2005

Effects Of Reduced Ras And Volume On Anaerobic Zone Performance For A Septic Wastewater Biological Phosphorous Removal System

Daniel Magro

University of Central Florida

EFFECTS OF REDUCED RAS AND VOLUME ON ANAEROBIC ZONE PERFORMANCE FOR A SEPTIC WASTEWATER BIOLOGICAL PHOSPHOROUS REMOVAL SYSTEM

by

DANIEL MAGRO
B.S. Florida Institute of Technology, 2001

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Civil and Environmental Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Spring Term
2005

Major Professor: Andrew Amis Randall, Ph.D.

ABSTRACT

Enhanced Biological Phosphorous Removal (EBPR) performance was found to be adequate with reduced Return Activated Sludge (RAS) flows (50% of available RAS) to the anaerobic tank and smaller than typical anaerobic zone volume (1.08 hours hydraulic retention time or HRT). Three identical parallel biological nutrient removal (BNR) pilot plants were fed with strong, highly fermented (160 mg/L VFAs), domestic/industrial wastewater from a full scale wastewater treatment facility (WWTF). The pilot plants were operated at 100%, 50%, 40% and 25% RAS (percent of available RAS) flows to the anaerobic tank with the remaining RAS to the anoxic tank. In addition, varying anaerobic HRT (1.08 and 1.5 hours), and increased hydraulic loading (35% increase) was examined. The study was divided in four Phases, and the effect of these process variations on EBPR were studied by having one different variable between two identical systems. The most significant conclusions were that only bringing part of the RAS to the anaerobic zone did not decrease EBPR performance, instead changing the location of P release and uptake. Bringing less RAS to the anaerobic and more to the anoxic tank decreased anaerobic P release and increased anoxic P release (or decreased anoxic P uptake). Equally important is that with VFA rich influent wastewater, excessive anaerobic volume was shown to hurt overall P removal even when it resulted in increased anaerobic P release.

Computer modeling with BioWin and UCTPHO was found to predict similar results to the pilot test results. Modeling was done with reduced RAS flows to the anaerobic zone (100%, 50%, and 25% RAS), increased anaerobic volume, and increased hydraulic loading. The most significant conclusions were that both models predicted EBPR did not deteriorate with less RAS to the anaerobic zone, in fact, improvements in EBPR were observed. Additional scenarios were also consistent with pilot test data in that increased anaerobic volume did not improve EBPR and increased hydraulic loading did not adversely affect EBPR.

To my wife Fernanda, for her love and support during the preparation of this thesis.

ACKNOWLEDGMENTS

I give thanks to my advisor Associate Professor Dr. Andrew A. Randall, P.E., for all the advice and guidance throughout the progress of this research project. Successfully completing this thesis would not have been possible without all your advice and knowledge.

The opportunity by the City of Lakeland, Florida, to perform this study and the assistance by City personnel, Robert Conner, P.E., Ed McDonald, Scott Miller, and Tim Lokken, is gratefully acknowledged.

Special thanks goes to the Envisors team for the opportunity to work on the City of Lakeland Pilot Test Project. I would not have been able carry out such a research project without that opportunity.

Finally, I thank all my family, especially my parents, for thanks to their support and encouragement I was able to reach this goal.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ADF	Average Day Flow
AR	Anoxic Recycle
DO	Dissolved Oxygen
EBPR	Enhanced Biological Phosphorous Removal
Eff	Effluent
Inf	Influent
NARCY	Nitrogen Recycle
NR	Nitrogen Recycle
MDF	Maximum Day Flow
MGD	Million Gallons Per Day
ORP	Oxygen Reduction Potential
P	Phosphorous
PAO	Phosphorous Accumulating Organisms
RAS	Return Activated Sludge
SDNR	Specific Denitrification Rate
SKN	Soluble Kjeldahl Nitrogen
SOP	Soluble Ortho Phosphorous
SRT	Solids Retention Time
TCOD	Total Carbonaceous Oxygen Demand
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solids
VFA	Volatile Fatty Acids
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WWTF	Wastewater Treatment Facility

CHAPTER I: GENERAL INTRODUCTION

Typical Enhanced Biological Phosphorous Removal (EBPR) systems return 100% of the available Return Activated Sludge (RAS) to an anaerobic zone, with a hydraulic retention time as high as two hours for adequate fermentation and P release by the Polyphosphate Accumulating Organisms (PAOs). Nevertheless, when upgrading an existing Wastewater Treatment Facility (WWTF) to operate as a typical EBPR system there can be hydraulic (e.g. piping, pump capacity, tank capacity) and budget limitations that can make it desirable to retrofit for EBPR without modifying existing reactors, piping, and capacity.

This was the case at the City of Lakeland, Florida, where the effluent treated water from one of the City's WWTF is used as cooling water at a power plant. Excessive phosphorous levels (4.5 mg/L-P average with peaks of 20 mg/L-P) in the effluent water were found to cause cooling tower scaling resulting in higher maintenance costs. The City elected to implement EBPR at the WWTF to reduce the effluent phosphorous concentration to 1.0 mg/L-P or less. However, because this WWTF had undergone several expansions and process modifications, it was cost prohibitive to modify the existing Modified Ludzack-Ettinger (MLE) facility to operate as a typical EBPR system without very significant re-piping, disturbance of existing electrical conduits, and increasing pump capacity. Retrofitting an abandoned trickling filter tank for the anaerobic zone and the location of a RAS pump station from two of the four secondary

clarifiers made implementing EBPR financially advantageous, however, it would result in using a smaller than typical anaerobic zone and returning only half of the available RAS to the anaerobic zone. It was not certain to what extent EBPR would take place with these basic limitations and therefore, the City chose to conduct a pilot test to study EBPR with reduced RAS rates and a smaller than normal anaerobic zone.

The influent wastewater was domestic with a significant industrial component, and highly septic due to the extensive collection system. The high organic loading experienced by the facility, the high influent VFA concentration and the possibility of EBPR inhibitory compounds from any of the industrial wastewater sources were additional factors considered while conducting the pilot test study.

The study was performed with three main objectives. The primary objective was to determine if EBPR would take place (and to what degree) when only 50% of the available RAS was returned to the anaerobic zone and the rest to the anoxic zone; the second objective was to determine if the available anaerobic tank volume was sufficient for VFA uptake and P release by Phosphorous Accumulating Organisms (PAOs); and the third objective was to evaluate overall EBPR system performance during periods of average and high influent flows.

Many EBPR process configurations have been studied and are documented in the literature; however, the process configuration proposed by this study has not been adequately investigated.

CHAPTER II: LITERATURE REVIEW

2.1 Background

The main objective of wastewater treatment processes is to remove organic carbon, nitrogen and phosphorous from the influent wastewater. Depending on the characteristics of the effluent disposal system, the effluent from a Wastewater Treatment Facility (WWTF) often has stringent quality standards. Although there are several chemical processes available to remove phosphorous from wastewater, biological processes are generally used by WWTFs due to their economical advantages.

There is a wide variety of biological process configurations being used today, and each has advantages and disadvantages over the others. They are all based on process zones that operate as anaerobic, anoxic, aerobic, or combinations of them with recycles to target specific performance or nutrient removal. In the case of Phosphorous (P) removal, Enhanced Biological Phosphorous Removal (EBPR) processes are used, which if properly operated, have been reported to decrease effluent P levels to less than 3 mg/L-P and more frequently to less than 1 mg/L-P (Grady, Daigger, and Lim, 1999).

2.2 EBPR Description

EBPR takes place when appropriate conditions are provided for the biomass in wastewater treatment systems. It is based on sustaining an adequate Phosphorous Accumulating Organism (PAO) population within the biomass and their ability to store

higher percentages of P than their regular nutrient requirement of 2.3% P. P removal is then accomplished via the waste sludge. Although process parameters vary depending on the influent wastewater characteristics, this is usually accomplished by providing alternating anaerobic and aerobic conditions for the biomass.

The Comeau-Wentzel and Mino Models for EBPR are widely accepted by the wastewater treatment community (Grady et al,1999). Both models suggest that in the anaerobic zone the PAOs uptake and store (in the form of polyhydroxyalkanoic acids, or PHAs) readably biodegradable substrate (typically short chain volatile fatty acids, or VFAs) to meet their metabolic needs when they encounter more favorable (aerobic) environments. Energy to store the VFAs is obtained from polyphosphate degradation which results in P release outside the cell wall. The only significant difference between both models is the process in which VFAs are reduced to PHAs. In the Comeau-Wentzel model, reducing equivalents come from the TCA cycle. In the Mino model they come from glycogen. Experimental studies have shown that the Mino mechanism is the dominant one in EBPR systems. Although there is an observable P concentration increase in the anaerobic zone, the presence of oxygen in the aerobic zone allows the PAOs to oxidize the stored PHAs and the energy obtained is used for P uptake and storage as ATP within the cell. The result is a decrease of P levels in the aerobic zone resulting in a net soluble P concentration decrease. Figure 2.1 is a schematic diagram depicting the Mino model for aerobic and anaerobic conditions.

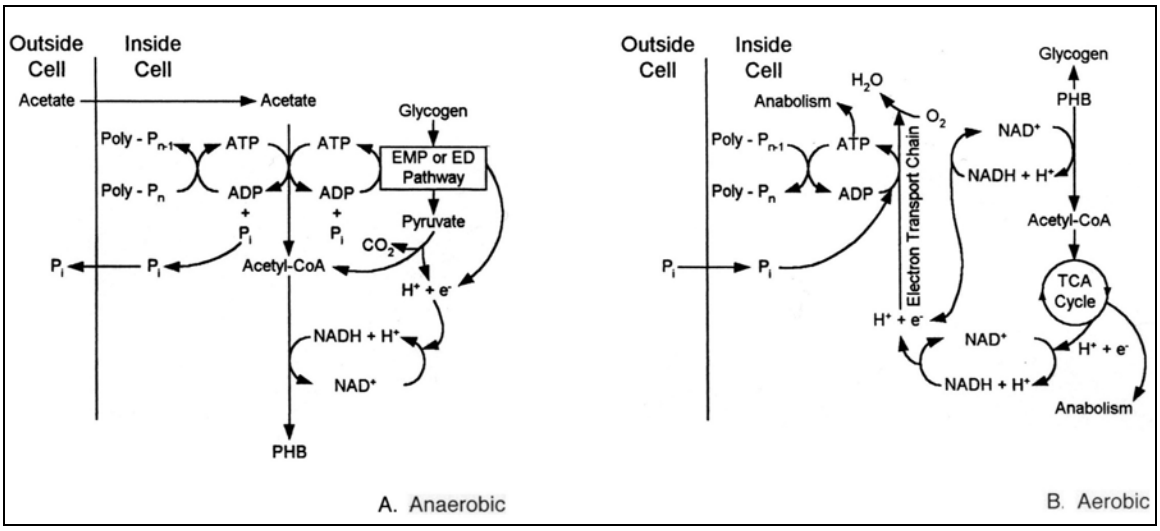

Figure 2.1 – Schematic Diagram of the Mino Model (Grady et al,1999)

EBPR systems are susceptible to conditions that can result in utilization of substrate without P release in the anaerobic zone. If significant nitrate levels are present in the recycle that feeds the anaerobic zone with biomass, the PAOs will utilize the available substrate to meet their metabolic needs without releasing P and storing PHAs resulting in a decrease of EBPR performance (Grady et al, 1999). For this reason, EBPR process design must consider and minimize nitrate loading into the anaerobic zone.

2.3 EBPR Process Configurations

Several EBPR process configurations have been widely studied and implemented. Although each is based on the same principle of alternating anaerobic and aerobic zones, the number of zones, recycles and the anaerobic nitrate protection methods vary among processes. Common processes that target biological P removal are the Phoredox and the Phostrip, while others that target both N and P removal are the A^2/O, Five Stage Bardenpho, University of Cape Town (UCT), and the Modified UCT (MUCT).

The Phoredox process provides anaerobic followed by aerobic conditions, and 100% of the available RAS from the clarifier is returned back to the anaerobic zone. Process optimization consists of operating at a high-rate (3 to 5 days SRT) to maximize P removal and minimize nitrification. Nitrogen will not be removed via nitrification and denitrification and will go through the process mostly unchanged. Figure 2.2 shows a simplified schematic of the Phoredox process.

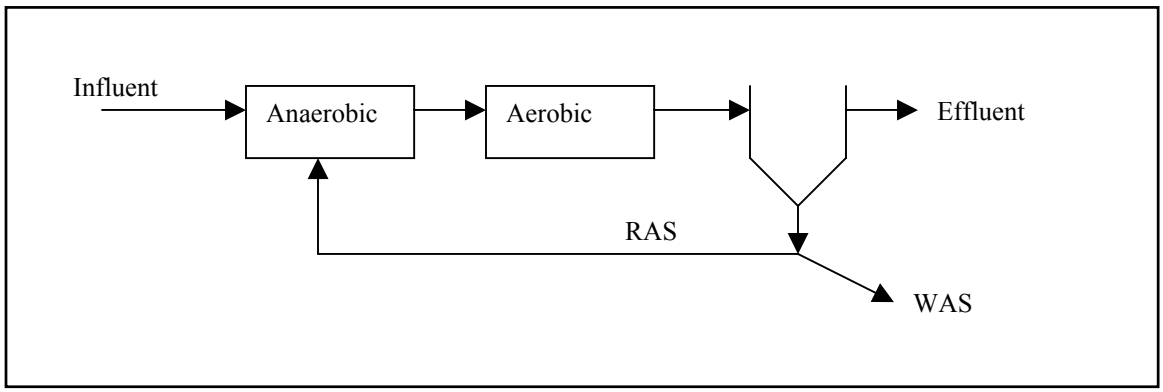

Figure 2.2 - Phoredox Process

The Phostrip process consists of a regular activated sludge process, with the difference that 30 to 40% of the RAS is passed through a clarifier (or stripper tank) that maintains anaerobic conditions. Phosphorous release occurs in this anaerobic zone (with assistance from a VFA source) and the settled sludge is returned to the aerobic zone. The supernatant from the stripper tank is chemically treated for P removal. Unlike the Phoredox process, which only removes P via the waste sludge, the Phostrip also removes P via the chemically treated supernatant from the stripper tank. Figure 2.3 shows a simplified schematic of the Phostrip process.

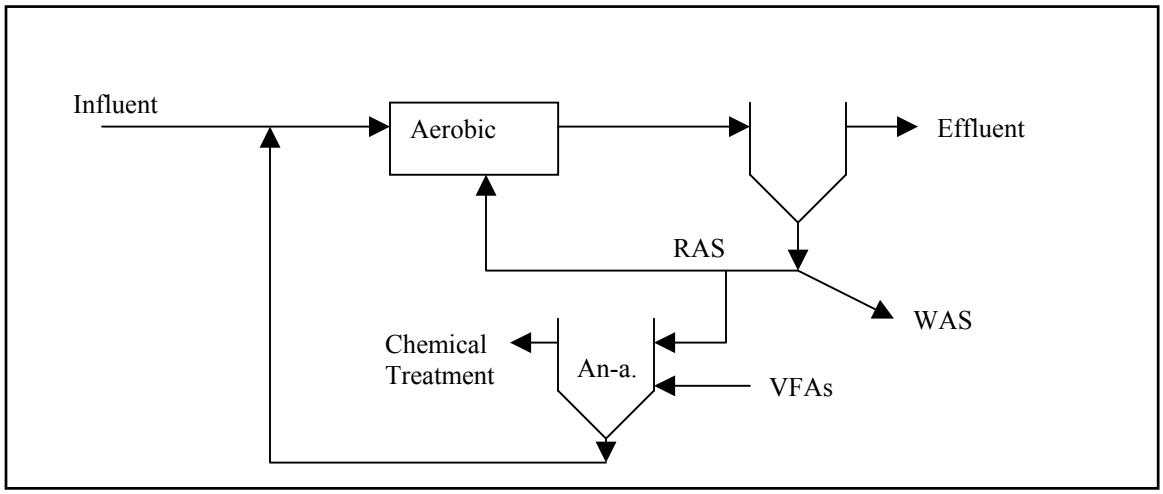

Figure 2.3 - Phostrip Process

Advantages of the Phoredox and Phostrip processes are that excellent P removal has been observed and minimum reactor volume is necessary. However, the aerobic zone must be carefully monitored and controlled to prevent nitrification from occurring. The presence of nitrates in the RAS would reach the anaerobic zone and adversely impact P removal (Grady et al, 1999).

EBPR processes that also remove nitrogen, offer better protection to the anaerobic zone from nitrates in the RAS. For example, the A^2/O process is similar to the Phoredox process but with an anoxic zone between the anaerobic and aerobic zones. A recycle returns mixed liquor from the aerobic zone to the anoxic zone where denitrification takes place, and 100% of the RAS is returned to the anaerobic zone. The process is operated to nitrify in the aerobic zone and denitrify in the anoxic zone; however, if the anoxic zone does not completely denitrify, there is a direct route for nitrates in the RAS to reach the anaerobic zone. Figure 2.4 shows a simplified schematic of the A^2/O process.

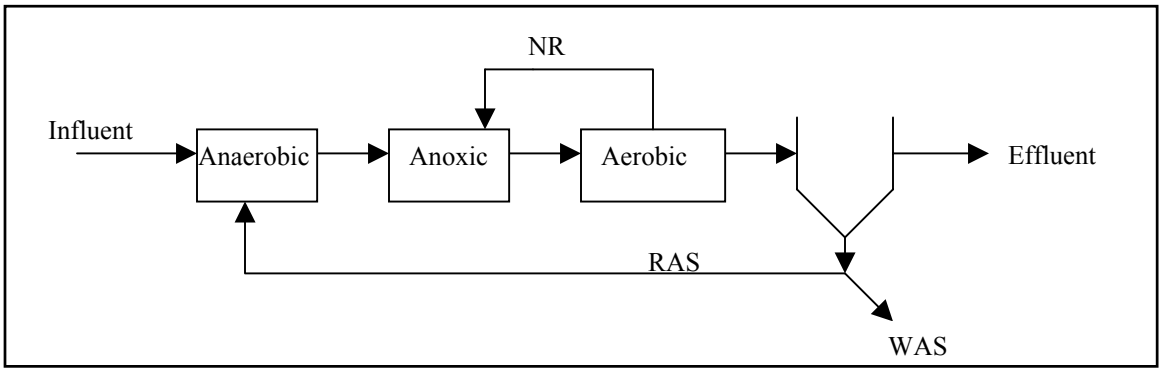

Figure 2.4 - A^2/O Process

The Five Stage Bardenpho process is an expansion from the Four Stage Bardenpho with the addition of an anaerobic zone at the head of the process to achieve P removal. The process consists of an anaerobic zone followed by anoxic, aerobic, anoxic and a final aerobic zone. Mixed liquor is recycled from the first aerobic zone back to the first anoxic zone (NR) and 100% of the RAS is returned to the anaerobic zone. The first three zones operate similarly to the A^2/O process; however, the second anoxic zone offers additional nitrate removal/protection. The second aerobic zone is significantly smaller than the first since its main purpose is to aerate the mix liquor to improve settling in the secondary clarifier. This last aerobic zone is small and nitrates are generally not formed. Figure 2.5 shows a simplified schematic of the Five Stage Bardenpho process.

