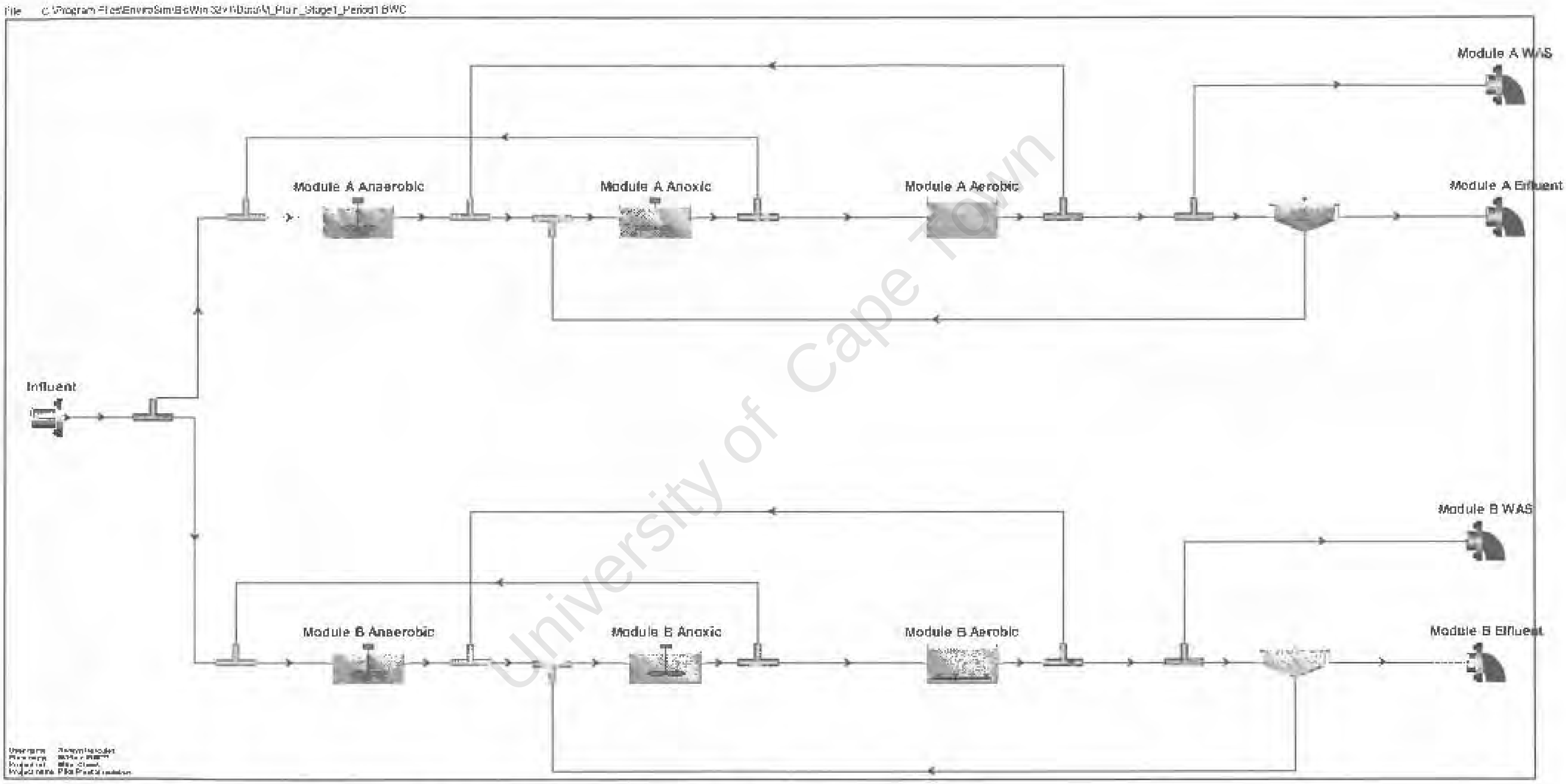


Figure K1 : Process configuration for simulation in *BIOWIN* and *UCTPHO*.

Table K1 : Comparison of measured "site" effluent concentrations with *BIOWIN* and *UCTPHO* prediction results.

Module A Effluent Concentrations

Long Term Period	measured Effluent COD_t (mgCOD/l)	*BIOWIN* Effluent COD_t (mgCOD/l)	measured Effluent S_{us} (mgCOD/l)	*BIOWIN* Effluent S_{us} (mgCOD/l)	*UCTPHO* Effluent S_{us} (mgCOD/l)	measured Effluent TKN_t (mgN/l)	*BIOWIN* Effluent TKN_t (mgN/l)	measured Effluent FSA (mgN/l)	*BIOWIN* Effluent FSA (mgN/l)	*UCTPHO* Effluent FSA (mgN/l)	measured Effluent NO_3 (mgN/l)	*BIOWIN* Effluent NO_3 (mgN/l)	*UCTPHO* Effluent NO_3 (mgN/l)	measured Effluent Total P (mgP/l)	*BIOWIN* Effluent Total P (mgP/l)	measured Effluent Ortho P (mgP/l)	*BIOWIN* Effluent Ortho P (mgP/l)	*UCTPHO* Effluent Ortho P (mgP/l)	measured Effluent Alkalinity (mg/l)	*BIOWIN* Effluent Alkalinity (mg/l)	*UCTPHO* Effluent Alkalinity (mg/l)
I	43.60	46.10	40.11	40.10	37.80	0.49	2.73	9.29	0.95	0.70	3.06	14.60	15.20	6.20	4.80	5.01	4.72	1.20	63.73	70.50	70.00
II	37.31	44.47	32.11	32.87	35.50	3.28	2.02	1.86	2.70	0.80	12.49	25.40	25.20	2.04	1.46	1.19	1.26	0.00	56.32	11.00	10.00
III	46.26	57.25	42.21	45.03	49.40	13.76	7.76	10.49	5.77	10.00	10.05	33.54	30.70	1.33	0.79	0.36	0.71	0.00	118.01	5.50	65.00
IV	260.67	80.19	120.89	76.08	74.30	90.09	68.63	61.80	65.91	60.40	0.49	0.02	2.10	5.65	0.25	6.91	0.18	0.00	339.65	336.50	405.00
V	74.60	87.58	63.00	65.88	71.30	30.61	26.06	24.23	23.64	22.00	1.62	10.02	12.40	1.79	0.33	1.47	0.25	0.00	189.59	163.50	185.00
VI	51.07	78.41	47.73	52.18	59.20	7.00	8.09	4.30	5.75	5.00	14.10	32.63	26.60	4.65	0.53	3.31	0.40	0.00	30.43	4.00	45.00
VII	64.56	77.13	59.06	69.16	79.00	7.78	11.23	7.15	9.29	3.50	15.27	32.80	34.00	8.49	0.29	4.85	0.19	0.00	108.92	5.00	5.00
VIII	70.64	92.23	65.62	70.24	79.10	14.13	12.05	4.95	10.00	5.00	12.52	36.34	37.10	2.32	0.35	1.98	0.23	0.00	68.56	4.06	0.00