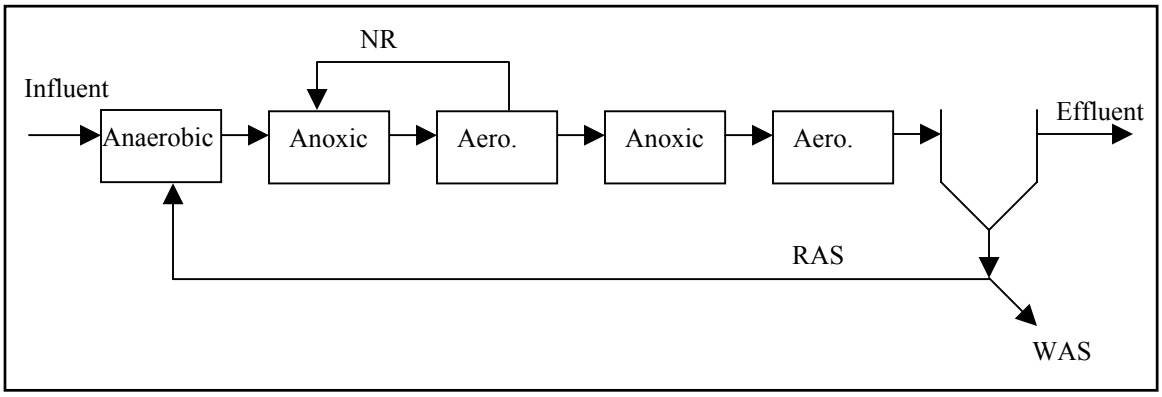

Figure 2.5 - Five Stage Bardenpho Processes

The UCT process significantly reduces the probability of nitrate intrusion to the anaerobic zone. The process consists of an anaerobic zone followed by anoxic and aerobic zones. While a recycle returns aerobic mixed liquor (NR) to the anoxic zone similar to the A^2/O process, 100% of the RAS is returned to the anoxic zone and a second recycle returns anoxic mixed liquor (AR) to the anaerobic zone. Because this anoxic mixed liquor does not contain nitrates (assuming complete denitrification by the anoxic zone), the anaerobic zone is protected from nitrates. Because of the possibility of incomplete denitrification in the anoxic zone, the MUCT process inserts an additional anoxic zone following the anaerobic, to receive 100% of the RAS. The anoxic recycle (AR) instead originates from this first anoxic zone, which is unlikely to contain nitrates (Grady et al, 1999). Figure 2.6 shows a simplified schematic of the UCT and MUCT processes.

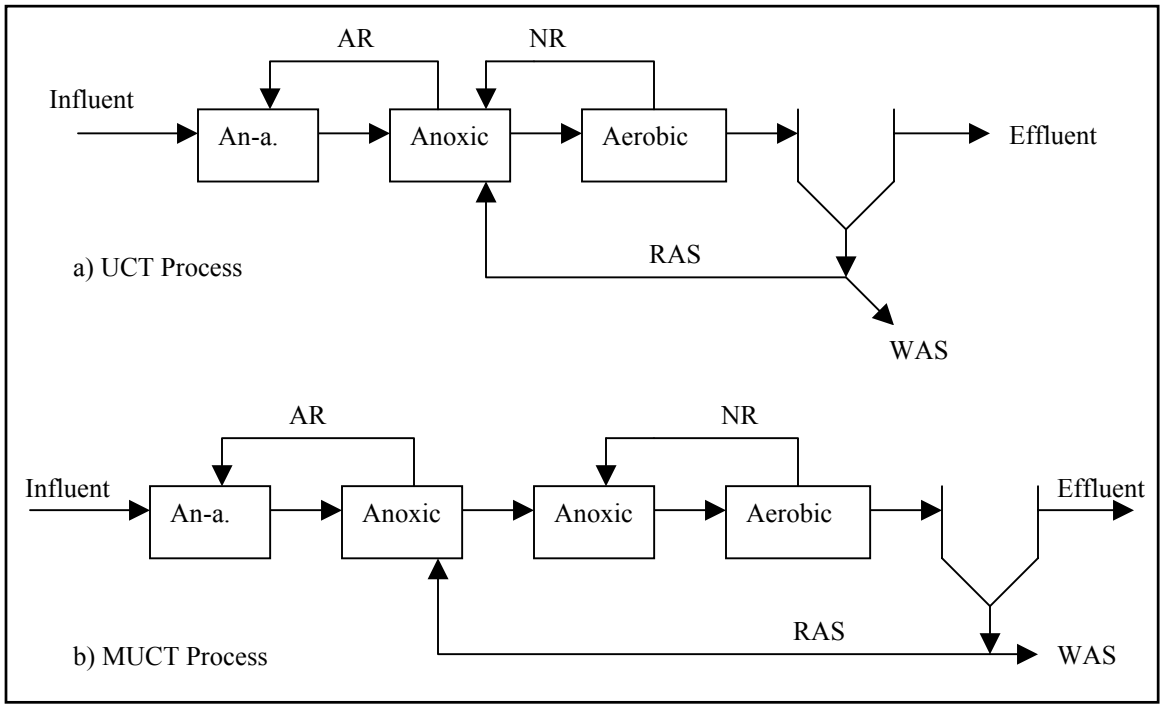

Figure 2.6 - a) UCT and b) MUCT Processes

In recent years the MUCT process has shown limitations since the AR recycles many microbes which have already utilized their polyphosphate back to the anaerobic zone (personal communication, Wentzel, 2003). In addition, bulking and other problems occur (personal communication, Oleskiewicz, 2003). Thus the UCT is preferred over the MUCT.

Several other biological processes have been developed and successfully implemented; however, there have been no previous studies on splitting the RAS between the anaerobic and anoxic zones.

2.4 EBPR Computer Modeling

The complexity of wastewater treatment processes has increased from carbon removal to include nutrient (N and P) removal by creating the conditions for nitrification,

denitrification and EBPR. Advances in understanding the theory behind the biological reactions that take place in wastewater treatment systems has allowed development of computer based programs with models that predict the performance of the treatment systems. The first model to be widely used was the Activated Sludge Model No. 1 (ASM1) produced by the International Association on Water Pollution Research and Control (IAWPRC). The ASM1 model incorporated carbon removal, nitrification and denitrification, but did not include biological P removal (Barker, and Dold, 1997). The ASM1 model was later revised to include the effects of PAOs and was called the ASM2 model. Although the ASM2 model excluded the effects of PAO growth in the anoxic zone, it was later determined that P uptake can take place simultaneously with P release when VFAs are available under anoxic conditions. In both cases, the relative rates of each process determine whether a net P uptake or P release is observed in the anoxic zone (Barker et al., 1997). The models use a series of switching functions and individual reaction rate expressions to model kinetic behavior for each reaction process. The defined stoichiometry and kinetic relationships are used to model the system.

One of these individual processes models the uptake of VFAs in the anaerobic zone, which is assumed to be zero order with respect to the VFA concentration and first order with respect to the PAO concentration. The switching functions that regulate P release turn off the process if either VFAs or the PAO population is small (Barker et al., 1997). The importance of this individual process to biological P removal, suggests that the anaerobic zone should contain a significant mass fraction and therefore brings into question the performance of a system that does not return all the available RAS to the anaerobic zone.

The University of Cape Town produced a family of dynamic models, one of which is called UCTPHO, which includes both N and P removal processes (Haas, Wentzel, Ekama, 2001a). Another computer model that has become widely used is BioWin, which originated mainly from models developed by the University of Cape Town and the International Water Association (IWA), and is commercially available from Envirosim & Associates, Canada (Haas, and Wentzel, 2002a). In addition to the biological processes that take place in wastewater treatment, the model incorporates other unit operations such as grit removal, primary sedimentation, and secondary sedimentation among others. BioWin makes use of considerably more processes and is therefore more complex that the ASM2 and UCTPHO models, which can lead to difficulties in calibrating and using the computer software (Haas et al., 2002a).

BioWin uses default settings for the processes unless the user modifies them; however, the first version of the program was shown to have several deficiencies with these settings, which were later updated and made part of the second BioWin version. BioWin continues to evolve from version to version. It has been shown that the default settings in the older versions of BioWin over predicted denitrification rate which can lead to under designed anoxic zones and internal recycle flows (Haas, and Wentzel, 2002b).

Comparisons of UCTPHO and BioWin running identical wastewater treatment configurations and influent characteristics have demonstrated that there are significant differences in the predictions of both models, often between 1 and 3 mg/L as N or P for effluent nitrate and phosphorous, respectively (Haas et al., 2001a). In all three models that include both biological N and P removal (ASM2, UCTPHO and BioWin models) the interactions between the processes that take place become complex and may be highly

sensitive to the default or user defined settings (Haas et al., 2001a). EBPR systems that operate with un-fermented influent wastewater generally require a higher anaerobic volume for adequate fermentation and significant VFA production. Both UCTPHO and BioWin include fermentation as a process, however, UCTPHO uses a simplified approach (first order reaction that is 100% efficient), while BioWin uses a Monod-type relationship that allows COD loss to other processes (Haas et al., 2001a).

Another significant difference between both models is that BioWin, unlike UCTPHO, includes denitrification by the PAO population. The PAOs in BioWin can therefore uptake P in both the aerobic and anoxic zones, while in UCTPHO the PAOs do not uptake P in the anoxic zone (Haas et al., 2001a).

CHAPTER III: RESULTS AND DISCUSSION

3.1 Pilot Test Technical Paper

3.1.1 Introduction

Enhanced Biological Phosphorous Removal has successfully reduced effluent phosphorous levels in many WWTFs; however, the ability to do so has not been adequately studied when 100% of the RAS flow is not available to the anaerobic zone. Most widely accepted EBPR configurations return 100% of the available RAS to an anaerobic zone, with a hydraulic retention time as high as two hours for adequate fermentation and phosphorous release by the polyphosphate accumulating organism (PAOs) (Randall, Barnard, and Stensel, 1992). Nevertheless, when retrofitting existing WWTFs that were not originally designed to have an anaerobic zone, hydraulic and budget limitations can make it difficult to install the necessary RAS piping and anaerobic volume to implement a typical EBPR system.

In the City of Lakeland, Florida, the Glendale WWTF was originally constructed in 1926 and is currently operating as a conventional activated sludge facility with primary clarification. It was the City's desire to use an abandoned tank as an anaerobic zone to implement EBPR at this facility. However, not only was the volume of this proposed anaerobic tank small compared to conventional EBPR systems (hydraulic retention time of 1.08 hours at average flows), but piping limitations only made it financially feasible to

return 40% of the RAS to the proposed anaerobic tank from two of the secondary clarifiers. In addition, during clarifier downtime the available RAS for the anaerobic tank could be as low as 25%.

It was uncertain if EBPR would take place and reduce phosphorous concentrations to acceptable levels (1.0 mg/L-P) with the reduced RAS flow rates and the smaller than typical anaerobic zone volume. The City elected to perform a pilot test study to investigate these issues and study how various operational parameters could affect overall full scale EBPR performance.

3.1.2 Methodology

3.1.2.1 Wastewater

The wastewater used in this study was from the Glendale Wastewater Treatment Facility in Lakeland, Florida, a strong and septic domestic wastewater with a significant industrial component. Average influent wastewater concentrations were 1,100 mg/L TCOD, 45 mg/L TKN, 15 mg/L TP, and 500 mg/L $TCBOD_5$. The influent wastewater was highly fermented with VFA concentrations averaging 160 mg/L, and sometimes as high as 320 mg/L. The influent wastewater was diluted at various stages during the study to reduce the concentrations to the design strength (based on a 358 mg/L BOD_5) when pilot flows were increased to simulate ultimate design capacity. At the time of the study the influent wastewater strength to the facility was approximately 40% stronger than design based on the permitted BOD_5. Because the pilot systems were fed from different tanks that were sometimes re-filled with wastewater on different days, the influent characteristics were not identical between systems during the same phase.

3.1.2.2 Study Operation and Experiments

Three identical parallel BNR pilot plants (P1, P2 and P3) installed at the WWTF in question, were fed with primary clarifier effluent from the full scale WWTF, and operated with varying RAS flow rates, anaerobic volumes, and influent flow rates (average daily or maximum daily flow, i.e. ADF or MDF). For much of the study, P2 operated as a Phorodox system (i.e. with 100% RAS return to the anaerobic zone), in effect acting as a control for studying the effects of splitting RAS between the anaerobic and anoxic zones. The pilot plants were seeded with mixed liquor from the full-scale process and the systems were fed continuously using peristaltic pumps. Sludge was manually wasted from the aeration tanks daily to maintain the desired Solids Retention Time (SRT), which was varied through the testing phases. The tanks were mixed with small gear motors, except the aeration reactors which were mixed and aerated with the air bubbles created by fish tank air blowers and fine stone air diffusers.

The flow rates used during the study were based on the full scale WWTF design of 13.7 mgd Average Day Flow (ADF) and 18.5 mgd Maximum Day Flow (MDF), which correspond to the pilot test scale flows of 116 L/day and 158 L/day, respectively. Influent wastewater was pumped from an influent tank into the first of four anaerobic tanks connected in series with a combined total anaerobic volume of 7.22 L (1.5 hours HRT at ADF). The first anaerobic tank in all three systems was the smallest with 1.31 L, while the following three anaerobic tanks were 1.97 L each. Piping was installed to by-pass one of the anaerobic tanks reducing the anaerobic volume to 5.25 L (1.08 hours HRT at ADF). The anaerobic tanks were followed by one anoxic tank with a 7.7 L

volume (1.6 hours HRT at ADF), followed by a 24.3 L aerobic zone (5.0 hours HRT at ADF). Due to the difficulty of maintaining a specific dissolved oxygen (DO) level in small-scale reactors, the aerobic zone was vigorously aerated to maintain a dissolved oxygen concentration (4.0 mg/L or greater) that would ensure adequate aerobic conditions. A 20 L clarifier returned part of the RAS to the first or second anaerobic tank and the rest to the anoxic tank. The total RAS flow rate was maintained at approximately 75% of the influent flow (86 L/day), but was adjusted as required to maintain an adequate secondary sludge blanket level in the clarifiers (but was always the same for the parallel systems). The NARCY flow was set at four times the influent flow of 460 L/day, pumping mixed liquor to the anoxic zone. A total of eight tanks (from the first anaerobic to the effluent holding tank) made up each pilot test system. A tank numbering system was used where the first number is the pilot test system (1, 2, or 3) and the second the tank number (1 thru 8). For example, P2-3 is tank 3 of system 2, and PX-3 refers to tank 3 of all systems. Figure 3.1.1 shows a process schematic of the three pilot test systems.

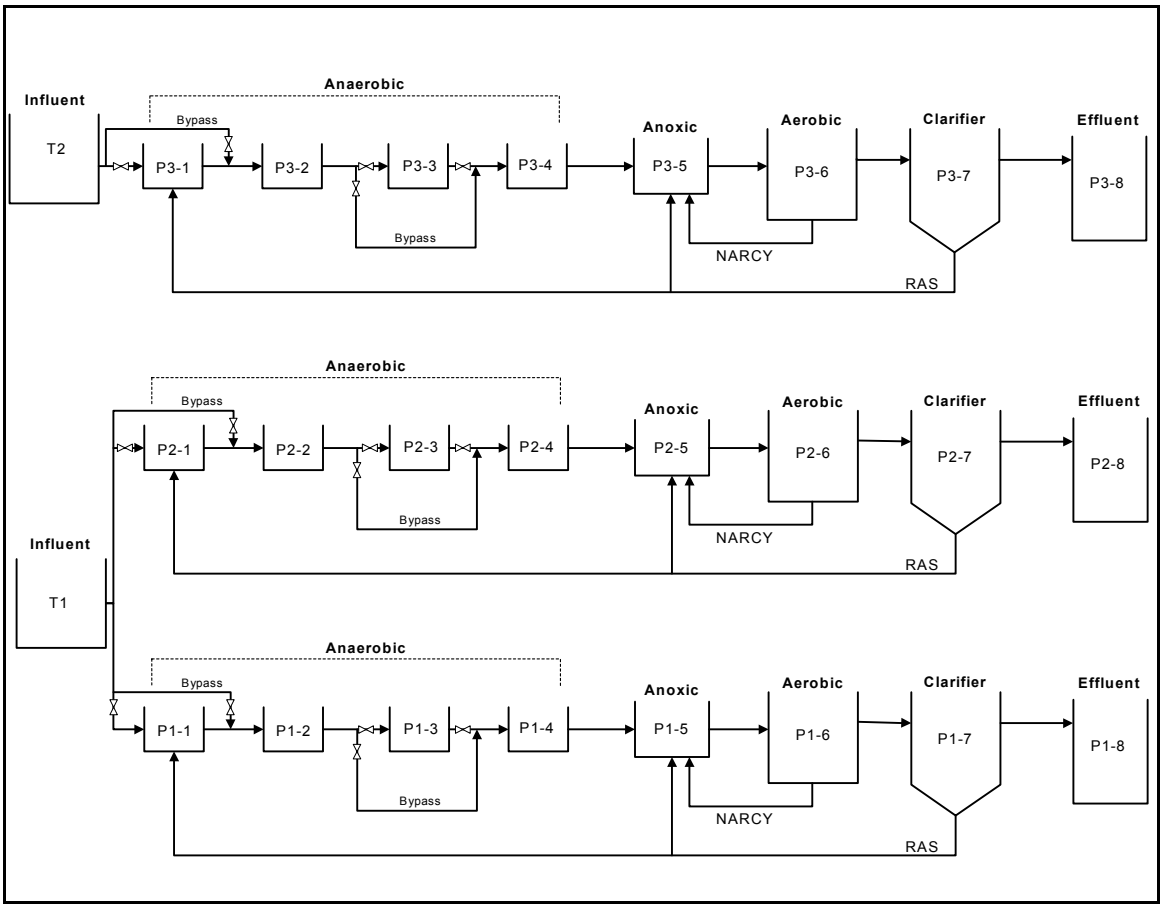

Figure 3.1.1 – Pilot Test System Process Schematic

The three pilot plants were operated with one distinct variable changed between any two systems, and the study was divided into four main phases each designed to answer specific questions. Table 3.1.1 shows the phase breakdown and the parameters varied between the phases and systems.

Table 3.1.1 – Pilot Test Phase Summary

		Simulated Flowrate			Simulated Influent Dilution			% RAS to Anaerobic Zone			Anaerobic Reactors Online			Influent to P-1 or P-2			Actual Aerobic SRT; Temperature		
		P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
Phase 1	**MDF at present wastewater concentrations; RAS split and high hydraulic loading (MDF) also studied.**	ADF	ADF	MDF	No Dilution	No Dilution	Dilution for Infiltration Event (74%WW)	50%	100%	50%	3	3	3	Influent piped to P-1			4.9 days, 17 deg C		
Phase 2A	**Nitrification (SRT) Study Phase;RAS split also studied.**	ADF	ADF	Full Scale Flowrate (7.3 MGD)	Dilution to Lower BOD (62%WW)	Dilution to Lower BOD (62%WW)	No Dilution	50%	100%	N/A	3	3	0	Influent piped to P-1			2.7 to 3.0 days; 22 to 23 deg C		
Phase 2B		ADF	ADF	Full Scale Flowrate (7.3 MGD)	Dilution to Lower BOD (62%WW)	Dilution to Lower BOD (62%WW)	No Dilution	50%	100%	N/A	3	3	0	Influent piped to P-1			4.9 to 5.5 days; 21 to 22 deg C		
Phase 2C		ADF	ADF	Full Scale Flowrate (7.3 MGD)	Dilution to Lower BOD (62%WW)	Dilution to Lower BOD (62%WW)	No Dilution	50%	100%	N/A	3	3	0	Influent piped to P-1			5.7 to 6 days; 26 deg C		
Phase 3	**Endogenous denitrification of RAS; Anaerobic volume and MDF also studied.**	ADF	ADF	MDF	Dilution to Lower BOD (62%WW)	Dilution to Lower BOD (62%WW)	Dilution to Lower BOD and for Infiltration Event (46%WW)	50%	50%	50%	3	4	4	Influent by-passed to P-2			6 to 6.1 days, 27 deg C		
Phase 4	**RAS split studied (assuming higher anaerobic volume)**	ADF	ADF	ADF	Dilution to Lower BOD (62%WW)	Dilution to Lower BOD (62%WW)	Dilution to Lower BOD (62%WW)	50%	25%	40%	4	4	4	Influent piped to P-1			6.2 to 6.4 days; 29 to 30 deg C		

3.1.2.3 Phase 1

The systems ran for eight weeks during this first phase of operation. The objectives of this phase were to ensure there were no inhibitory compounds in the

wastewater that would prevent EBPR from taking place, study the effect of reduced RAS flow to the anaerobic zone, and study the effect of a peak flow event on EBPR.

Phase 1 tests were performed by operating P1 and P2 at the scaled down ADF (116 L/day), and P3 at the scaled down MDF (157 L/day). Systems P1 and P2 were fed with primary clarifier overflow and P3 was fed with diluted primary clarifier overflow (74% wastewater + 26% tap water) to represent the wastewater strength during peak flow infiltration events. Only 50% (43 L/day) of the available RAS was pumped to the anaerobic zone and the remaining 50% to the anoxic tanks in systems P1 and P3, while P2 was operated with 100% RAS to the anaerobic zone. In all three systems, during this phase only three of four anaerobic tanks were used with an effective anaerobic volume of 5.25 L. The average SRT during Phase 1 was 4.5 days (similar to the full scale plant's minimum SRT range) and the average temperature, which was not controlled, was 21°C.