Module B Effluent Concentrations

Long Term Period	measured Effluent COD_t (mgCOD/l)	*BIOWIN* Effluent COD_t (mgCOD/l)	measured Effluent S_{us} (mgCOD/l)	*BIOWIN* Effluent S_{us} (mgCOD/l)	*UCTPHO* Effluent S_{us} (mgCOD/l)	measured Effluent TKN_t (mgN/l)	*BIOWIN* Effluent TKN_t (mgN/l)	measured Effluent FSA (mgN/l)	*BIOWIN* Effluent FSA (mgN/l)	*UCTPHO* Effluent FSA (mgN/l)	measured Effluent NO_3 (mgN/l)	*BIOWIN* Effluent NO_3 (mgN/l)	*UCTPHO* Effluent NO_3 (mgN/l)	measured Effluent Total P (mgP/l)	*BIOWIN* Effluent Total P (mgP/l)	measured Effluent Ortho P (mgP/l)	*BIOWIN* Effluent Ortho P (mgP/l)	*UCTPHO* Effluent Ortho P (mgP/l)	measured Effluent Alkalinity (mg/l)	*BIOWIN* Effluent Alkalinity (mg/l)	*UCTPHO* Effluent Alkalinity (mg/l)
I	39.00	46.57	35.88	38.69	37.50	1.36	2.77	0.66	0.95	0.50	14.60	15.77	15.00	6.30	4.98	5.22	4.82	1.90	49.15	66.50	70.00
II	40.38	44.10	33.42	31.96	35.00	2.07	3.76	0.08	1.92	0.80	15.79	24.86	22.90	4.69	1.91	1.55	1.78	0.60	30.60	12.50	10.00
III	53.95	53.07	47.41	42.85	48.20	4.79	2.99	2.37	1.17	2.40	16.25	20.99	21.70	3.07	2.72	1.30	2.62	0.00	51.90	34.00	55.00
IV	54.67	63.61	48.67	59.76	54.60	2.28	2.98	1.02	1.09	0.70	13.57	18.54	15.30	7.96	0.57	7.66	0.49	0.00	71.03	59.50	65.00
V	70.43	84.25	58.29	60.97	70.10	8.04	4.51	5.20	2.34	5.20	13.17	18.40	16.00	2.32	0.45	3.26	0.30	0.00	94.44	57.50	95.00
VI	60.38	74.42	57.00	49.07	58.40	5.46	4.64	1.21	2.45	0.70	16.96	28.70	23.00	4.28	0.55	3.43	0.41	0.00	56.13	6.00	15.00
VII	87.07	76.56	79.50	71.93	79.00	38.03	29.67	28.01	27.62	28.30	7.29	9.50	11.80	2.75	0.29	2.62	0.16	0.00	163.38	154.00	170.00
VIII	112.46	88.75	83.54	78.81	77.50	13.43	7.49	2.78	5.50	7.80	17.16	31.64	27.90	2.96	0.95	0.78	0.83	1.20	65.65	5.00	30.00

Table K2 : Comparison of measured "site" reactor concentrations with *BIOWIN* and *UCTPHO* prediction results.

Module A Reactor Concentrations

Long Term Period	measured Anaerobic NO_3 (mgN/l)	*BIOWIN* Anaerobic NO_3 (mgN/l)	*UCTPHO* Anaerobic NO_3 (mgN/l)	measured Anoxic NO_3 (mgN/l)	*BIOWIN* Anoxic NO_3 (mgN/l)	*UCTPHO* Anoxic NO_3 (mgN/l)	measured Aerobic NO_3 (mgN/l)	*BIOWIN* Aerobic NO_3 (mgN/l)	*UCTPHO* Aerobic NO_3 (mgN/l)	measured Aerobic Total P (mgP/l)	*BIOWIN* Aerobic Total P (mgP/l)	measured Anaerobic Ortho P (mgP/l)	*BIOWIN* Anaerobic Ortho P (mgP/l)	*UCTPHO* Anaerobic Ortho P (mgP/l)	measured Anoxic Ortho P (mgP/l)	*BIOWIN* Anoxic Ortho P (mgP/l)	*UCTPHO* Anoxic Ortho P (mgP/l)
I	N/A	0.01	0.00	N/A	4.79	5.00	N/A	14.46	15.20	N/A	175.63	N/A	29.49	37.90	N/A	11.94	11.50
II	1.40	0.03	0.00	7.22	11.70	9.80	11.75	25.40	23.20	N/A	199.38	18.60	33.55	35.50	6.04	12.65	12.30
III	0.21	0.00	0.00	3.39	0.09	0.10	10.00	33.55	30.70	143.99	216.01	29.99	25.29	66.80	11.14	22.82	45.70
IV	0.11	0.00	0.00	0.07	0.00	0.00	2.00	0.02	2.10	104.43	167.95	13.03	39.38	57.60	9.24	35.02	33.00
V	0.21	0.00	0.00	0.13	0.05	0.20	1.59	10.02	12.40	241.22	240.06	34.10	58.62	77.50	12.66	26.52	32.80
VI	0.51	0.04	0.00	6.94	14.75	0.40	11.73	28.51	26.60	164.50	206.51	25.69	46.79	64.50	10.26	16.32	34.50
VII	0.48	0.00	0.00	6.73	1.34	0.50	10.09	32.80	34.00	201.24	232.04	23.92	44.56	49.90	10.05	28.33	31.70
VIII	0.18	0.00	0.00	8.32	1.29	0.30	13.51	36.34	37.10	163.57	263.84	24.48	43.82	53.40	7.25	29.31	35.60