3.1.2.4 Phase 2

This Phase was subdivided into three sub-phases (2A, 2B, and 2C) lasting 5, 3 and 3 weeks respectively. Because of an unexpected lack of nitrification observed during Phase 1, the Phase 2 objectives were to verify that the pilot test systems would indeed nitrify in a manner comparable to the full scale system, study the SRT required for complete nitrification, and determine the relative effect on the efficiency of EBPR of piping 50% vs. 100% of the available RAS to the anaerobic zone.

Phases 2A, 2B, and 2C were operated at 3.0, 4.5 and 6.0 days SRT and the average temperatures were 23°C, 22°C, and 26°C, respectively. The influent flow rate into systems P1 and P2 was representative of the design ADF, and system P3 was

operated at HRTs identical to the current full scale process flow rate (7.3 MGD or 65 L/day). Nitrification probably did not occur in the pilots during Phase 1 because of the low average temperatures (16.9°C) and the low SRT. Nitrification did occur at full scale but it was later found that the full scale SRT had been underestimated, and thus the pilot SRT was lower than the full scale plant. Other differences that may have contributed to the lack of nitrification was the use of the high strength (581 mg/L BOD_5) influent wastewater with the ultimate design flow rates, resulting in organic loadings greater than the ultimate design maximum. As a result, the influent wastewater in Phase 2 systems P1 and P2 was diluted to 62% wastewater to lower the strength to the design levels (358 mg/L BOD_5), and the influent was not diluted for system P3 (since it simulated present flows which were much lower). The pH was not suspected to be a cause of nitrification problems since it was within the acceptable range for nitrifiers. Additional aeration was also provided to assure adequate DO levels (> 4 mg/L) were present at all times.

Only 50% (43 L/day) of the available RAS was pumped to the anaerobic zone and the remaining 50% to the anoxic tanks in system P1, while P2 was operated with 100% RAS to the anaerobic zone. Systems P1 and P2 used three anaerobic reactors with a total volume of 5.25 L, while system P3 did not have any anaerobic zones on-line since it was replicating the current full scale process to study the full scale nitrification-denitrification instead of studying EBPR. The results from P3 during Phase 2 are not included in this paper, as they did not provide information on EBPR performance.

3.1.2.5 Phase 3

The systems ran for three weeks during this phase. The objectives of this phase were to study the effects of using the first tank as an endogenous RAS denitrification zone instead of an anaerobic zone, continue to study the effect of reduced RAS flow rates to the anaerobic zone, continue to study the effect of maximum day flow, and study the effect of increased anaerobic zone volume.

The influent flow rate into systems P1 and P2 was maintained at ADF and the wastewater was diluted to 62% wastewater to simulate the design wastewater strength of the WWTF. The influent flow rate into system P3 was the equivalent of MDF and the wastewater was diluted to 46% wastewater to simulate the design wastewater strength of the WWTF during an infiltration event. All three systems were operated at 50% of the available RAS pumped to the first anaerobic zone, while the influent was bypassed to the second anaerobic zone to create an endogenous RAS denitrification zone in the first anaerobic tank. Excluding the first anaerobic tank that was used as a denitrification zone, system P1 used two anaerobic zones with a volume of 3.94 L, and systems P2 and P3 used three anaerobic zones with a 5.91 L anaerobic volume each. The SRT of all three systems was maintained at 6 days and the average temperature was 27°C.

3.1.2.6 Phase 4

This last phase of the study lasted three weeks and the systems were operated to study the effect of reduced RAS flow rates to the anaerobic tanks. Specifically, systems P1, P2 and P3 were operated with 50%, 25%, and 40% of the available RAS, respectively. All three systems were operated at the equivalent of the ADF, the

wastewater was diluted to 62% wastewater to simulate the actual WWTF design wastewater strength, and all four anaerobic tanks were used with an anaerobic volume of 7.22 L each. The SRT was maintained approximately at 6 days and the average temperature was 29 to 30°C.

3.1.2.7 Analysis

Samples were taken from all tanks in the systems (26 sampling points) two times per week. A portion of each sample was filtered, preserved with sulfuric acid and stored in a refrigerator until tested by a Nutrient Auto Analyzer model FS3000 (OI Analytical, College Station, Texas), generally within a four day period. The parameters measured were Total Suspended Solids (TSS), Volatile Suspended Solids (VSS), Total Carbonaceous Oxygen Demand (TCOD), Soluble Carbonaceous Oxygen Demand (SCOD), ammonia, Total Kjeldahl Nitrogen (TKN), Soluble Kjeldahl Nitrogen (SKN), nitrite/nitrate, Soluble Ortho Phosphorous (SOP), and Total Phosphorous (TP). Measurements such as temperature, pH, dissolved oxygen (DO), ex-situ oxygen uptake rate (OUR), sludge settling tests, and oxygen reduction potential (ORP) were collected from the appropriate system locations. Analysis in each case was conducted according to Standard Methods for Water and Wastewater Treatment (APHA, 1995).

Because of several operational difficulties encountered throughout the pilot testing period (i.e. clogged piping, pump malfunction, mixer failure, etc.), the laboratory data collected was scrutinized to eliminate data points that were considered unreliable for the analysis. In addition, only a few of the results from Phase 1 were used for the analysis, because most data points were not representative due to a lack of nitrification in

all three systems. It is well known that EBPR performance is highly susceptible to nitrates when these are pumped to the anaerobic zone with the RAS (Randall et al., 1992), and therefore studying a non-nitrifying system did not represent the full scale nitrifying process.

Because scaled down clarifiers are not representative of full scale systems, the data used for the analysis was calculated without the effect of the clarifier (aerobic SOP used instead of effluent SOP) to study the performance of the biological process alone.

3.1.3 Results and Discussion

The results discussed in this section were observed during the active pilot testing period and were used as a basis to make operational modifications. A summary of the results and associated mass balance calculation results are presented in Table 3.1.2 for the three pilot test systems.

Table 3.1.2 – Summary of Results

	Phase 1			Phase 2A		Phase 2B		Phase 2C		Phase 3			Phase 4		
Pilot Test System (P1, 2, 3)	P1	P2	P3	P1	P2	P1	P2	P1	P2	P1	P2	P3	P1	P2	P3
Influent Flow (L/day)	107	106	152	114	99	121	119	123	122	116	109	147	115	116	111
RAS flow to Anaerobic (L/day)	42	84	81	43	87	43	86	44	89	43	43	43	50	25	40
Influent TP (mg/L-P)	14.4	14.4	10.3	9.0	9.0	8.6	8.6	15.7	15.7	12.0	12.0	7.0	17.2	17.2	20.5
Aerobic SOP (mg/L-P)	0.1	0.1	0.2	0.2	1.5	0.1	0.3	0.2	0.5	2.2	3.2	1.0	1.5	1.9	1.1
Net P Removal w/o clarifier (mg/L-P)	14.3	14.3	10.1	8.5	7.5	8.5	8.3	15.5	15.2	9.9	8.8	6.0	15.7	15.3	19.3
Total P Loading (mg/day-P)	1540	1529	1529	996	894	1040	1019	1929	1914	1390	1311	1033	1973	1989	2277
Mass of P Removed due to EBPR (mg/day-P)	779	701	944	504	347	532	569	1459	1467	830	668	536	1305	1285	1665
Total Anaerobic P Release (mg/day-P)	5301	17797	2991	2032	2739	6008	6245	6309	7352	4232	5116	7857	9397	7866	12489
Anoxic P Uptake (mg/day-P)	-2198	7428	-6614	-7084	-5795	33	1329	734	2668	911	672	2024	-229	-1910	-2237
Aerobic P Uptake (mg/day-P)	9282	12055	11320	10115	9367	7044	5900	7499	6527	4525	5462	6793	11594	11723	17293
Total P Release (mg/day-P)	7499	17797	9605	9115	8534	6008	6245	6309	7352	4232	5116	7857	9626	9776	14726
Total P Uptake (mg/day-P)	9282	19482	11320	10115	9367	7077	7229	8232	9195	5435	6133	8817	11594	11723	17293
P-uptake / P-release	1.24	1.09	1.18	1.11	1.10	1.18	1.16	1.30	1.25	1.28	1.20	1.12	1.20	1.20	1.17
Net P Removal (mg/day-P)	1783	1684	1715	1000	833	1069	985	1924	1843	1203	1017	959	1969	1948	2567
Percent P of MLSS	4.7	4.3	6.0	4.8	4.3	4.8	5.4	9.9	11.1	8.4	7.6	5.8	8.4	8.4	10.2
Aerobic Ammonia (mg/L-N)	16.3	14.8	13.8	9.2	10.4	2.9	6	0.1	0.3	0.1	0.1	0.1	0.1	0.2	0.7
Nitrification (mg/day-N)	37	102	11	409	148	1453	896	2004	2132	1471	1530	1695	2053	2259	2912
Anoxic NOx (mg/L-N)	0.07	0.02	0.02	0	0	0.05	0.03	0.48	0.59	2.16	2.34	1.45	1.73	0.23	0.43
Aerobic NOx (mg/L-N)	0.13	0.02	0.04	0.6	0	2.23	1.38	3.47	3.77	4.38	4.68	3.9	4.77	3.57	4.77
Effluent NOx (mg/L-N)	0.1	0.17	0.02	0.5	0.2	1.8	1.18	2.7	2.9	3.62	4.08	3.34	3.8	2.73	3.2
Anaerobic Denit (mg/day-N)	2	13	0	83	73	100	122	116	246	154	173	141	198	76	133
Anoxic Denit (mg/day-N)	22	71	7	307	105	1072	618	1398	1354	751	800	935	1223	1698	2098
Anox SDNR (mgN/mgVSSday)	0.0005	0.0014	0.0002	0.0223	0.0087	0.0386	0.0264	0.0503	0.0527	0.0346	0.0413	0.0416	0.0372	0.0491	0.0635
Influent TCOD	1008	1008	587	609	615	615	615	620	620	439	439	383	881	881	994
Influent TCOD:TP	70.0	70.0	57.0	69.2	68.3	71.5	71.5	39.5	39.5	36.6	36.6	54.7	51.2	51.2	48.5
Yield (mgVSS/mgCOD)	0.43	0.63	0.49	0.81	0.48	0.57	0.51	0.65	0.56	0.58	0.58	0.74	0.62	0.59	0.52
Aerobic SRT (days)	5.09	4.95	4.66	2.56	2.55	5.04	4.97	5.75	5.68	5.92	5.95	5.88	6.00	6.40	6.17
Aerobic MLSS (mg/L)	6813	7218	4893	2132	1823	4505	3735	4540	3880	3288	3110	3708	5287	5550	5360
Anaerobic Mass Fraction (%)	10.4	24.0	13.2	9.5	14.9	9.3	14.7	9.4	14.5	17.6	17.3	18.1	13.9	8.6	11.5
Temperature (C)	16.7	17.2	16.9	22.2	22.7	22.2	22.9	25.6	25.6	27.0	27.2	26.8	29.3	28.9	28.8

3.1.3.1 Reduced RAS Study

Data from Phases 1, 2, and 4 were compared for this analysis. The most notable feature of the RAS analysis data is how similar the net performance of the processes was when the RAS split was varied (from 25% to 100% to the anaerobic zone) between the anoxic and anaerobic zones. Although the net phosphorous removal was very similar in all phases, except Phases 2A and B, the process zone where phosphorous release and uptake occurred generally varied. Table 3.1.3 presents a summary of the results compared and Figure 3.1.2 shows a graphical representation of the RAS split effect on system P release and uptake.

Table 3.1.3. RAS Split Comparisons

Parameter	Phase 1		Phase 2A		Phase 2B		Phase 2C		Phase 4		
Pilot System	P2	P1	P2	P1	P2	P1	P2	P1	P2	P3	P1
Percent RAS to anaerobic zone	100%	50%	100%	50%	100%	50%	100%	50%	25%	40%	50%
Total Anaerobic P Release (mg/day-P)	17797	5301	2739	2032	6245	6008	7352	6309	7866	12489	9397
Anoxic P Uptake (mg/day-P)	7428	-2198	-5795	-7084	1329	33	2668	734	-1910	-2237	-229
Aerobic P Uptake (mg/day-P)	12055	9282	9367	10115	5900	7044	6527	7499	11723	17293	11594
Total P Release (mg/day-P)	17797	7499	8534	9115	6245	6008	7352	6309	9776	14726	9626
Total P Uptake (mg/day-P)	19482	9282	9367	10115	7229	7077	9195	8232	11723	17293	11594
P-uptake / P-release	1.09	1.24	1.10	1.11	1.16	1.18	1.25	1.30	1.20	1.17	1.20
Net P Removal (mg/day-P)	1684	1783	833	1000	985	1069	1843	1924	1948	2567	1969
Percent P of MLSS	4.3	4.7	4.3	4.8	5.4	4.8	11.1	9.9	8.4	10.2	8.4

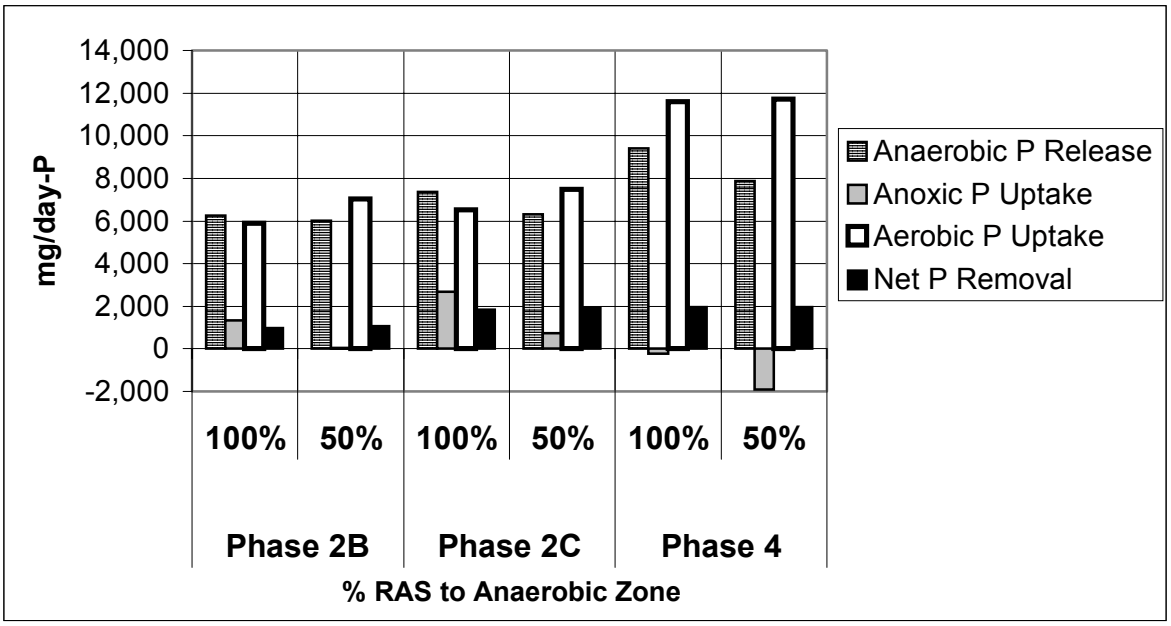

Figure 3.1.2 - % RAS Effect on System P Release / Uptake

In Phase 1, the phosphorous release and uptake may have been artificially high in system P2 due to poor solids distribution, which was partially caused by inadequate anaerobic tank mixing. It is notable that the net phosphorous removal in systems P1 and P2 was almost the same because of a higher phosphorous uptake in P2, particularly in the anoxic zone, which compensated for the higher phosphorous release in the anaerobic zone.

In the other phases, it is also noted that the change in RAS split did not have much effect on the net phosphorous removal or percent phosphorous of the biomass. However, the distribution of phosphorous release and uptake was different between systems. When 50% of the RAS was introduced directly into the anoxic zone, anaerobic P release was lower and anoxic phosphorous release was significantly greater (note anoxic P release is higher in system P1 during Phases 1 and 2, and P2 with 25% RAS also had a higher

anoxic P release when compared to P1 in Phase 4). This resulted in a higher aerobic phosphorous uptake, which compensated for the higher release and resulted in similar net phosphorous removal when compared to the 100% RAS system. Often the total P release and uptake were very similar, and relocating the RAS simply shifted the location of the observed release and uptake.

The observed anoxic P uptake or release depended on the strength of P release in the anaerobic zone. As observed in Phases 1, 2 and 4 (systems P1 and P2), the systems with a smaller anaerobic P release had a higher anoxic P release or lower P uptake. In Phases 1 and 2A, system P1 had a lower anaerobic P release and higher anoxic P release than system P2. This was also the case in Phase 4, systems P1 and P2, where anoxic P release was stronger in P2 (with 25% RAS) than in P1 (with 50% RAS) while the anoxic nitrate concentrations were 0.23 and 1.73 mg/L-N in systems P2 and P1, respectively. In Phase 4, it was observed that the net phosphorous removal and the phosphorous removal due to EBPR were nearly the same when comparing system P2 (25% RAS) and P1 (50% RAS). However, while the total phosphorous release and uptake were virtually identical, the introduction of more RAS (75% in system P2) to the anoxic zone redistributes more of the phosphorous release to this zone, compensated by a greater aerobic zone uptake, resulting in the same net phosphorous removal as system P1. Phase 4 results also show that RAS could be as low as 25% and still maintain EBPR for at least three weeks (the duration of Phase 4).

Redistribution of P release and uptake, with no significant change in net P removal, accompanied the diversion of RAS to the anoxic zone. While it is not known if any bulk liquid VFAs remained unsequestered after the anaerobic zones (i.e. in anoxic

zone influent) it is certain that the other essential substrates, aerobically formed intracellular polyphosphate and glycogen, would have been present in greater abundance in the anoxic zone of system P1 (Phases 1 and 2) or systems P2 and P3 (Phase 4), corresponding to the higher P release/lower P uptake observed. In addition, the flux of polyphosphate and glycogen to the anaerobic zones would have been lower to the systems with low anaerobic RAS rates. Since the anaerobic zones were subdivided it was possible to observe the more rapid SCOD sequestration and P release that accompanied higher RAS return to the anaerobic zone. Table 3.1.4 presents SCOD uptake and SOP release comparisons.

Table 3.1.4. SCOD Uptake and SOP Release Comparisons

			Px-1	Px-2	Px-3	Px-4
Phase 2C	**SCOD (mg/L)**	**P2**	157	149	-	157
		P1	195	158	-	154
	SOP (mg/L-P)	**P2**	36.9	43.3	-	44.2
		P1	34.4	43.8	-	49.4
Phase 4	**SCOD (mg/L)**	**P2**	248	245	179	178
		P3	196	185	217	173
		P1	201	200	215	187
	SOP (mg/L-P)	**P2**	48.6	58.5	65.5	70.6
		P3	69.5	77.5	88.2	98.8
		P1	56	65.7	70.5	69.9

It can be seen that in Phase 2C system P2 had more rapid P release and SCOD uptake in the first anaerobic zone than system P1. The same phenomena can be seen in Phase 4 data where P3 and P1 had more rapid P and SCOD transformation than did P2 which had a 25% RAS to the anaerobic zone. It is likely that VFA/SCOD uptake and P release were polyphosphate and/or glycogen limited in the anaerobic zones of low RAS systems. However, the presence of polyphosphate and glycogen in greater abundance in

the anoxic zone is probably what drove greater anoxic zone P releases when RAS was diverted there. It was notable that net P removals did not change, however, this result was consistent with similar shifts in P release/uptake without net P removal changes observed with prefermentation for P limited wastewaters (McCue et al., in press).

Comparisons with system P3 in Phase 4 were somewhat problematic because the influent phosphorous was over 3 mg/L-P higher due to the variability in the wastewater dilution process (the system was fed from a separate influent tank (T2) than the other two systems). However, the superior performance of P3 could not be explained entirely from the influent phosphorous concentration difference. The pilot test anaerobic zones had just been added for system P3, although EBPR was taking place prior to this addition due to the high organic loadings. Previous work has pointed out that EBPR systems, when first put on line, will display extremely high phosphorous removal for 1 to 3 months and then decline to a more stable phosphorous removal (Randall et al, 1997). This is probably because the PAOs get established quicker than their competitor organisms. However, there was no obvious detrimental effects of operating with a 40% RAS relative to 50% RAS.