Long Term Period	measured Aerobic Ortho P (mgP/l)	*BIOWIN* Aerobic Ortho P (mgP/l)	*UCTPHO* Aerobic Ortho P (mgP/l)	measured Anaerobic Denit rate (mgN/l/h)	*BIOWIN* Anaerobic Denit rate (mgN/l/h)	*UCTPHO* Anaerobic Denit rate (mgN/l/h)	measured Anoxic Denit rate (mgN/l/h)	*BIOWIN* Anoxic Denit rate (mgN/l/h)	*UCTPHO* Anoxic Denit rate (mgN/l/h)	measured Aerobic VSS (mgVSS/l)	*BIOWIN* Aerobic VSS (mgVSS/l)	*UCTPHO* Aerobic VSS (mgVSS/l)	measured Aerobic TSS (mgTSS/l)	*BIOWIN* Aerobic TSS (mgTSS/l)	measured Aerobic OUR (mgO/l/h)	*BIOWIN* Aerobic OUR (mgO/l/h)	*UCTPHO* Aerobic OUR (mgO/l/h)
I	N/A	4.90	1.20	N/A	1.253	1.300	N/A	4.809	6.800	3824	2547	2758	4257	3178	N/A	45.1	48.7
II	2.20	1.36	0.00	0.24	3.280	2.800	0.252	5.170	5.600	2621	2312	2223	3604	3460	N/A	46.0	44.8
III	1.55	0.71	0.00	0.14	0.009	0.000	0.018	5.624	5.100	2322	2519	2123	3150	3336	N/A	51.3	49
IV	0.44	0.18	0.00	0.01	0.021	0.000	0.019	0.005	0.600	2085	2381	2191	2503	2959	N/A	20.8	23.3
V	3.78	0.25	0.00	0.00	0.124	0.100	0.166	4.933	6.000	3787	3063	3058	5006	3802	N/A	42.9	46.8
VI	3.61	0.70	0.00	0.01	4.036	0.100	0.158	3.981	8.400	2860	2628	3317	3878	3338	N/A	49.8	64.9
VII	5.87	0.19	0.00	0.21	0.145	0.100	0.000	4.567	7.000	3817	2412	2602	4858	3178	N/A	39.0	57.5
VIII	2.17	0.23	0.00	0.29	0.641	0.100	0.000	6.831	7.500	2702	3249	2922	3626	4439	N/A	49.5	65.3