A reduction in anaerobic mass fraction is also a consequence of splitting the RAS to the anoxic zone, but this did not seem to harm EBPR even though the anaerobic mass fraction in P1 was 43 to 65% of that in P2. However, the anoxic P release and lower anoxic P uptake observed in system P1 vs. P2, suggests that the higher anoxic mass fraction and receipt of polyphosphate/glycogen rich RAS caused part of it to act as an anaerobic zone. This was observed when the anoxic zone was underloaded with nitrates (complete denitrification: Phase 1, 2A and 2B) or overloaded (Phase 2C and 4). The

anaerobic mass fraction was as low as 9.3%, which should be sufficient for septic wastewater, implying that the partial RAS bypass was not detrimental to EBPR if adequate mass fraction is present for the degree of sepsis of the wastewater. The lower fraction could be an issue in EBPR systems relying on reactor fermentation to produce VFAs and thus needing higher anaerobic mass fractions.

Due to the lack of nitrification in Phases 1, 2A and 2B, data from those Phases was not relevant in assessing the effect of RAS split on nitrogen removal. The systems achieved complete nitrification in Phase 2C, and the results show great similarity in N removal in spite of the RAS split. Complete nitrification was achieved in P1 and P2 (effluent ammonia 0.1 and 0.3 mg/L-N, respectively), and the aerobic nitrate levels were practically the same (3.47 and 3.77 mg/L-N in systems P1 and P2, respectively). However, anaerobic zone denitrification in P2 (246 mg/day-N) was double that in P1 (116 mg/L-N) during Phase 2C. This was because nitrate load to the anaerobic zone was double that for P2 due to the %RAS difference, and this higher nitrate input to P2 may explain why the P1 system was sometimes superior for EBPR. Similarly, in Phase 4, anaerobic denitrification was greater when more RAS was returned to the anaerobic zones in the 25, 40 and 50% RAS systems (76, 133 and 198 mg/L-N in systems P2, P3 and P1, respectively).

3.1.3.2 Anaerobic Volume Study

A direct comparison can be made during Phase 3 between systems P1 and P2, and also an inter-phase comparison can be made for system P1 between Phases 4 and 2C to determine if increasing the existing trickling filter (anaerobic zone) volume would be

beneficial. However, this second comparison is less reliable because there were other variables present. Table 3.1.5 presents a summary of the results obtained. This data suggests that additional anaerobic zone volume may not necessarily improve EBPR performance under current conditions; however, additional volume may be beneficial for operational flexibility to deal with varying flow and loading conditions, particularly if future wastewater is less septic.

Table 3.1.5. Anaerobic Volume Comparisons

Parameter	**Phase 3 (With RAS Denitrification Zone)**		**Phase 4**	**Phase 2C**
Pilot System	**P2**	**P1**	**P1**	**P1**
(Anaerobic Volume)	**(HiVol)**	**(LowVol)**	**(HiVol)**	**(LowVol)**
Actual Anaerobic HRT (hours)	1.30	0.82	1.51	1.03
Anaerobic Mass Fraction	17.3	17.6	13.9	9.4
Net P Removal w/o clarifier (mg/L-P)	8.8	9.9	15.7	15.5
Mass of P Removed due to EBPR (mg/day-P)	668	830	1305	1459
Total Anaerobic P Release (mg/day-P)	5116	4232	9397	6309
Anoxic P Uptake (mg/day-P)	672	911	-229	734
Aerobic P Uptake (mg/day-P)	5462	4525	11594	7499
P-uptake / P-release	1.20	1.28	1.20	1.30
Net P Removal (mg/day-P)	1017	1203	1969	1924
Percent P of MLSS	7.6	8.4	8.4	9.9

The lower volume pilot system in both comparisons had a comparable or superior net phosphorous removal on both a mass and concentration basis. On a mass basis (mass of P removed due to EBPR), and in terms of percent phosphorous of the MLSS, the lower volume systems were superior. The additional anaerobic volume systems had a greater

anaerobic phosphorous release, which is typically proportional to the subsequent aerobic uptake (assuming P release is accompanied by VFA uptake) resulting in a greater removal. However, this was not the case for these systems by observing the phosphorous release and uptake ratios. The low volume systems had significantly higher P uptake/P release ratios averaging 1.29, while the high volume systems averaged 1.20. This was most likely because all the VFAs and other carbon sources, which could be used for EBPR, were taken into the cells very rapidly, and during the additional HRT the organisms continued with secondary phosphorous release to meet metabolic needs. In the additional anaerobic reactor for P2 an additional 6 mg/L-P was released, but only 15 mg/L SCOD was sequestered (a value so low it is arguably greater than zero given the precision of the COD test). This secondary phosphorous release, which is anaerobic phosphorous release not accompanied by VFA uptake, unlike the primary anaerobic phosphorous release, is detrimental to phosphorous removal because the PAOs do not take in VFAs necessary for aerobic P uptake (Randall et al., 1992). It is notable that anaerobic HRTs often approach or exceed 2 hours and have large anaerobic mass fractions even in locations with year-round septic wastewaters. The pilot results bring into question this design practice, especially when flow variability is low or equalization is used. This observation is not new, having been observed in the full scale plant in Kelowna, Canada (Randall et al., 1992).

This implies that over design of anaerobic zones can be detrimental to final effluent quality, and controlling the volume of the anaerobic tank may be of importance. During periods of high organic loading of septic sewage, the reduced anaerobic volume would actually perform better than with the expanded volume. However, this might not

be the case during periods of low organic loading when primary clarifier solids are fed into the anaerobic tank. Hydrolysis of primary solids to soluble, readily degradable COD and then fermentation of VFAs, is a much slower process than uptake of VFAs that come into the plant in septic wastewaters (Randall et al, 1992). In addition, if in the future complex organic molecules found in the influent wastewater were not fermented to VFAs prior to entering the WWTF, the additional volume for fermentation would also be needed.

Nitrogen removal was minimally affected by the anaerobic volume difference. The systems with a smaller anaerobic volume showed slightly better effluent nitrate levels (3.6 vs. 4.1 mg/L-N in Phase 3, and 2.7 vs. 3.8 mg/L-N in Phases 2C and 4, respectively). Effluent ammonia levels were below detectable levels in the four systems compared (0.1 mg/L-N).

3.1.3.3 Increased Hydraulic Loading Study

Relevant MDF comparisons can be made with the Phase 1 data between pilot test systems P3 and P1, and with Phase 3 data between systems P3 and P2. In addition, a third comparison can be made between pilot systems P3 and P1 in Phase 3; however, this comparison is less reliable because the anaerobic zone volume was not the same in both systems. The results indicated that the overall EBPR performance did not significantly deteriorate at MDF with the phosphorous loadings experienced during pilot testing. Table 3.1.6 presents a summary of the results compared.

Table 3.1.6. Hydraulic Loading Comparisons

Parameter	Phase 3			Phase 1	
Pilot System	P3	P2	P1	P3	P1
(Anaerobic Volume; Flow)	(HiVol; MDF)	(HiVol; ADF)	(LowVol; ADF)	(LowVol; MDF)	(LowVol; ADF)
Influent TP (mg/L-P)	7.0	12.0	12.0	10.3	14.4
Aerobic SOP (mg/L-P)	1.0	3.2	2.2	0.2	0.1
Net P Removal w/o clarifier (mg/L-P)	6.0	8.8	9.9	10.1	14.3
Total P Loading (mg/day-P)	1033	1311	1390	1529	1540
Mass of P Removed due to EBPR (mg/day-P)	536	668	830	944	779
Total Anaerobic P Release (mg/day-P)	7857	5116	4232	2991	5301
Anoxic P Uptake (mg/day-P)	2024	672	911	-6614	-2198
Aerobic P Uptake (mg/day-P)	6793	5462	4525	11320	9282
Total P Release (mg/day-P)	7857	5116	4232	9605	7499
Total P Uptake (mg/day-P)	8817	6133	5435	11320	9282
P-uptake / P-release	1.12	1.20	1.28	1.18	1.24
Net P Removal (mg/day-P)	959	1017	1203	1715	1783

The comparison between systems P3 and P2 in Phase 3 is somewhat problematic because the influent TP loadings were significantly different (P2 was 3 mg/L-P higher than P3). Prior to this analysis, the influent TP concentration has generally been directly proportional to the influent TP loading. The most notable result is that the net phosphorous removal was equal for both systems, and the aerobic SOP concentration was lower for system P3 operating at MDF. To understand the data it is also helpful to compare P3 vs. P1 in Phase 1. In this Phase the TP loadings were practically equal, while the influent TP concentration was much lower in P3 due to wastewater being diluted to simulate the infiltration event. In this case the net phosphorous removal on a concentration basis (10.1 mg/L-P) is deceptive. System P3 actually removed the same

amount of phosphorous as P1, and more of it was due to EBPR. This meant that the phosphorous concentration leaving each process was virtually identical. In system P3, which was operating at MDF during Phase 3, the aerobic SOP concentration was lower than system P2, which was operating at ADF. This was most likely because the total phosphorous loading/influent TP concentration was actually lower.

The results seem to indicate that the overall performance of the systems does not significantly deteriorate at MDF if the overall loadings have not changed. However there were once again significant changes in the location where phosphorous release and uptake occurred. The change in phosphorous release between the anaerobic and anoxic zones due to the MDF was not consistent in both Phase 3 and 1. However, there was consistency in that there was greater total phosphorous release, and greater total aerobic phosphorous uptake in the MDF systems vs. the ADF systems. However this did not result in greater net phosphorous removals, and the uptake/release ratios were smaller in the MDF systems.

The nitrogen removal was not significantly different between the two systems in Phase 3, and during Phase 1 there was no nitrification.

3.1.3.4 RAS Denitrification Zone Study

Phase 3 of the pilot test was operated using a portion of the full-scale anaerobic tank as an anoxic zone by bypassing the influent around the first anaerobic tank in all three systems. However, only one inter-Phase comparison can be made for pilot system P1 between Phases 3 and 2C because the pilot test was not designed to isolate and study this factor. As a result, this comparison is less reliable because all parameters were not

identical (variable influent, temperature, etc.). EBPR performance generally decreased during this Phase as a result of creating an endogenous denitrification zone at the head of the anaerobic tank via baffling; however, this likely occurred because the pilot test anoxic volume was too large for the NO_x flux received (3.3 to 4.1 mg/L-N RAS NO_x concentrations). Table 3.1.7 presents a summary of the results compared.

Table 3.1.7. Additional Denitrification Zone Comparison

Parameter	**Phase 3**	**Phase 2C**
Pilot System	P1	P1
(Px-1 as denitrification zone)	(with extra denit. zone)	(without extra denit. zone)
Influent TP (mg/L-P)	12.0	15.7
Aerobic SOP (mg/L-P)	2.2	0.2
Net P Removal w/o clarifier (mg/L-P)	9.9	15.5
Total P Loading (mg/day-P)	1390	1929
Mass of P Removed due to EBPR (mg/day-P)	830	1459
Total Anaerobic P Release (mg/day-P)	4232	6309
P Release in Denitrification Zone (mg/day-P)	2205	N/A
Anoxic P Uptake (mg/day-P)	911	734
Aerobic P Uptake (mg/day-P)	4525	7499
Total P Release (mg/day-P)	4232	6309
Total P Uptake (mg/day-P)	5435	8232
P-uptake / P-release	1.28	1.30
Net P Removal (mg/day-P)	1203	1924
Percent P of MLSS	8.4	9.9

While it is difficult to reach any absolute conclusions, the phosphorous removals and effluent levels during Phase 3 were worse than any phase except during Phase 2A and 2B. In Phase 3, the first anaerobic zone was serving as an endogenous denitrification zone for the RAS stream before it became in contact with the influent in the anaerobic tanks.

However, another critical factor can be observed by referring to Figure 3.1.3 below. All the phases were consistent in that net phosphorous removals were directly

proportional to the influent TP concentrations. In other words, if the influent TP concentration increased, the net phosphorous removals increased. If the influent TP concentration decreased, then the net phosphorous removals decreased.

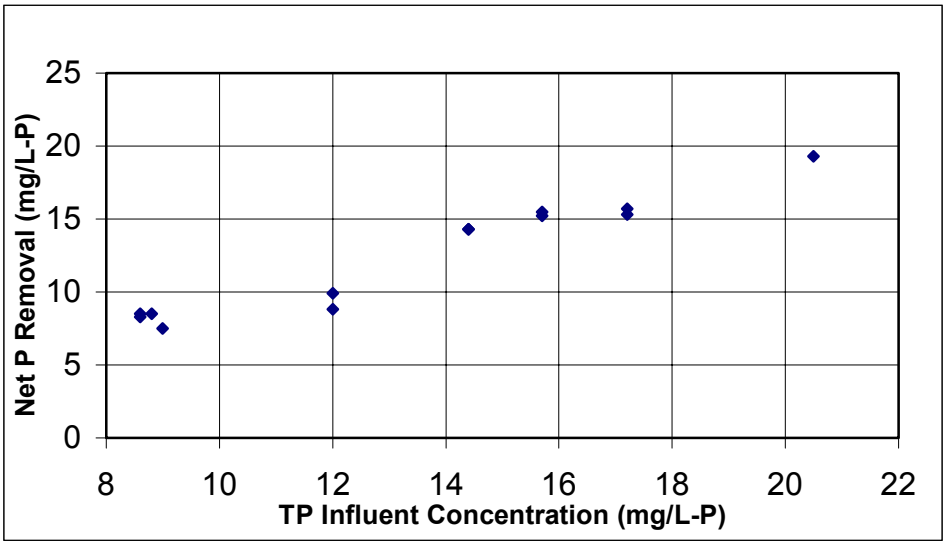

Figure 3.1.3 - Correlation of Net P Removal with Influent TP Concentration

From the figure we can see that while much of the apparent difference in Phase 3 was actually due to a much lower influent TP concentration, part of the effect was apparently due to a detrimental impact of oversizing the denitrification zone. Phase 3 definitely experienced the lowest percent removals in the study. However, it can be seen from the figure that the Phase 3 data points (found above the 12 mg/L-P value on the influent axis) were not that far off of the expected net P removal slope, given their lower influent level, suggesting this detrimental effect was relatively small. This correlation also seems to hold when using the TP loadings instead of the influent TP concentrations.

The detrimental effect was probably a result of the zone being in excess of the requirements for the nitrate flux into the zone, suggesting it is important not to oversize

the first zone of the anaerobic tank if it may also be used as a denitrification zone. The Phase 3 nitrate levels in the RAS denitrification zones were below detection limit for the testing method, or zero for all practical purposes. The clarifier data does show several days when the nitrate levels were elevated and others when it was lower. For example, system P1 had effluent/clarifier nitrates from 1.1 to 8.1 mg/L-N, which would be equal or proportional to the concentrations in the RAS recycle. However, RAS denitrification zone (P1-1) effluent nitrate levels only varied from 0.09 to 0.3 mg/L-N, all of which are so low it is hard to say if they are significantly different from zero. This conclusion is supported by the fact that the high effluent nitrates did not consistently correspond to the high RAS nitrates. Therefore, if there was complete nitrification during sampling events with 8.1 mg/L-N that indicates that there was far more denitrification capacity than required when the RAS nitrates were lower. This means that reactor P1-1 was actually in an anaerobic condition most of the time, which led to significant secondary phosphorous release (2205 mg/day-P in RAS denitrification zone), potentially explaining any decreased phosphorus removals. The data shows that while clarifiers SOPs in Phase 3 varied from 1.8 to 3.9 mg/L, the SOP in the RAS denitrification zones varied from 14.2 to 54.2 mg/L showing considerable secondary P release. To avoid this scenario in a full scale process, it may be beneficial to subdivide the RAS anoxic zone so the volume can be varied according to nitrate levels.

One of the most significant aspects of the figure above showing the correlation of phosphorous removal with influent TP, is that the systems showed the capacity to increase EBPR in response to large increases in influent TP. This was true even when influent TP was as high as 20.5 mg/L-P. At these high influent phosphorus levels the

systems were not able to achieve the desired effluent SOP levels of 1 mg/L-P, and sometimes were above 2 mg/L-P. These results were still a surprising achievement considering the highly elevated influent TP levels experienced, which were fortunately accompanied by very robust increases in phosphorous removals.

3.1.4 Conclusions

The main conclusion for this study is that Enhanced Biological Phosphorous Removal performance was found to be adequate, and sometimes superior, with reduced RAS flows (50% of available RAS) to the anaerobic tank and smaller anaerobic zone volume (1.08 hours HRT). Results also show that overall EBPR performance did not significantly deteriorate at increased hydraulic loadings, at least for this very septic wastewater. The strong EBPR performance observed with these process variations is most likely a result of the highly fermented VFA rich wastewater, requiring a smaller than typical anaerobic zone mass fraction and volume.

When the RAS stream to the anaerobic zone was varied from 100% to 25% and the remaining RAS was pumped to the anoxic zone, similar EBPR performance was observed. In spite of the reduced anaerobic mass fraction, strong phosphorous release was observed, sometimes even higher than when piping 100% of the RAS to the anaerobic zone. Net phosphorous removal was generally similar, however, where phosphorous release and uptake occurred was affected. The systems with a smaller %RAS experienced a lower anaerobic P release but higher anoxic P release (or smaller anoxic P uptake), which suggests that the higher anoxic mass fraction and the

introduction of polyphosphate and glycogen rich RAS caused part of it to carry the function of an anaerobic zone.

Results from the systems operating with different anaerobic volumes show that higher anaerobic zone volume does not necessarily improve EBPR performance. With fermented, VFA rich wastewater, the anaerobic volume should not be oversized since the additional HRT is not necessary for P release and VFA uptake by the PAOs. However, if influent VFA levels are reduced, a larger anaerobic zone may be necessary for fermentation. Anaerobic zone over design may lead the organisms to continue with secondary P release.

In addition to these observations, increases in hydraulic loading to this EBPR system showed phosphorous removal was not affected, suggesting overall performance does not significantly deteriorate at MDF when the overall P loadings were not changed. It may be that high hydraulic loads would upset a system relying on in-reactor hydrolysis and fermentation for VFAs, but high hydraulic loads did not upset EBPR here. This suggests prefermentation for fresh wastewaters might result in a more robust process with respect to hydraulic variations and upsets.

When the first anaerobic zone was used as a RAS denitrification zone with the influent bypassed, a small detrimental effect in EBPR performance was observed. This detrimental effect is suspected to be a result of the zone being in excess of the required denitrification volume. Similar to the previous anaerobic zone volume results, this suggests it is important not to oversize the first anaerobic zone in case it is used as an endogenous RAS denitrification zone. It may be beneficial to subdivide such zones so the volume can be adjusted to match changes in RAS nitrate levels.

In conclusion, this study shows that EBPR may be implemented successfully in the full-scale process with the RAS piping limitations and the reduced available anaerobic volume. To optimize the full-scale operation, process flexibility will be important to improve process performance during periods of reduced influent VFA levels or increased RAS nitrate concentrations. Thus additional anaerobic volume is still important to have in terms of future flexibility and can be made available using adjustable weirs to vary liquid height or having anaerobic zones that can be taken on or off line. However, the RAS piping limitations were acceptable and should not be detrimental to EBPR at the plant. These findings benefit the wastewater treatment community when cost and piping limitations prohibit a typical EBPR system implementation. More cost effective retrofits and more optimized anaerobic zone designs for EBPR systems could result from these findings.

3.2 Computer Modeling Analysis

3.2.1 Introduction

Computer based modeling software for wastewater treatment processes have recently gained popularity and are increasingly being adopted by the wastewater treatment community for research, design, and optimization purposes among others. A common program for wastewater treatment modeling is BioWin, which was developed based on older models written by the University of Cape Town (UCT) and the International Water Association (IWA) (Hass et al, 2002a). A predecessor to BioWin

was UCTPHO, which was developed by the University of Cape Town (Hass et al, 2001b).

A computer modeling analysis was performed with BioWin and UCTPHO to investigate if these wastewater treatment computer models predict the performance observed from the bench scale pilot test systems presented earlier in this study. Both models were used to compare the systems with varying RAS quantities to the anaerobic zone, with additional anaerobic volume, and with increased hydraulic loading. The same influent concentrations were used throughout the analysis, to observe and compare the predicted results of both BioWin and UCTPHO. It was uncertain if the models would predict the results observe din the pilot test and how they would differ from each other.

3.2.2 Methodology

Both computer models were set up with the same configuration, influent wastewater, flowrates, and volumes as the pilot test scale systems. The fraction of influent COD which is readily biodegradable COD (Fbs) and the fraction of readily biodegradable COD which is VFAs (Fac) parameters were set at 0.50 and 0.80, respectively, for BioWin, and 0.61 and 0.80, respectively, for UCTPHO. This difference in Fbs between both models is necessary because BioWin defines Fbs as the fraction of the total influent COD which is readily biodegradable, while UCTPHO defines Fbs as the fraction of influent biodegradable COD which is readily biodegradable COD. Using these wastewater characteristics, both models had the same influent wastewater concentrations as follows: COD = 200 mg/L, TKN = 25 mg/L, TP = 15 mg/L, and Soluble readily biodegradable COD (Sbsa) = 80 mg/L. UCTPHO was run with the

default kinetic data and stoichiometric parameters, while several kinetic and stoichiometric settings were changed in BioWin to match UCTPHO so that the results could be comparable between both models.

The RAS to the anaerobic zone in both models was varied (100%, 50%, 25% and 0% of the available RAS) while the rest was sent to the anoxic zone. Unlike BioWin, UCTPHO does not allow splitting the RAS to two different reactors, therefore, to get around this an additional tank of a negligible volume was created, which received all the available RAS (87 L/day). A recycle from this tank to the anoxic tank was used to control the RAS flow to the second tank (the first anaerobic tank). The influent flow (116 L/day) completely by-passed to the second tank of the system (the first anaerobic tank) (See Figure 3.2.1).

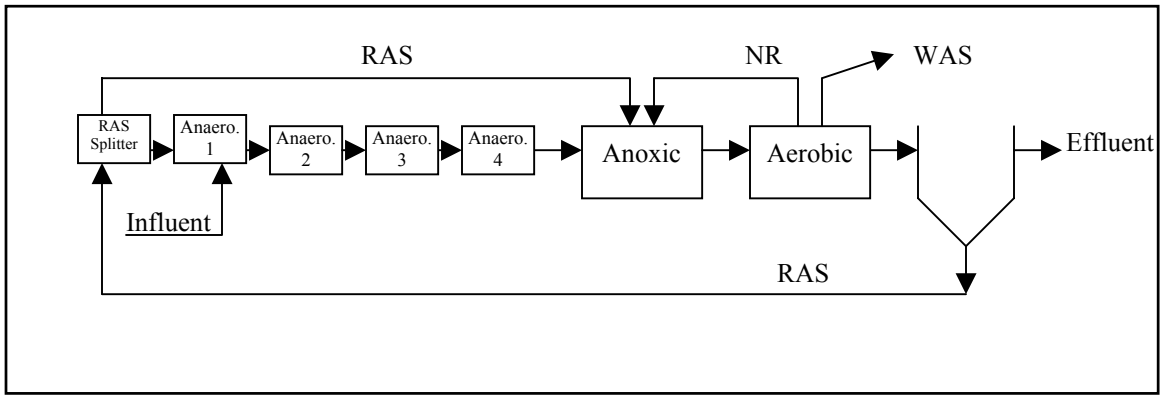

Figure 3.2.1 – UCTPHO Model Simulated

The system set up in BioWin is shown in Figure 3.2.2.

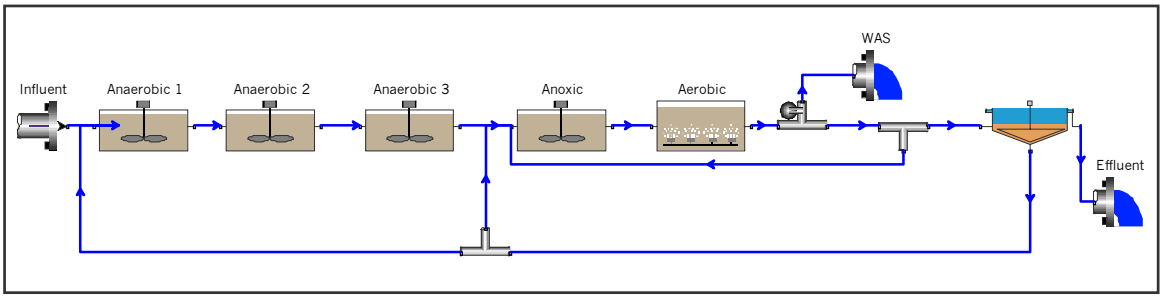

Figure 3.2.2 – BioWin Model Simulated

Although both computer models were set-up similarly, conclusions between model outputs and pilot test data may not be entirely accurate because the computer models use many settings and default values that may not be the same as actual conditions in the pilot test. For this reason, this modeling analysis may lead to more accurate statements and observations when comparing the model's systems relative to each other to investigate if they predict the same trends observed during the pilot test.

Both computer models were also run with the same incremental anaerobic volume (from 1.02 hours to 1.50 hours HRT) as the pilot test systems and compared with 100%, 50%, and 25% RAS to the anaerobic zone. The effects of peak hydraulic loading was studied by increasing the influent flow to the peak flow (157 L/day) modeled with the pilot test system and the influent COD, TKN, and TP concentrations were decreased (148 mg/L, 19 mg/L, and 11 mg/L, respectively) to keep the influent loading levels constant. UCTPHO does not allow specifying the WAS flow and where the WAS is removed from the system. To have comparable systems with respect to solids, the total system SRT was set at 9 days in both models, which typically resulted in aerobic SRTs of approximately 6 days.

The data collected from all the modeling runs was compiled and mass balance calculations were performed to study the results (see Appendix C).

3.2.3 Results and Discussion

The overall results show that both models had small differences in terms of effluent P concentrations and net P removal. The VSS concentrations were similar for both computer models. During the initial runs of BioWin, the VSS levels were observed as high as 8,000 mg/L, but after manipulation of the Fbs and Fac values as described above, the VSS concentrations were more realistic (between 1000 and 4000 mg/L). Using equivalent Fbs and Fac values for both models, BioWin consistently had slightly lower VSS levels than UCTPHO, but in both cases they were within the typical range of values (1000 to 3000 mg/L).

3.2.3.1 RAS % Comparisons

When evaluating the performance of the systems with the % RAS variations, the results from both computer models had many similarities. In general, the most significant conclusion is that the systems with reduced RAS to the anaerobic zone had better overall performance in both BioWin and UCTPHO. In BioWin, the 25% RAS system had the highest anaerobic P release, aerobic P uptake, P uptake/release ratio, total P release, total P uptake, best net P removal, and lowest effluent P, followed by the 50% and 100% RAS systems. See Table 3.2.1 for a summary of the %RAS variation results in BioWin.

Table 3.2.1 - BioWin %RAS Modeling Results

	Units	100%RAS	50% RAS	25% RAS	0% RAS
Total P Loading	mg/day-P	1740.0	1740.0	1740.0	1740.0
Mass of P Removed due to EBPR	mg/day-P	817.4	969.6	1066.5	719.3
Total Anaerobic P Release	mg/day-P	3329.3	3793.4	3908.7	-62.6
Anoxic P Uptake	mg/day-P	1290.6	1462.7	1404.6	-1413.4
Aerobic P Uptake	mg/day-P	3108.2	3568.4	3848.6	2307.8
Total P Release	mg/day-P	3329.3	3793.4	3908.7	1413.4
Total P Uptake	mg/day-P	4398.8	5031.1	5253.2	2370.4
Pup/Prel	-	1.32	1.33	1.34	1.68
Net P Removal	mg/day-P	1069.5	1237.7	1344.4	957.0
Effluent PO4-P	mg/L	5.78	4.33	3.41	6.75

A similar performance was observed with UCTPHO, however, in this case the results are arguably equal for all practical purposes. The 25% RAS system had the highest net P removal, mass of P removed due to EBPR, and best P uptake/release ratio; however, unlike BioWin, the 100% RAS system had slightly stronger anaerobic P release followed by the 25%, and 50% RAS systems. See Table 3.2.2 for a summary of the %RAS variation results in UCTPHO.

Table 3.2.2 - UCTPHO %RAS Modeling Results

	Units	100%RAS	50% RAS	25% RAS	0% RAS
Total P Loading	mg/day-P	1740.0	1740.0	1740.0	1740.0
Mass of P Removed due to EBPR	mg/day-P	1148.7	1194.5	1228.6	1241.4
Total Anaerobic P Release	mg/day-P	4822.7	4789.4	4803.9	-46.4
Anoxic P Uptake	mg/day-P	-712.5	-769.9	-791.1	-5347.9
Aerobic P Uptake	mg/day-P	6904.0	6974.5	7044.9	6763.1
Total P Release	mg/day-P	5535.2	5559.3	5594.9	5347.9
Total P Uptake	mg/day-P	6904.0	6974.5	7044.9	6809.5
Pup/Prel	-	1.25	1.25	1.26	1.27
Net P Removal	mg/day-P	1368.8	1415.2	1450.0	1461.6
Effluent PO4-P	mg/L	3.20	2.80	2.50	2.40

When comparing both computer models, they predicted the main observation from the pilot test that sending a portion of the available RAS to the anaerobic zone does not necessarily decrease EBPR performance for a septic wastewater. Although both models had similar results, the results from the BioWin systems showed a much larger difference between systems than UCTPHO. It can be argued that UCTPHO results were too similar to make any conclusions. A significant difference between both models was that BioWin had anoxic P uptake in all systems (except 0% RAS), while UCTPHO had anoxic P release in all systems with stronger release when 50% RAS was sent to the anoxic zone. This observation in UCTPHO was similar to the pilot test in that sending more RAS to the anoxic zone caused a shift in P release (or reduced P uptake) to the anoxic zone; however, that shift in the anoxic zone was not seen with BioWin. This difference in anoxic P release or uptake behavior between both models agrees with Haas et al, 2001a, in that anoxic behavior by the PAOs is significantly different between both models. Specifically, BioWin includes a denitrifying anoxic PAO growth factor, while

UCTPHO does not (Hass et al, 2001a). This difference is likely what caused the observed anoxic P uptake in BioWin and anoxic P release in UCTPHO. Both anoxic P release and uptake were observed during various phases of the pilot test systems.

When the systems were modeled with 0% RAS to the anaerobic zone, they were essentially operating as a MLE process. Although the nitrate concentration in the anoxic zones was higher than 5 mg/L, analysis of the results from both 0% RAS models show strong anoxic P release followed by aerobic P uptake resulting in the highest P uptake/release ratios and better than expected effluent P concentrations. This extensive P removal observed with a non EBPR system was probably caused by the high influent VFA concentration (80 mg/L in both models). The 0% RAS system in BioWin had the highest P uptake/release ratio, however, it had the worst effluent P concentration. This suggests that although the 25% RAS system had the best performance, at some point between 25% and 0% RAS, P removal is significantly reduced. On the other hand, UCTPHO's 0% RAS system was very similar to the 25% RAS system in terms of P effluent quality. Additional manipulation of the models showed significant deterioration of EBPR when the influent VFA concentrations were decreased.

The EBPR improvement in the systems with less % RAS to the anaerobic zone may be partially explained by looking at the aerobic Zbp, Zba, and Zbh (PAO, autotrophic, and heterotrophic organism population, respectively) values in the BioWin model. Table 3.2.3 shows Zbp, Zba, and Zbh values from BioWin's output.

Table 3.2.3 – Aerobic Zone Microorganism Population

	Zbh (Heterotrophs) (mg/L)	Zba (Autotrophs) (mg/L)	Zbp (PAOs) (mg/L)
100% RAS	452.0	54.6	766.7
50% RAS	425.9	56.7	921.7
25 % RAS	411.9	59.1	1045.2
0 % RAS	565.5	63.3	708.1

These results show that when the anaerobic zones were not utilized (0% RAS), the PAO population was the lowest, while the heterotrophs and autotrophs had the highest populations. The heterotroph population was expected to decrease with more RAS to the anaerobic zone because most of they are not active in this zone; however, the heterotrophs population was significantly low in the 25% RAS system, and then gradually increased in the higher % RAS systems. When less RAS was sent to the anaerobic zone (25% RAS), the PAO population was the highest, which could be the explanation for the stronger EBPR observed. The system PAO total mass was also calculated and it followed the same trend as the aerobic zone with more PAOs with reduced RAS to the anaerobic zone (28.4, 32.5 and 35.5 grams of PAOs in total system for 100%, 50% and 25% RAS, respectively).

Some default settings in BioWin were modified to determine the reason why the PAO population increased when less RAS was sent to the anaerobic zone. The PAO anoxic growth (Neta Anoxic Growth) was increased from 0.0 to 0.4, however, anoxic growth of PAO had negligible effects on the PAO population and effluent P levels. Similarly, the anoxic P uptake per unit PHB utilized for growth (Anoxic P/PHB Upt.) value was decreased from 0.65 to 0.0, however, this also had negligible effect on PAOs. The third parameter varied was the dissolved oxygen (DO) level in the aerobic zone to

evaluate the effect of the aerobic zone on the PAO population, especially when reducing the RAS to the anaerobic zone increases the PAO mass fraction in the aerobic zone. The aerobic DO was reduced from 4 mg/L to 0.2 mg/L and the results are shown in Figures 3.2.3 and 3.2.4 below.

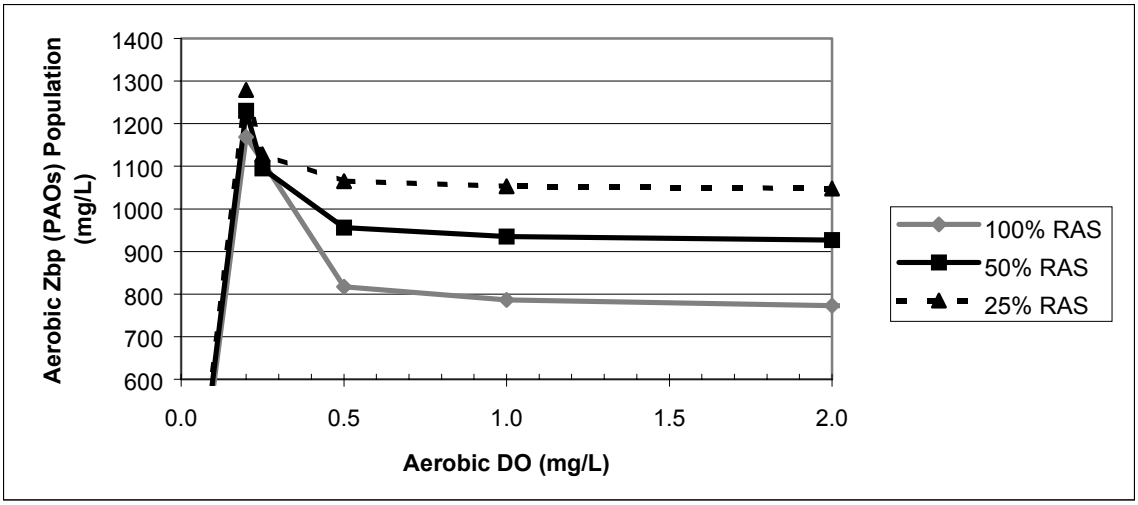

Figure 3.2.3 – Aerobic DO Effect on PAO Population

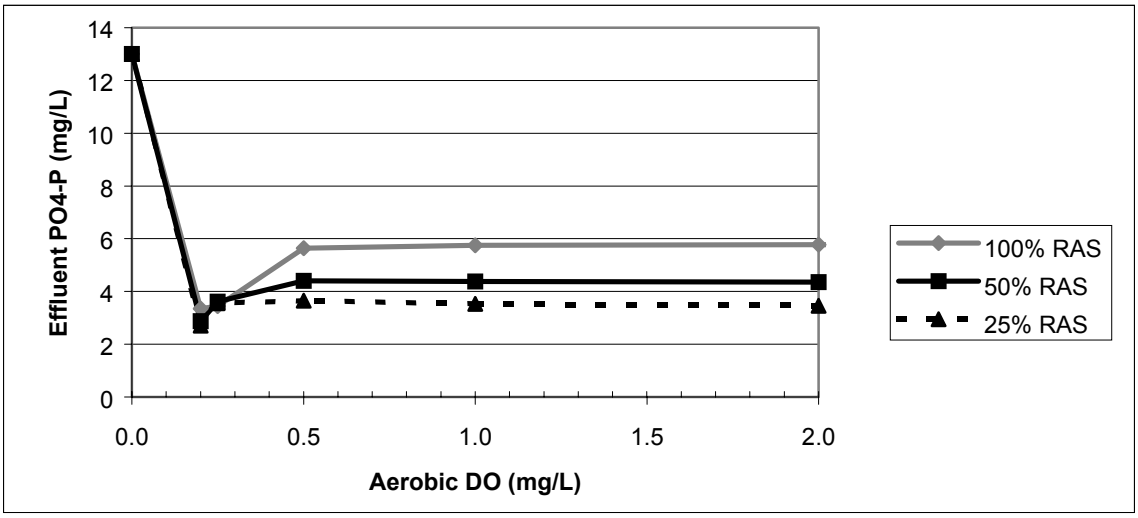

Figure 3.2.4 – Aerobic DO Effect on Effluent P

The PAO population was relatively constant at aerobic DO levels above 0.5 mg/L, however, at DO levels between 0.5 and 0.2 mg/L, the PAO population increased and effluent P levels decreased. At DO levels below 0.2 mg/L, the PAO population was completely lost and EBPR seized to occur. It is also notable that when the aerobic DO was decreased to 0.25 mg/L, the PAO population became almost equal for the three % RAS variations, while at higher DO levels, the PAO population was lower with more RAS to the anaerobic zone. The system PAO total mass was 41.3, 38.6 and 38.2 grams of PAOs in total system for 100%, 50% and 25% RAS, respectively, when the aerobic DO was reduced to 0.25 mg/L. Reducing the DO level in the aerobic zone diminishes the effect of the kinetic relationships in that zone, therefore allowing the aerobic effect on the RAS split to be reduced. This observation suggests that maintaining a higher PAO aerobic mass fraction (as is the case of 50% and 25% RAS) increases the PAO population resulting in better EBPR.

Most likely the EBPR improvement observed with less RAS to the anaerobic zone is caused by the highly septic wastewater. To evaluate this effect, the influent VFA concentration was reduced from by half and also eliminated completely, while maintaining a constant readily biodegradable COD (RBCOD). The results showed that when no VFAs were present, EBPR did not take place. When the VFA levels were decreased by 50%, the difference in EBPR performance at different RAS splits was less apparent. This suggests that below a certain influent VFA level, EBPR will still take place and diverting part of the RAS to the anoxic zone me actually decrease EBPR performance.

These modeling results follow the trend observed by the pilot test in that reduced RAS to the anaerobic zone improved net P removal. See Table 3.2.4 for a relative comparison of reduced RAS systems to the 100% RAS system for both models and two phases of the pilot test.

Table 3.2.4 - Relative %RAS Comparisons

	% RAS	P-Release relative to 100% system (mg/day)	P-Uptake relative to 100% system (mg/day)	Net P Removal relative to 100% system (mg/day)
Pilot Test	50% Ph. 2C	-1043	-963	+81
	50% Ph. 2A	+581	+748	+167
UCTPHO	50%	+24	+70	+46
	25%	+60	+141	+81
BioWin	50%	+464	+632	+168
	25%	+579	+854	+275

As shown in Table 3.2.4 above, both models showed an increment in total P release and P uptake when less RAS reached the anaerobic zone, however, the trend was not consistent during all phases of the pilot test (Phase 2C).

3.2.3.2 Anaerobic Volume Comparisons

There were various performance similarities between both computer models when additional anaerobic volume was made available for the 25%, 50% and 100% RAS systems. Both models with additional anaerobic volume had higher anaerobic P release and higher anoxic P uptake (or lower anoxic P release); however, in both cases the P uptake/release ratio was slightly higher for the lower volume systems. Although there were minor differences when comparing P uptake/release ratios, the net P removal and effluent P levels were usually similar. Observations from the pilot test system showed

similar trends to the models in that increasing the anaerobic volume increases anaerobic P release and aerobic P uptake, but does not necessarily improve EBPR for this septic wastewater. A difference between the pilot test and the modeling results is that the anoxic P uptake in the pilot test was higher for the low anaerobic volume system. See Tables 3.2.5, 3.2.6, and 3.2.7 for the BioWIn, UCTPHO, and pilot test respectively, anaerobic volume comparison results.