Module B Reactor Concentrations

Long Term Period	measured Anaerobic NO_3 (mgN/l)	*BIOWIN* Anaerobic NO_3 (mgN/l)	*UCTPHO* Anaerobic NO_3 (mgN/l)	measured Anoxic NO_3 (mgN/l)	*BIOWIN* Anoxic NO_3 (mgN/l)	*UCTPHO* Anoxic NO_3 (mgN/l)	measured Aerobic NO_3 (mgN/l)	*BIOWIN* Aerobic NO_3 (mgN/l)	*UCTPHO* Aerobic NO_3 (mgN/l)	measured Aerobic Total P (mgP/l)	*BIOWIN* Aerobic Total P (mgP/l)	measured Anaerobic Ortho P (mgP/l)	*BIOWIN* Anaerobic Ortho P (mgP/l)	*UCTPHO* Anaerobic Ortho P (mgP/l)	measured Anoxic Ortho P (mgP/l)	*BIOWIN* Anoxic Ortho P (mgP/l)	*UCTPHO* Anoxic Ortho P (mgP/l)
I	N/A	0.01	0.00	N/A	6.41	6.10	N/A	15.65	15.00	N/A	189.16	N/A	27.50	33.70	N/A	11.24	10.20
II	0.39	0.03	0.00	8.01	14.15	12.40	14.78	24.86	22.90	N/A	195.27	22.22	30.16	31.20	9.38	9.85	9.20
III	0.18	0.00	0.00	5.17	4.14	5.70	14.91	21.00	21.70	190.71	171.98	31.49	16.68	44.30	13.33	9.49	17.40
IV	0.13	0.02	0.00	5.01	8.52	5.70	10.57	18.34	15.30	291.35	143.11	27.85	32.01	35.10	15.05	10.43	11.00
V	0.10	0.01	0.00	3.29	7.30	5.20	11.07	18.40	16.00	157.11	205.96	28.25	49.43	62.40	10.21	15.42	19.10
VI	0.27	0.04	0.00	5.34	14.75	9.30	15.03	28.51	23.00	198.81	206.51	31.33	46.79	43.50	13.05	16.32	14.10
VII	0.14	0.00	0.00	1.67	0.33	0.50	9.51	9.30	11.80	79.00	203.14	20.39	38.26	41.20	13.03	14.94	15.80
VIII	0.26	0.02	0.00	4.44	13.02	8.90	13.58	31.64	27.90	143.57	202.13	31.02	24.21	32.60	16.19	10.52	13.90

Long Term Period	measured Aerobic Ortho P (mgP/l)	*BIOWIN* Aerobic Ortho P (mgP/l)	*UCTPHO* Aerobic Ortho P (mgP/l)	measured Anaerobic Denit rate (mgN/l/h)	*BIOWIN* Anaerobic Denit rate (mgN/l/h)	*UCTPHO* Anaerobic Denit rate (mgN/l/h)	measured Anoxic Denit rate (mgN/l/h)	*BIOWIN* Anoxic Denit rate (mgN/l/h)	*UCTPHO* Anoxic Denit rate (mgN/l/h)	measured Aerobic VSS (mgVSS/l)	*BIOWIN* Aerobic VSS (mgVSS/l)	*UCTPHO* Aerobic VSS (mgVSS/l)	measured Aerobic TSS (mgTSS/l)	*BIOWIN* Aerobic TSS (mgTSS/l)	measured Aerobic OUR (mgO/l/h)	*BIOWIN* Aerobic OUR (mgO/l/h)	*UCTPHO* Aerobic OUR (mgO/l/h)
I	N/A	5.03	1.90	N/A	2.205	1.800	N/A	5.363	6.700	5142	2796	2715	5473	3470	N/A	50.2	48.6
II	4.45	1.78	0.60	0.34	4.183	3.600	0.750	5.085	5.400	3146	2301	2213	4082	3431	N/A	46.7	45.5
III	1.26	2.62	0.00	0.25	0.627	1.700	1.122	7.285	6.400	2893	2226	1948	3829	2869	N/A	47.2	45.3
IV	7.56	0.50	0.00	0.29	2.506	1.700	0.679	4.013	4.600	3204	1838	1890	4321	2281	N/A	33.5	32.5
V	1.74	0.30	0.00	0.16	2.225	1.500	1.571	6.146	6.500	2123	2580	2578	2819	3193	N/A	44.2	44.5
VI	3.43	0.70	0.00	0.21	4.036	2.400	1.296	3.981	6.600	2958	2628	2756	3914	3338	N/A	49.8	49.8
VII	2.06	0.16	0.00	0.08	0.145	0.100	0.791	4.567	5.800	1356	2412	2195	1815	3178	N/A	39.0	40.4
VIII	5.06	0.82	1.20	0.17	3.517	2.300	0.959	5.160	6.500	2249	2524	2172	3012	3446	N/A	49.5	49.7