Table 3.2.5 - BioWin Volume Comparison Results

		25%	**25%**	**50%**	**50%**	**100%**	**100%**
	Units	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**
Total P Loading	mg/day-P	1740	1740	1740	1740	1740	1740
Mass of P Removed due to EBPR	mg/day-P	1080	1067	966	970	907	817
Total Anaerobic P Release	mg/day-P	4229	3909	3934	3793	3448	3329
Anoxic P Uptake	mg/day-P	1403	1188	1321	1262	1160	1116
Aerobic P Uptake	mg/day-P	4185	4065	3847	3769	3346	3283
Total P Release	mg/day-P	4229	3909	3934	3793	3448	3329
Total P Uptake	mg/day-P	5588	5253	5168	5031	4506	4399
Pup/Prel	-	1.32	1.34	1.31	1.33	1.31	1.32
Net P Removal	mg/day-P	1360	1344	1234	1238	1058	1070
Effluent PO4-P	mg/L	3.28	3.41	4.36	4.33	5.88	5.78

Table 3.2.6 - UCTPHO Volume Comparison Results

		25%	25%	50%	50%	100%	100%
	Units	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**
Total P Loading	mg/day-P	1740	1740	1740	1740	1740	1740
Mass of P Removed due to EBPR	mg/day-P	1228	1229	1171	1195	1114	1149
Total Anaerobic P Release	mg/day-P	4887	4804	4876	4789	4898	4823
Anoxic P Uptake	mg/day-P	-779	-791	-706	-770	-672	-713
Aerobic P Uptake	mg/day-P	7115	7045	6974	6974	6904	6904
Total P Release	mg/day-P	5665	5595	5582	5559	5570	5535
Total P Uptake	mg/day-P	7115	7045	6974	6974	6904	6904
Pup/Prel	-	1.23	1.26	1.25	1.26	1.24	1.25
Net P Removal	mg/day-P	1450	1450	1392	1415	1334	1369
Effluent PO4-P	mg/L	2.50	2.50	3.00	2.80	3.50	3.20

Table 3.2.7 – Pilot Test Volume Comparison Results

		Phase 3 (With RAS Denitrification Zone)		**Phase 4**	**Phase 2C**
		P2	P1	P1	P1
	Units	(HiVol)	(LowVol)	(HiVol)	(LowVol)
Total P Loading	mg/day-P	1311	1390	1973	1929
Mass of P Removed due to EBPR	mg/day-P	668	830	1305	1459
Total Anaerobic P Release	mg/day-P	5116	4232	9397	6309
Anoxic P Uptake	mg/day-P	672	911	-229	734
Aerobic P Uptake	mg/day-P	5462	4525	11594	7499
Total P Release	mg/day-P	5116	4232	9626	6309
Total P Uptake	mg/day-P	6133	5435	11594	8232
Pup/Prel	-	1.20	1.28	1.20	1.30
Net P Removal	mg/day-P	1017	1203	1969	1924
Effluent PO4-P	mg/L	3.2	2.2	1.5	0.2

As in the bench scale pilot test, the anaerobic volume in the computer models was increased by adding a fourth anaerobic tank of 1.97 L to the system, which allowed direct evaluation of its performance. In both models, the soluble P concentration in the

anaerobic tank series generally increased from 14.5 mg/L-P to values approximately between 28.3 and 48.5 mg/L-P by the third or fourth anaerobic tanks depending on the % RAS to the anaerobic zone. Generally 75 % of the P release was observed in the first anaerobic tank with decreased P release in the following tanks. By observing the soluble P concentration in the anaerobic tanks, it became obvious that less than 5% of the P release was occurring in the third anaerobic tank and even less release (3%) in the fourth anaerobic tank when provided. This observation from the computer modeling output could be correlated to the VFA concentration in the anaerobic tanks. Most of the influent VFAs were consumed in the first anaerobic tank and less in the second and third anaerobic tanks. The systems with higher % RAS to the anaerobic zone had significantly higher VFA consumption and in all cases the VFA concentration was reduced to less than 1 mg/L by the third anaerobic tank (except the 25% RAS system in BioWin, which was about 4.3 mg/L in the third anaerobic tank). See Table 3.2.8 for model VFA concentration results.

Table 3.2.8 – BioWin Anaerobic VFA Concentrations

		25%	25%	50%	50%	100%	100%
	Units	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**
Influent	mg/L	80	80	80	80	80	80
Anaerobic 1	mg/L	43.2	43.1	27.0	26.4	15.2	14.3
Anaerobic 2	mg/L	17.5	17.7	4.8	4.6	1.7	1.5
Anaerobic 3	mg/L	4.2	4.3	0.7	0.7	0.2	0.2
Anaerobic 4	mg/L	0.8	-	0.2	-	0.1	-

The desired P release mechanism for EBPR systems should occur in the presence of VFAs, and therefore there is no benefit from the additional anaerobic volume unless substantial VFAs remain in the last anaerobic zone, which was the case with the 25%

RAS system. This higher anaerobic volume system was the only one that performed better than the lower volume system in BioWin, because it was the only system that had a VFA concentration higher than 1 mg/L by the third anaerobic tank. The same behavior was not observed in UCTPHO's 25% RAS system because there were not significant VFAs available for the extra anaerobic volume.

This modeling analysis of anaerobic VFA levels was not performed with the pilot test results because no VFA data was collected; however, this modeling data may explain why the pilot test also showed no benefit from additional anaerobic volume.

From these modeling anaerobic volume results, it can be concluded that there is not much benefit to the extra volume for highly fermented/septic wastewaters, unless the system is operating at a reduced RAS rate to the anaerobic zone, which would increase the possibility of VFAs reaching the last additional anaerobic volume. A drawback to excessive anaerobic volume is that secondary P release could decrease EBPR performance. Mathematically neither model has a mechanism to show secondary P release, which is why neither of the computer models showed signs of secondary P release. Although secondary P release was not apparent in the models, it should be taken into consideration for a more accurate evaluation of the effects of additional anaerobic volume.

3.2.3.3 Hydraulic Loading Analysis

The modeling results from the increased hydraulic loading scenarios showed that the systems were not adversely affected by the higher flows. Both models actually

showed better overall results. Table 3.2.9 shows the BioWin, UCTPHO and pilot test results with increased hydraulic loading.

Table 3.2.9 – Increased Hydraulic Loading Comparison Results

		BioWin	**UCTPHO**	**Pilot Test (Phase 3, P3)**
	Units	**50% RAS**	**50% RAS**	**50% RAS**
Total P Loading	mg/day-P	1727.0	1727.0	1033
Mass of P Removed due to EBPR	mg/day-P	981.3	1176.1	536
Total Anaerobic P Release	mg/day-P	3940.0	4838.3	7857
Anoxic P Uptake	mg/day-P	-1638.2	-2222.7	2024
Aerobic P Uptake	mg/day-P	6845.2	8458.3	6793
Total P Release	mg/day-P	3940.0	7061.0	7857
Total P Uptake	mg/day-P	5207.0	8458.3	8817
Pup/Prel	-	1.3	1.20	1.12
Net P Removal	mg/day-P	1267.0	1397.3	959
Effluent PO4-P	mg/L	2.90	2.10	1.0

When comparing the results between both models, UCTPHO outperformed BioWin with the exception of the Pup/Prel ratio, which is consistent with previous pilot test observations. A significant effect of increasing the hydraulic loading is that in UCTPHO the anoxic P release was higher and BioWin also had large amounts of anoxic P release. These results suggest that peak flows into the system may shift some P release to the anoxic zone without decreasing overall system performance. The increased anoxic P release trend was only observed in one of the two pilot test phases that studied this scenario.

3.2.4 Conclusions

The main conclusion from this computer modeling analysis with BioWin and UCTPHO is that both models predicted the overall behavior of the EBPR system with reduced RAS to the anaerobic zone. This was the primary question and reason why this study was conducted. A summary of the conclusions from this modeling study is as follows:

- Similar to the pilot test, the models showed that reduced RAS did not adversely affect EBPR.
- In both models reduced RAS to the anaerobic zone typically increased P release, P uptake, net P removal, and decreased effluent P levels.
- BioWin showed greater sensitivity to % RAS variations than UCTPHO.
- BioWin incorporates anoxic P uptake while UCTPHO does not.
- Increased anaerobic volume does not necessarily improve EBPR for this septic wastewater.
- Additional anaerobic volume was only advantageous with the 25% RAS system due to slower VFA consumption.
- Increased hydraulic volume did not adversely affect EBPR in both models, but a shift in P release to the anoxic zone was observed.
- Results from UCTPHO showed greater similarity to the pilot test results than BioWin, with the exception of differences resulting from the anoxic zone P release/uptake capabilities between both models.
- Higher PAO populations were observed when RAS was diverted to the anoxic zone, most likely because the aerobic PAO mass fraction was higher.

- Decreased influent VFA levels reduced the EBPR improvement observed as a result of diverting part of the RAS to the anoxic zone.

APPENDIX A: METHODS AND MATERIALS

Experimental Design

The pilot test system was designed to enable laboratory testing and evaluation of the effectiveness of various flow and loading scenarios, and closely resembled the full scale wastewater treatment facility utilizing scaled down reactors and flow rates to maintain similar hydraulic and biological conditions. Some process components being evaluated could be scaled down and simulated (anaerobic, anoxic, and aerobic volumes, HRT, SRT, and flow rates), while other components could not (aeration rates, clarifier performance, etc.). Provisions were made to ensure they did not adversely affect the key components being studied.

Several hydraulic considerations were taken into account for the pilot test design and operation. The most significant hydraulic considerations between the full and pilot test scale systems were the wastewater flow rates, HRT's, and tank volumes, which were used to size the pilot test pumps and tanks. The scale down factor of the pilot test resulted from an evaluation of the available space in the room where the study was conducted, and the largest influent tank that could practically fit into the designated pilot test room to provide at least 3 days of uninterrupted influent wastewater storage. The 13.7 MGD average day flow full scale facility was scaled down to a 116 liters/day influent flow rate pilot scale system. When the peak flow event (18.5 MGD full scale) was studied, the pilot system was fed at 157 liters/day.

The anaerobic zone was divided into four separate tanks connected in series to enable sequential measurement of soluble P levels in each anaerobic tank to determine if more or less anaerobic volume was of any benefit to the EBPR process. The anoxic and

aerobic zones were a scaled down volume from the full scale WWTF to provide the same HRT. Figure A1 shows a simplified schematic of the pilot test process.

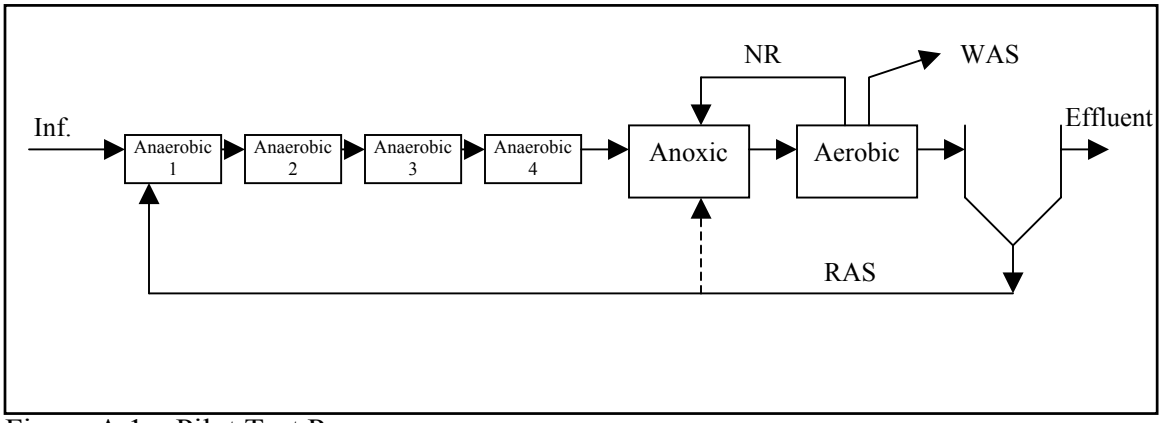

Figure A.1 – Pilot Test Process

As mentioned above, the average influent flow was set at 116 L/day, while the peak flow scenario was simulated at 157 L/day. The NARCY flow, or nitrogen recycle (NR), returned mixed liquor from the aeration zone to the anoxic zone at a rate 4 times the influent flow (4 x 116 L/day = 464 L/day), which was similar to the full scale system. The RAS flow was kept constant at 87 L/day (75% of the average influent flow) returning sludge from the clarifier settled solids to the anaerobic zone or anoxic zone. When the scenario of 50% RAS to the anaerobic zone was studied, approximately 44 L/day of RAS was sent to the anaerobic zone and the rest to the anoxic zone, which again corresponds to 50% of the available (87 L/day) RAS.

Operation and Maintenance of Systems

Equipment maintenance was performed daily (Monday through Friday) to ensure proper operation of the pilot test system. Typical daily operation and maintenance

activities consisted of sampling, re-filling the influent wastewater holding tanks, checking and adjusting the peristaltic pump flow rates and manually removing mixed liquor from the aeration zone (WAS).

Pump flow rates were checked instantaneously by measuring the time required to fill a graduated cylinder, while the average influent flows were checked by recording the water levels in the influent and effluent holding tanks and the time elapsed between both level readings. Pump flow rates generally only needed minor adjustments (5%). The WAS volume removed from the system was varied depending on the solids mass balance calculation results to maintain the desired SRT.

During most of the study, the influent wastewater was diluted with tap water to reduce the influent loading as part of the peak flow study and to feed the systems with the full scale WWTF influent wastewater design strength. Because tap water contains a residual concentration of chlorine, a 10% solution of sodium thiosulfate was mixed with the tap water to eliminate the free chlorine residual ion in the water and avoid disinfecting any portion of the influent wastewater.

Sample Collection

Samples were collected from each reactor, or tank, of all three pilot test systems, and the influent wastewater holding tanks resulting in a total of 26 sampling points during each event. To collect the data for the parameters necessary to evaluate the systems, two (2) 175 mL samples were collected from each reactor and one was immediately filtered. Due to the proximity of the laboratory to the pilot system (one minute walking distance), the

samples were not chilled, however, they were delivered within the same hour after collection.

A typical sampling event lasted about two hours and the samples were immediately delivered to the WWTF operated certified laboratory located approximately 300 feet from the pilot test systems. Sampling events took place two times per week (Tuesdays and Thursdays) throughout the duration of the pilot testing period (25 weeks total).

Analytical Methods

Analytical methods used to measure parameter and collect system data were performed according to Standard Methods for the Examination of Water and Wastewater (19^{th} ed. 1995). Samples destined for soluble constituent testing were filtered using Whatman glass microfiber filters (1.5 micron) assisted by a vacuum pump. If necessary, portions of the samples were preserved and stored by laboratory staff until testing could be accommodated with the laboratory's testing schedule. Samples were generally tested not more than four days after collection.

1) Chemical Oxygen Demand (COD)

   The COD level was measured by the laboratory following Standard Methods, 1995 procedures.

2) Total and Volatile Suspended Solids (TSS and VSS)

   TSS and VSS concentrations were measured by the laboratory following Standard Methods, 1995 procedures.

3) Total Phosphorous (TP) and Soluble Ortho-Phosphorous (SOP)

TP and SOP concentrations were measured automatically using a Nutrient Auto Analyzer model Flow Solutions 3000 by OI Analytical (College Station, Texas), which uses EPA compliant methods.

4) Total and Soluble Kjedahl Nitrogen, Ammonia, and Nitrates

Nitrogen component concentrations were also measured automatically using a Nutrient Auto Analyzer model Flow Solutions 3000 by OI Analytical (College Station, Texas), which uses EPA compliant methods.

5) Sludge Volume Index (SVI)

The SVI was measured three times per week for all three pilot test systems. SVI testing was performed by collecting one (1) liter of mixed liquor from the aeration zones and mixing it in a standard one-liter graduated cylinder. The contents was shaken and then allowed to settle. The final volume occupied by the sludge blanket was divided by the mixed liquor TSS concentration to obtain the SVI in units of mL/gVSS.

6) Zone Settling Velocity (ZSV)

During the SVI testing described previously, the sludge blanket level was measured during settling at various time intervals and the results were tabulated. The gradient of slope determined the SVI in units of feet/hour.

7) Oxygen Uptake Rate (OUR)

The ex-site OUR was determined by measuring the DO over a period of time (generally 5 minutes) from a sample of mixed liquor. The slope of the graph gives the OUR in units of mgO_2/L-min.

APPENDIX B: NITROGEN ANALYSIS

A nitrogen mass balance analysis was performed across the system to determine the effect of the anaerobic zone on the Specific De-Nitrification Rate (SDNR). Table B.1 below shows a summary of the results, which are discussed in the following paragraphs.

Table B.1 - Nitrogen Mass Balance Analysis Results

Phase	P3 0% RAS	P1 50%RAS	P2 100%RAS	Order
Aerobic NH_3 (mg/L)				
2A	6.1	9.2	10.4	P2>P1>P3
2B	1.5	2.9	6.0	P2>P1>P3
2C	0.2	0.1	0.3	P2>P3>P1
Nitrification (mgN/day)				
2A	1404	409	148	P3>P1>P2
2B	1763	1453	896	P3>P1>P2
2C	2808	2004	2132	P3>P2>P1
Aerobic SRT (days)				
2A	2.94	2.56	2.55	
2B	4.52	5.04	4.97	
2C	5.95	5.75	5.68	
Anoxic Nitrate (mg/L)				
2A	0.04	0.02	0.02	P3>P1>P2
2B	0.18	0.05	0.03	P3>P1>P2
2C	0.76	0.48	0.59	P3>P2>P1
Anoxic Denitrification (mgN/day)				
2A	1070	307	105	P3>P1>P2
2B	1394	1072	618	P3>P1>P2
2C	1965	1398	1354	P3>P1>P2
Anoxic SDNR (mgN/mgVSS-day)				
2A	0.04039	0.02232	0.00874	P3>P1>P2
2B	0.03893	0.03861	0.02639	P3>P1>P2
2C	0.04484	0.05033	0.05265	P2>P1>P3
Anoxic SCOD Used (mgO/day)				
2A	3061	877	301	P3>P1>P2
2B	3986	3067	1768	P3>P1>P2
2C	5619	3997	3872	P3>P1>P2

Relevant comparisons to study the effect of the anaerobic zones on anoxic SDNR can be made during Phases 2A, 2B and 2C by comparing denitrification rates (or anoxic

SCOD consumption) in pilot test system P3 with P1 and P2. During these phases, P3 did not have any anaerobic zones on-line while P1 and P2 had three anaerobic zones on-line.

In Phases 2A and 2B comparisons between the three systems are consistent. System P3 had higher nitrification rates, higher denitrification rates, and higher SDNR followed by system P1 and then P2. The higher nitrification rates observed in system P3 were probably a result of the higher anoxic mass fraction given the SRT and temperature was similar in all three systems. However, during these first two phases the anoxic nitrate concentration was below 0.1 or 0.2 mg/L in all three systems, which impedes making an anoxic SDNR comparison knowing the denitrification rates could have been higher if more nitrate was available. The difference in denitrification rates between all three systems can only be attributed to the different nitrate loads to the anoxic zones of each system (P3 with the highest and P2 with the lowest nitrate load). The nitrate loads were significantly different during these phases because the pilot test system was being operated to replicate the full scale WWTF being studied; therefore, the influent water was not diluted like with systems P1 and P2.

Similarly, in Phase 2C with all three systems completely nitrifying, the nitrification rates were dependent on the nitrogen flux into the system and were not comparable (aerobic ammonia <0.3 mg/L). However, the anoxic nitrate concentration in all three systems was above 0.48 mg/L making the denitrification rates comparable. The anoxic SDNR in P3 was lower than in P1 and P2 (0.04484, 0.05033 and 0.05265 mgN/mgVSS-day, respectively). Because P3 had no anaerobic zones, these results indicate that the anaerobic zones do not deteriorate the anoxic denitrification rate.

The anoxic denitrification rate in system P3 during Phase 2C was also considerably higher than in P1 and P2 (1965, 1398 and 1354 mgN/day, respectively), which suggests that the lower SDNR in P3 is not a result of less denitrification, but a higher VSS/TSS ratio. It has been observed that systems with higher P content in the biomass have lower VSS/TSS ratios (Grady, Daigger and Lim, 1999). Because systems P1 and P2 had higher %P in the biomass than in P3 during Phase 2C (9.9, 11.1, and 6.3%, for P1, P2 and P3, respectively), it may have lowered the anoxic VSS content and therefore increased the SDNR in P1 and P2. This correlation holds when comparing system P1 with P2 in Phase 2C. System P2 (100% RAS directed to the anaerobic zones) had slightly less anoxic denitrification, however, the SDNR was higher possibly due to the lower anoxic VSS concentration (3607 and 3340 mg/L in P1 and P2, respectively), and higher %P biomass levels.

The average temperature during Phases 2A, 2B and 2C was 22, 21 and 27°C respectively. In addition to the increased nitrification rates, the higher temperature during Phase 2C may have also contributed to the increased SDNRs in all three systems.

APPENDIX C: DATA RESULTS

Table C.1 - Pilot Test Data

PILOT 1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	V w/ Clar	V wo Clar
Tank Vol	1.31	1.97	1.97	1.97	7.7	24.3	20	59.22	39.22

DATA	FLOW RATES						TSS									VSS								
	Influent	WAS	Effluent	NARCY	RAS	%	T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8	T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8
Phase	(L/day)	(L/day)	(L/day)	(L/day)	(L/day)	RAS	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
1	107.1	4.4	102.8	445.3	84.2	0.5	217.0	4700.0	4820.0		5026.7	7041.7	6813.3	28.3	12.3	196.7	4223.3	4344.0		4511.7	6155.0	5908.3	28.0	12.3
2A	113.7	7.9	105.8	457.2	86.8	0.5	112.8	1496.0	1328.0		1300.0	2064.0	2132.0	31.8	7.2	106.8	1332.0	1188.0		1170.0	1784.0	1808.0	28.6	8.2
2B	121.3	4.2	117.2	460.0	86.0	0.5	91.5	3030.0	2825.0		2625.0	4315.0	4505.0	25.8	8.5	85.5	2640.0	2482.5		2310.0	3607.5	3812.5	24.3	8.5
2C	122.9	3.6	119.3	460.0	88.7	0.5	74.0	3223.3	2756.7		2626.7	4296.7	4540.0	25.0	4.5	73.3	2836.7	2440.0		2340.0	3606.7	3763.3	28.0	6.0
3	115.5	3.6	111.9	460.0	86.0	0.5	94.8	10930.0	2164.0		2076.0	3452.0	3288.0	15.8	3.8	86.0	8790.0	1844.0		1784.0	2814.0	2654.0	15.2	3.0
4	114.7	3.7	111.0	460.0	100.7	0.5	340.7	3876.7	3636.7	4000.0	3660.0	5363.3	5286.7	16.0	6.7	312.7	3210.0	3023.3	3350.0	3070.0	4266.7	4183.3	18.0	5.0

VSS/TSS Ratio									TCOD									sCOD								
T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8	T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8	T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8
									(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0.904	0.899	0.902		0.899	0.874	0.867	0.962	1.034	1008.3							215.5		599.5	348.7	310.5		304.8	196.0	196.8	189.2	
0.944	0.890	0.893		0.899	0.865	0.847	0.874	1.170	609.4							192.8		459.2	303.4	308.6		270.2	151.4	142.4	127.2	
0.934	0.871	0.878		0.880	0.836	0.848	0.975	1.024	615.3							156.3		481.0	319.3	238.8		225.5	180.8	130.8	120.5	
1.023	0.883	0.888		0.893	0.841	0.829	1.367	1.100	620.3							136.3		417.0	195.3	158.3		154.3	97.0	76.7	86.3	
0.910	0.806	0.852		0.860	0.817	0.808	1.099	1.100	439.4							126.6		237.8	143.0	144.6		151.8	112.6	106.0	115.2	
0.917	0.828	0.832	0.838	0.840	0.796	0.792	1.343	0.839	880.7							155.7		408.7	201.0	199.7	214.7	187.0	140.7	123.7	130.3	

NH^{4+}									TKN									sKN								
T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8	T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8	T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
27.6					18.1	16.3	16.1		45.1						401.8	20.1		36.5					21.0	17.9	17.6	
17.1					10.5	9.2	9.4		26.1						185.8	14.1		21.4					14.1	12.2	11.9	
14.5					4.8	2.9	3.2		27.3						323.8	7.2		21.4					9.8	7.0	6.0	
17.5					2.4	0.1	0.4		20.4						296.7	1.9		16.6					9.3	1.7	1.3	
12.1					2.0	0.1	0.1		23.9						216.2	3.3		16.7					5.9	2.6	1.9	
16.0					2.9	0.1	0.3		25.6						304.3	4.3		18.7					4.3	1.6	1.6	

NO^{2-}/NO^{3-}									SOP									TP								
T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8	T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8	T1	P1-1	P1-2	P1-3	P1-4	P1-5	P1-6	P1-7	P1-8
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0.03	0.03	0.07		0.03	0.07	0.13	0.10		12.2	34.0	41.2		46.8	14.7	0.1	3.2		14.4						198.5	3.5	
0.55	0.02	0.02		0.02	0.02	0.64	0.54		6.8	13.7	16.5		19.4	15.6	0.2	0.6		8.8						112.4	2.5	
0.22	0.02	0.02		0.02	0.05	2.23	1.80		5.1	29.0	38.2		43.0	10.6	0.1	0.5		8.6						238.0	2.5	
0.03	0.04	0.04		0.05	0.48	3.47	2.70		7.3	34.4	43.8		49.4	11.4	0.2	0.5		15.7						237.0	2.2	
0.04	0.20	0.02		0.04	2.16	4.38	3.62		7.1	54.2	28.0		36.3	9.0	2.2	2.9		12.0						198.0	4.0	
0.10	0.03	0.02	0.04	0.03	1.73	4.77	3.80		12.2	56.0	65.7	70.5	69.9	18.7	1.5	3.2		17.2						317.7	3.4	

PILOT 2	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	V w/ Clar	V wo Clar
Tank Vol	1.31	1.97	1.97	1.97	7.7	24.3	20	59.22	39.22

DATA	FLOW RATES						TSS									VSS									
	Influent	WAS	Effluent	NARCY	RAS	%	T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8	T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8
Phase	(L/day)	(L/day)	(L/day)	(L/day)	(L/day)	RAS	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
1	106.3	4.4	102.0	444.0	84.2	1.00	217.0	22946.7	7376.7		14813.3	7631.7	7218.3	39.5	15.3	196.7	19526.7	6440.0		13305.0	6606.7	6163.3	33.3	13.7
2A	99.4	7.9	91.5	457.2	86.8	1.00	121.5	2230.0	1832.5		1835.0	1757.5	1822.5	32.3	15.0	116.5	1992.5	1650.0		1665.0	1562.5	1615.0	33.5	16.0
2B	118.8	4.3	114.6	460.0	86.0	1.00	91.5	4415.0	3752.5		3700.0	3610.0	3735.0	21.0	7.8	85.5	3815.0	3272.5		3185.0	3042.5	3145.0	20.0	7.3
2C	121.9	3.6	118.3	460.0	88.7	1.00	74.0	4496.7	3876.7		3840.0	3950.0	3880.0	23.3	6.3	73.3	3853.3	3366.7		3333.3	3340.0	3246.7	38.7	8.3
3	108.9	3.6	105.3	460.0	86.0	0.50	94.8	7748.0	1772.0	1804.0	1832.0	3120.0	3110.0	15.2	5.2	86.0	6124.0	1638.0	1564.0	1588.0	2512.0	2548.0	19.8	4.8
4	115.7	3.7	112.0	460.0	100.7	0.25	340.7	2666.7	2400.0	2183.3	2170.0	5593.3	5550.0	4.0	3.0	312.7	2283.3	2100.0	1930.0	1936.7	4493.3	4413.3	4.7	4.0

VSS/TSS Ratio									TCOD									sCOD								
T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8	T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8	T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8
									(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0.90	0.85	0.87		0.90	0.87	0.85	0.86	0.90	1008.3							181.3		599.5	316.0	231.7		268.5	235.0	159.5	168.5	
0.96	0.89	0.91		0.91	0.89	0.89	1.04	1.09	615.0							205.0		457.8	267.3	232.3		200.8	162.5	159.0	133.0	
0.93	0.86	0.87		0.86	0.84	0.84	0.93	0.97	615.3							167.5		481.0	187.0	242.0		193.3	196.3	164.8	134.8	
1.02	0.86	0.87		0.87	0.85	0.84	1.56	1.87	620.3							121.3		417.0	157.3	149.3		157.3	113.7	118.3	97.3	
0.91	0.79	0.95	0.87	1.18	0.82	0.80	1.07	0.90	439.4							113.0		237.8	88.8	169.4	148.4	133.2	107.8	100.4	85.6	
0.92	0.86	0.88	0.88	1.62	0.80	0.82	1.42	1.28	880.7							131.3		408.7	247.7	245.3	178.7	177.7	108.3	109.7	135.0	

NH^{4+}									TKN									sKN								
T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8	T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8	T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
27.6					17.3	14.8	14.6		45.1						409.5	16.9		36.5					19.6	16.0	15.7	
16.6					11.5	10.4	10.7		25.5						263.0	14.6		20.5					14.0	14.6	13.9	
14.5					7.6	6.0	6.3		27.3						273.3	10.3		21.4					13.2	10.9	10.0	
17.5					2.6	0.3	0.5		20.4						218.0	4.5		16.6					8.5	1.3	1.4	
12.1					2.3	0.1	0.2		23.9						215.4	3.7		16.7					4.1	1.7	1.6	
16.0					2.9	0.2	0.4		25.6						338.3	2.5		18.7					4.2	2.5	2.4	

NO^{2-}/NO^{3-}									SOP									TP								
T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8	T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8	T1	P2-1	P2-2	P2-3	P2-4	P2-5	P2-6	P2-7	P2-8
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0.03	0.05	0.10	0.00	0.02	0.02	0.18	0.17		12.2	102.0	46.7		102.4	19.1	0.1	2.1		14.4						219.7	2.9	
0.62	0.02	0.02	0.00	0.02	0.02	0.25	0.18		7.1	14.8	17.5		20.7	16.1	1.5	2.5		9.0						98.4	4.8	
0.22	0.05	0.02	0.00	0.02	0.03	1.38	1.18		5.1	29.2	36.5		35.6	9.1	0.3	0.2		8.6						189.0	2.4	
0.03	0.05	0.06	0.00	0.07	0.59	3.77	2.90		7.3	36.9	43.3		44.2	10.3	0.5	0.5		15.7						224.3	2.2	
0.04	0.14	0.07	0.07	0.04	2.34	4.68	4.08		7.1	14.2	26.3	37.4	43.4	11.6	3.2	3.9		12.0						189.0	5.4	
0.10	0.12	0.02	0.03	0.03	0.23	3.57	2.73		12.2	48.6	58.5	65.5	70.6	19.2	1.9	3.7		17.2						314.7	4.1	

PILOT 3	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	V w/ Clar	V wo Clar
Tank Vol	1.31	1.97	1.97	1.97	7.7	24.3	20	59.22	39.22

DATA	FLOW RATES						TSS									VSS									
	Influent	WAS	Effluent	NARCY	RAS	%	T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8	T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8
Phase	(L/day)	(L/day)	(L/day)	(L/day)	(L/day)	RAS	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
1	151.5	4.3	147.2	438.4	82.6	0.50	148.4	7635.0	3250.0	0.0	3547.5	4610.0	4892.5	31.8	22.8	135.2	6825.0	2915.0	0.0	3252.5	4082.5	4335.0	36.3	23.0
2A	90.7	7.9	82.8	370.0	72.0		159.6					3954.0	3666.0	16.4	6.8	146.0					3442.0	3164.0	16.6	7.2
2B	88.9	5.0	83.9	370.0	72.0		121.5					5590.0	4925.0	21.8	14.8	112.5					4650.0	4075.0	19.8	13.8
2C	96.5	3.6	92.9	370.0	76.7		114.0					6730.0	4643.3	25.7	12.0	103.3					5690.0	3900.0	31.0	12.7
3	147.2	3.6	143.6	460.0	86.0	0.50	106.0	8812.0	3210.0	2016.0	2210.0	3660.0	3708.0	14.5	4.2	95.6	8186.0	2592.0	1718.0	1676.0	2918.0	2900.0	13.2	3.8
4	111.3	3.7	107.6	460.0	100.7	0.40	445.0	3340.0	2966.7	3100.0	3020.0	5453.3	5360.0	11.3	6.0	406.0	2903.3	2423.3	2676.7	2593.3	4293.3	4180.0	10.7	6.7

VSS/TSS Ratio									TCOD									sCOD								
T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8	T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8	T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8
									(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0.91	0.89	0.90	0.00	0.92	0.88	0.89	1.40	1.04	587.2							321.4		450.8	336.0	310.8	0.0	365.0	216.2	171.4	172.4	
0.91					0.87	0.86	1.28	1.16	894.2							258.0		674.6					245.6	243.4	211.2	
0.93					0.83	0.83	0.95	0.93	767.5							232.3		654.8					249.3	232.8	195.8	
0.92					0.85	0.84	1.23	2.34	854.3							172.7		505.7					149.3	134.3	135.3	
0.91	1.38	0.83	0.86	0.82	0.80	0.78	0.99	1.09	383.2							110.6		180.2	95.0	114.2	98.0	103.8	80.8	76.0	91.8	
0.90	0.87	0.82	0.86	0.86	0.79	0.78	0.92	1.13	993.7							142.0		394.3	196.0	185.0	216.7	173.3	123.0	105.3	140.7	

NH^{4+}									TKN									sKN								
T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8	T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8	T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
19.9					14.7	13.8	13.1		32.0						214.6	37.8		26.5					18.1	16.4	15.1	
28.2					10.6	6.1	6.4		40.8						360.2	11.9		34.5					13.8	10.4	9.8	
23.3					4.2	1.5	1.6		43.1						395.8	6.5		35.2					10.2	7.0	7.2	
25.5					2.0	0.2	0.9		30.9						293.3	3.4		29.0					6.1	1.6	3.6	
8.2					2.2	0.1	0.2		21.6						251.8	3.0		13.6					3.8	1.7	1.4	
18.0					3.4	0.7	0.3		32.7						317.7	2.5		21.2					5.4	1.8	2.4	

NO^{2-}/NO^{3-}									SOP									TP								
T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8	T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8	T2	P3-1	P3-2	P3-3	P3-4	P3-5	P3-6	P3-7	P3-8
(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
0.02	0.02	0.02	0.00	0.02	0.02	0.04	0.02	0.0	9.1	20.3	23.6	0.0	24.2	17.1	0.2	2.5		10.3						112.5	7.8	
0.03					0.04	2.68	1.42	0.0	10.8					23.3	0.2	1.1		12.9						181.4	3.0	
0.03					0.18	3.50	2.70	0.0	8.2					13.9	0.3	0.4		11.8						371.0	1.9	
0.02					0.76	5.93	2.40	0.0	12.1					6.8	0.6	0.5		12.9						260.3	7.3	
0.02	0.04	0.03	0.02	0.03	1.45	3.90	3.34	0.0	4.9	24.5	34.2	42.1	47.2	10.8	1.0	1.8		7.0						240.0	4.0	
0.06	0.03	0.04	0.02	0.02	0.43	4.77	3.20	0.0	12.9	69.5	77.5	88.2	98.8	26.9	1.1	5.3		20.5						362.7	5.1	

Table C.2 - Computer Modeling Data

BIOWIN

	Units	100%RAS	50% RAS	25% RAS	0% RAS
Total P Loading	mg/day-P	1740.0	1740.0	1740.0	1740.0
Mass of P Removed due to EBPR	mg/day-P	817.4	969.6	1066.5	719.3
Total Anaerobic P Release	mg/day-P	3329.3	3793.4	3908.7	-62.6
Anoxic P Uptake	mg/day-P	1290.6	1462.7	1404.6	-1413.4
Aerobic P Uptake	mg/day-P	3108.2	3568.4	3848.6	2307.8
Total P Release	mg/day-P	3329.3	3793.4	3908.7	1413.4
Total P Uptake	mg/day-P	4398.8	5031.1	5253.2	2370.4
Pup/Prel	-	1.32	1.33	1.34	1.68
Net P Removal	mg/day-P	1069.5	1237.7	1344.4	957.0
Effluent PO4-P	mg/L	5.78	4.33	3.41	6.75

100 % RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	14.29	2649.79	1616.31	266.74	21.19	201.41		Mass of P Removed due to EBPR	mg/day-P	817
Anaerobic 2	1.53	2643.85	1626.48	266.74	26.39	201.41		Total Anaerobic P Release	mg/day-P	3329
Anaerobic 3	0.22	2641.88	1628.12	266.74	27.62	201.41		Anoxic P Uptake	mg/day-P	1291
Anoxic	0.01	2667.23	1601.8	266.76	10.44	998.7		Aerobic P Uptake	mg/day-P	3108
Aerobic	0	2675.46	1596.02	266.76	5.78	998.7		Total P Release	mg/day-P	3329
WAS	0	2675.46	1596.02	266.76	5.78	2.10E+00		Total P Uptake	mg/day-P	4399
Effluent	0	46.82	27.93	10.35	5.78	113.9		Pup/Prel	-	1.32
RAS Splitter	0	6180.32	3686.79	608.63	5.78	85.41		Net P Removal	mg/day-P	1070

50% RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	26.4	1870.16	1121.05	206.73	23.2	158.76		Mass of P Removed due to EBPR	mg/day-P	970
Anaerobic 2	4.63	1856.4	1138.29	206.73	33.28	158.76		Total Anaerobic P Release	mg/day-P	3793
Anaerobic 3	0.67	1852.11	1142.27	206.73	36.02	158.76		Anoxic P Uptake	mg/day-P	1463
Anoxic	0.01	2936.03	1708.35	317.08	9.68	999.8		Aerobic P Uptake	mg/day-P	3568
Aerobic	0	2946.19	1702.42	317.08	4.33	999.8		Total P Release	mg/day-P	3793
WAS	0	2946.19	1702.42	317.08	4.33	1.96E+00		Total P Uptake	mg/day-P	5031
Effluent	0	51.56	29.79	9.81	4.33	114.04		Pup/Prel	-	1.33
RAS Splitter	0	6805.7	3932.6	726.79	4.33	42.76		Net P Removal	mg/day-P	1238

25 % RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	43.13	1194.12	712.61	140.89	22.02	137.41		Mass of P Removed due to EBPR	mg/day-P	1067
Anaerobic 2	17.73	1176.75	732.83	140.89	34.26	137.41		Total Anaerobic P Release	mg/day-P	3909
Anaerobic 3	4.34	1165.03	743.65	140.89	41.64	137.41		Anoxic P Uptake	mg/day-P	1405
Anoxic	0.05	3177.32	1812.11	358.15	9.18	1001.12		Aerobic P Uptake	mg/day-P	3849
Aerobic	0	3188.71	1806.17	358.15	3.41	1001.12		Total P Release	mg/day-P	3909
WAS	0	3188.71	1806.17	358.15	3.41	1.79E+00		Total P Uptake	mg/day-P	5253
Effluent	0	55.8	31.61	9.62	3.41	114.21		Pup/Prel	-	1.34
RAS Splitter	0	7365.91	4172.25	822.85	3.41	21.41		Net P Removal	mg/day-P	1344

0 % RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	79.99	65.48	50.3	15.04	14.46	116.01		Mass of P Removed due to EBPR	mg/day-P	719
Anaerobic 2	79.98	65.48	50.3	15.04	14.46	116.01		Total Anaerobic P Release	mg/day-P	-63
Anaerobic 3	79.98	65.47	50.31	15.04	14.46	116.01		Anoxic P Uptake	mg/day-P	-1413
Anoxic	0.91	2873.85	1741.07	273.41	10.21	1002.69		Aerobic P Uptake	mg/day-P	2308
Aerobic	0.02	2879.24	1736.04	273.41	6.75	1002.69		Total P Release	mg/day-P	1413
WAS	0.02	2879.24	1736.04	273.41	6.75	1.59E+00		Total P Uptake	mg/day-P	2370
Effluent	0.02	50.39	30.38	11.41	6.75	114.41		Pup/Prel	-	1.68
RAS Splitter	0.02	6651.05	4010.25	622.75	6.75	8.58E-03		Net P Removal	mg/day-P	957

UCTPHO

	Units	100%RAS	50% RAS	25% RAS	0% RAS
Total P Loading	mg/day-P	1740.0	1740.0	1740.0	1740.0
Mass of P Removed due to EBPR	mg/day-P	1148.7	1194.5	1228.6	1241.4
Total Anaerobic P Release	mg/day-P	4822.7	4789.4	4803.9	-46.4
Anoxic P Uptake	mg/day-P	-712.5	-769.9	-791.1	-5347.9
Aerobic P Uptake	mg/day-P	6904.0	6974.5	7044.9	6763.1
Total P Release	mg/day-P	5535.2	5559.3	5594.9	5347.9
Total P Uptake	mg/day-P	6904.0	6974.5	7044.9	6809.5
Pup/Prel	-	1.25	1.25	1.26	1.27
Net P Removal	mg/day-P	1368.8	1415.2	1450.0	1461.6
Effluent PO4-P	mg/L	3.20	2.80	2.50	2.40

100 % RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	80	0.0		15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	6.6	2292.7	1765.4		29.5			Mass of P Removed due to EBPR	mg/day-P	1149
Anaerobic 2	0.1	2301.7	1772.3		33.2			Total Anaerobic P Release	mg/day-P	4823
Anaerobic 3	0	2306.1	1775.7		33.7			Anoxic P Uptake	mg/day-P	-713
Anoxic		2308.7	1777.7		13			Aerobic P Uptake	mg/day-P	6904
Aerobic		2311.3	1779.7		3.2			Total P Release	mg/day-P	5535
WAS		2311.3	1779.7		3.2	4.14		Total P Uptake	mg/day-P	6904
Effluent		0.0	0		3.2	111.86		Pup/Prel	-	1.25
RAS Splitter						87.00		Net P Removal	mg/day-P	1369

50% RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	80			15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	21.2	1553.6	1196.3		30.1			Mass of P Removed due to EBPR	mg/day-P	1195
Anaerobic 2	0.6	1565.5	1205.4		40.9			Total Anaerobic P Release	mg/day-P	4789
Anaerobic 3	0	1571.7	1210.2		41.7			Anoxic P Uptake	mg/day-P	-770
Anoxic		2432.9	1873.3		12.7			Aerobic P Uptake	mg/day-P	6974
Aerobic		2435.3	1875.2		2.8			Total P Release	mg/day-P	5559
WAS		2435.3	1875.2		2.8	3.94		Total P Uptake	mg/day-P	6974
Effluent		0.0	0		2.8	112.06		Pup/Prel	-	1.25
RAS Splitter						43.5		Net P Removal	mg/day-P	1415

25 % RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	80			15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	40.9	952.2	733.2		26.2			Mass of P Removed due to EBPR	mg/day-P	1229
Anaerobic 2	6.2	963.1	741.6		44.2			Total Anaerobic P Release	mg/day-P	4804
Anaerobic 3	0.2	969.9	746.8		47.9			Anoxic P Uptake	mg/day-P	-791
Anoxic	0	2536.9	1953.4		12.5			Aerobic P Uptake	mg/day-P	7045
Aerobic		2540.0	1955.8		2.5			Total P Release	mg/day-P	5595
WAS		2540.0	1955.8		2.5	3.79		Total P Uptake	mg/day-P	7045
Effluent		0.0	0		2.5	112.21		Pup/Prel	-	1.26
RAS Splitter						21.75		Net P Removal	mg/day-P	1450

0 % RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	80			15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	80	22.9	17.6		14.6			Mass of P Removed due to EBPR	mg/day-P	1241
Anaerobic 2	80	22.9	17.6		14.6			Total Anaerobic P Release	mg/day-P	-46
Anaerobic 3	80	22.9	17.6		14.6			Anoxic P Uptake	mg/day-P	-5348
Anoxic	0.2	2669.4	2055.4		12			Aerobic P Uptake	mg/day-P	6763
Aerobic	0	2674.3	2059.2		2.4			Total P Release	mg/day-P	5348
WAS		2674.3	2059.2		2.4	3.58		Total P Uptake	mg/day-P	6810
Effluent		0.0	0		2.4	112.42		Pup/Prel	-	1.27
RAS Splitter						0		Net P Removal	mg/day-P	1462

BIOWIN

		50%	50%	100%	100%	25%	25%
	Units	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**
Total P Loading	mg/day-P	1740	1740	1740	1740	1740	1740
Mass of P Removed due to EBPR	mg/day-P	966	970	907	817	1080	1067
Total Anaerobic P Release	mg/day-P	3934	3793	3448	3329	4229	3909
Anoxic P Uptake	mg/day-P	1321	1262	1160	1116	1403	1188
Aerobic P Uptake	mg/day-P	3847	3769	3346	3283	4185	4065
Total P Release	mg/day-P	3934	3793	3448	3329	4229	3909
Total P Uptake	mg/day-P	5168	5031	4506	4399	5588	5253
Pup/Prel	-	1.314	1.326	1.307	1.321	1.322	1.344
Net P Removal	mg/day-P	1234	1238	1058	1070	1360	1344
Effluent PO4-P	mg/L	4.36	4.33	5.88	5.78	3.28	3.41

50% RAS (High Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	27.02	1813.62	1090.4	200.06	23.05	158.72		Mass of P Removed due to EBPR	mg/day-P	966
Anaerobic 2	4.82	1800.04	1107.88	200.06	33.13	158.72		Total Anaerobic P Release	mg/day-P	3934
Anaerobic 3	0.7	1795.72	1111.97	200.06	35.92	158.72		Anoxic P Uptake	mg/day-P	1321
Anaerobic 4	0.18	1793.86	1113.02	200.06	36.92	158.72		Aerobic P Uptake	mg/day-P	3847
Anoxic	0	2847.14	1661.21	306.63	9.82	998.79		Total P Release	mg/day-P	3934
Aerobic	0	2857.6	1655.26	306.63	4.36	998.79		Total P Uptake	mg/day-P	5168
WAS	0	2857.6	1655.26	306.63	4.36	2.09E+00		Pup/Prel	-	1.31
Effluent	0	50.01	28.97	9.65	4.36	113.91		Net P Removal	mg/day-P	1234
RAS Splitter	0	6601.05	3823.64	702.61	4.36	42.72				

50% RAS (LOW Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	26.4	1870.16	1121.05	206.73	23.2	158.76		Mass of P Removed due to EBPR	mg/day-P	970
Anaerobic 2	4.63	1856.4	1138.29	206.73	33.28	158.76		Total Anaerobic P Release	mg/day-P	3793
Anaerobic 3	0.67	1852.11	1142.27	206.73	36.02	158.76		Anoxic P Uptake	mg/day-P	1262
Anoxic	0.01	2936.03	1708.35	317.08	9.68	999.8		Aerobic P Uptake	mg/day-P	3769
Aerobic	0	2946.19	1702.42	317.08	4.33	999.8		Total P Release	mg/day-P	3793
WAS	0	2946.19	1702.42	317.08	4.33	1.96E+00		Total P Uptake	mg/day-P	5031
Effluent	0	51.56	29.79	9.81	4.33	114.04		Pup/Prel	-	1.33
RAS Splitter	0	6805.7	3932.6	726.79	4.33	42.76		Net P Removal	mg/day-P	1238

100% RAS (High Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	15.19	2517.84	1543.76	251.67	21.01	201.26		Mass of P Removed due to EBPR	mg/day-P	907
Anaerobic 2	1.69	2511.85	1554.38	251.67	26.36	201.26		Total Anaerobic P Release	mg/day-P	3448
Anaerobic 3	0.24	2509.91	1556.13	251.67	27.61	201.26		Anoxic P Uptake	mg/day-P	1160
Anaerobic 4	0.08	2508.52	1556.61	251.67	28.27	201.26		Aerobic P Uptake	mg/day-P	3346
Anoxic	0	2534.88	1529.99	251.68	10.63	997.06		Total P Release	mg/day-P	3448
Aerobic	0	2543.37	1524.19	251.68	5.88	997.06		Total P Uptake	mg/day-P	4506
WAS	0	2543.37	1524.19	251.68	5.88	2.32E+00		Pup/Prel	-	1.31
Effluent	0	44.51	26.67	10.18	5.88	113.68		Net P Removal	mg/day-P	1058
RAS Splitter	0	5875.18	3520.89	573.68	5.88	85.26				

100% RAS (LOW Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	14.29	2649.79	1616.31	266.74	21.19	201.41		Mass of P Removed due to EBPR	mg/day-P	817
Anaerobic 2	1.53	2643.85	1626.48	266.74	26.39	201.41		Total Anaerobic P Release	mg/day-P	3329
Anaerobic 3	0.22	2641.88	1628.12	266.74	27.62	201.41		Anoxic P Uptake	mg/day-P	1116
Anoxic	0.01	2667.23	1601.8	266.76	10.44	998.7		Aerobic P Uptake	mg/day-P	3283
Aerobic	0	2675.46	1596.02	266.76	5.78	998.7		Total P Release	mg/day-P	3329
WAS	0	2675.46	1596.02	266.76	5.78	2.10E+00		Total P Uptake	mg/day-P	4399
Effluent	0	46.82	27.93	10.35	5.78	113.9		Pup/Prel	-	1.32
RAS Splitter	0	6180.32	3686.79	608.63	5.78	85.41		Net P Removal	mg/day-P	1070

25% RAS (High Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	43.2	1178.16	703.08	139.65	22.04	137.4		Mass of P Removed due to EBPR	mg/day-P	1080
Anaerobic 2	17.47	1160.93	723.46	139.65	34.28	137.4		Total Anaerobic P Release	mg/day-P	4229
Anaerobic 3	4.21	1149.4	734.16	139.65	41.57	137.4		Anoxic P Uptake	mg/day-P	1403
Anaerobic 4	0.81	1145.51	737.49	139.65	43.95	137.4		Aerobic P Uptake	mg/day-P	4185
Anoxic	0.01	3134.88	1786.91	354.83	9.22	1000.5		Total P Release	mg/day-P	4229
Aerobic	0	3146.74	1780.91	354.83	3.28	1000.5		Total P Uptake	mg/day-P	5588
WAS	0	3146.74	1780.91	354.83	3.28	1.87E+00		Pup/Prel	-	1.32
Effluent	0	55.07	31.17	9.43	3.28	114.13		Net P Removal	mg/day-P	1360
RAS Splitter	0	7268.96	4113.9	815.36	3.28	21.4				

25% RAS (LOW Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80	65	50	15	14.45	116		Total P Loading	mg/day-P	1740
Anaerobic 1	43.13	1194.12	712.61	140.89	22.02	137.41		Mass of P Removed due to EBPR	mg/day-P	1067
Anaerobic 2	17.73	1176.75	732.83	140.89	34.26	137.41		Total Anaerobic P Release	mg/day-P	3909
Anaerobic 3	4.34	1165.03	743.65	140.89	41.64	137.41		Anoxic P Uptake	mg/day-P	1188
Anoxic	0.05	3177.32	1812.11	358.15	9.18	1001.12		Aerobic P Uptake	mg/day-P	4065
Aerobic	0	3188.71	1806.17	358.15	3.41	1001.12		Total P Release	mg/day-P	3909
WAS	0	3188.71	1806.17	358.15	3.41	1.79E+00		Total P Uptake	mg/day-P	5253
Effluent	0	55.8	31.61	9.62	3.41	114.21		Pup/Prel	-	1.34
RAS Splitter	0	7365.91	4172.25	822.85	3.41	21.41		Net P Removal	mg/day-P	1344

UCTPHO

		50%	50%	100%	100%	25%	25%
	Units	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**	**High Vol**	**Low Vol**
Total P Loading	mg/day-P	1740	1740	1740	1740	1740	1740
Mass of P Removed due to EBPR	mg/day-P	1171	1195	1114	1149	1228	1229
Total Anaerobic P Release	mg/day-P	4876	4789	4898	4823	4887	4804
Anoxic P Uptake	mg/day-P	-706	-770	-672	-713	-779	-791
Aerobic P Uptake	mg/day-P	6974	6974	6904	6904	7115	7045
Total P Release	mg/day-P	5582	5559	5570	5535	5665	5595
Total P Uptake	mg/day-P	6974	6974	6904	6904	7115	7045
Pup/Prel	-	1.249	1.255	1.239	1.247	1.256	1.259
Net P Removal	mg/day-P	1392	1415	1334	1369	1450	1450
Effluent PO4-P	mg/L	3.00	2.80	3.50	3.20	2.50	2.50

50% RAS (High Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80			15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	22.4	1501.0	1155.8		29.5			Mass of P Removed due to EBPR	mg/day-P	1171
Anaerobic 2	0.6	1512.6	1164.7		40.9			Total Anaerobic P Release	mg/day-P	4876
Anaerobic 3	0	1518.8	1169.5		41.7			Anoxic P Uptake	mg/day-P	-706
Anaerobic 4		1522.6	1172.4		42.3			Aerobic P Uptake	mg/day-P	6974
Anoxic		2350.9	1810.2		12.9			Total P Release	mg/day-P	5582
Aerobic		2353.2	1812		3.0			Total P Uptake	mg/day-P	6974
WAS		2353.2	1812		3.0	4.08		Pup/Prel	-	1.25
Effluent		0.0	0		3.0	111.92		Net P Removal	mg/day-P	1392
RAS Splitter						43.5				

50% RAS (LOW Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80			15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	21.2	1553.6	1196.3		30.1			Mass of P Removed due to EBPR	mg/day-P	1195
Anaerobic 2	0.6	1565.5	1205.4		40.9			Total Anaerobic P Release	mg/day-P	4789
Anaerobic 3	0	1571.7	1210.2		41.7			Anoxic P Uptake	mg/day-P	-770
Anoxic		2432.9	1873.3		12.7			Aerobic P Uptake	mg/day-P	6974
Aerobic		2435.3	1875.2		2.8			Total P Release	mg/day-P	5559
WAS		2435.3	1875.2		2.8	3.94		Total P Uptake	mg/day-P	6974
Effluent		0.0	0		2.8	112.06		Pup/Prel	-	1.25
RAS Splitter						43.5		Net P Removal	mg/day-P	1415

100% RAS (High Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80			15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	7.8	2177.8	1676.9		29			Mass of P Removed due to EBPR	mg/day-P	1114
Anaerobic 2	0.1	2186.6	1683.7		33.2			Total Anaerobic P Release	mg/day-P	4898
Anaerobic 3	0	2191.2	1687.2		33.8			Anoxic P Uptake	mg/day-P	-672
Anaerobic 4		2193.8	1689.2		34.2			Aerobic P Uptake	mg/day-P	6904
Anoxic		2194.4	1689.7		13.3			Total P Release	mg/day-P	5570
Aerobic		2196.8	1691.5		3.5			Total P Uptake	mg/day-P	6904
WAS		2196.8	1691.5		3.5	4.36		Pup/Prel	-	1.24
Effluent		0.0	0		3.5	111.64		Net P Removal	mg/day-P	1334
RAS Splitter						87				

100% RAS (LOW Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80	0.0		15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	6.6	2292.7	1765.4		29.5			Mass of P Removed due to EBPR	mg/day-P	1149
Anaerobic 2	0.1	2301.7	1772.3		33.2			Total Anaerobic P Release	mg/day-P	4823
Anaerobic 3	0	2306.1	1775.7		33.7			Anoxic P Uptake	mg/day-P	-713
Anoxic		2308.7	1777.7		13			Aerobic P Uptake	mg/day-P	6904
Aerobic		2311.3	1779.7		3.2			Total P Release	mg/day-P	5535
WAS		2311.3	1779.7		3.2	4.14		Total P Uptake	mg/day-P	6904
Effluent		0.0	0		3.2	111.86		Pup/Prel	-	1.25
RAS Splitter						87.00		Net P Removal	mg/day-P	1369

25% RAS (High Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80			15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	41.2	933.1	718.5		26			Mass of P Removed due to EBPR	mg/day-P	1228
Anaerobic 2	6.7	944.0	726.9		43.9			Total Anaerobic P Release	mg/day-P	4887
Anaerobic 3	0.2	950.8	732.1		47.8			Anoxic P Uptake	mg/day-P	-779
Anaerobic 4	0	955.2	735.5		48.5			Aerobic P Uptake	mg/day-P	7115
Anoxic		2486.4	1914.5		12.6			Total P Release	mg/day-P	5665
Aerobic		2489.2	1916.7		2.5			Total P Uptake	mg/day-P	7115
WAS		2489.2	1916.7		2.5	3.87		Pup/Prel	-	1.26
Effluent		0.0	0		2.5	112.13		Net P Removal	mg/day-P	1450
RAS Splitter						21.75				

25% RAS (LOW Vol.)	**Sbsa**	**TSS**	**VSS**	**Total P**	**PO4-P**	**Flow(L/d)**			**Units**	
Influent	80			15	14.6	116		Total P Loading	mg/day-P	1740
Anaerobic 1	40.9	952.2	733.2		26.2			Mass of P Removed due to EBPR	mg/day-P	1229
Anaerobic 2	6.2	963.1	741.6		44.2			Total Anaerobic P Release	mg/day-P	4804
Anaerobic 3	0.2	969.9	746.8		47.9			Anoxic P Uptake	mg/day-P	-791
Anoxic	0	2536.9	1953.4		12.5			Aerobic P Uptake	mg/day-P	7045
Aerobic		2540.0	1955.8		2.5			Total P Release	mg/day-P	5595
WAS		2540.0	1955.8		2.5	3.79		Total P Uptake	mg/day-P	7045
Effluent		0.0	0		2.5	112.21		Pup/Prel	-	1.26
RAS Splitter						21.75		Net P Removal	mg/day-P	1450

PEAK FLOW EVENT

		BioWin	UCTPHO
	Units	50% RAS	50% RAS
Total P Loading	mg/day-P	1727.0	1727.0
Mass of P Removed due to EBPR	mg/day-P	981.3	1176.1
Total Anaerobic P Release	mg/day-P	3940.0	4838.3
Anoxic P Uptake	mg/day-P	-1638.2	-2222.7
Aerobic P Uptake	mg/day-P	6845.2	8458.3
Total P Release	mg/day-P	3940.0	7061.0
Total P Uptake	mg/day-P	5207.0	8458.3
Pup/Prel	-	1.3	1.20
Net P Removal	mg/day-P	1267.0	1397.3
Effluent PO4-P	mg/L	2.9	2.10

UCTPHO

50% RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	59.2			11	10.7	157		Total P Loading	mg/day-P	1727
Anaerobic 1	18.1	1493.4	1149.9		23.2			Mass of P Removed due to EBPR	mg/day-P	1176
Anaerobic 2	0.6	1501.8	1156.4		32.4			Total Anaerobic P Release	mg/day-P	4838
Anaerobic 3	0	1506.8	1160.2		33.2			Anoxic P Uptake	mg/day-P	-2223
Anoxic		2450.4	1886.8		11.4			Aerobic P Uptake	mg/day-P	8458
Aerobic		2453.0	1888.8		2.1			Total P Release	mg/day-P	7061
WAS		2453.0	1888.8		2.1	3.92		Total P Uptake	mg/day-P	8458
Effluent		0.0	0		2.1	153.08		Pup/Prel	-	1.20
RAS Splitter						43.5		Net P Removal	mg/day-P	1397

BioWin

50% RAS	Sbsa	TSS	VSS	Total P	PO4-P	Flow(L/d)			Units	
Influent	59.2	52	37	11	10.6	157		Total P Loading	mg/day-P	1727
Anaerobic 1	22.5	1923.92	1083.19	202.4	17.89	200.5		Mass of P Removed due to EBPR	mg/day-P	981
Anaerobic 2	4.98	1912.08	1097.07	202.4	26.27	200.5		Total Anaerobic P Release	mg/day-P	3940
Anaerobic 3	0.85	1908.01	1100.97	202.4	28.9	200.5		Anoxic P Uptake	mg/day-P	-1638
Anoxic	0.02	3145.68	1738.11	325.55	10.78	708		Aerobic P Uptake	mg/day-P	6845
Aerobic	0	3160.93	1729.77	325.55	2.93	708		Total P Release	mg/day-P	3940
WAS	0	3160.93	1729.77	325.55	2.93	1.50481		Total P Uptake	mg/day-P	5207
Effluent	0	49.29	26.98	7.96	2.93	155.5		Pup/Prel	-	1.32
RAS Splitter	0	8722.35	4773.16	893.19	2.93	43.5		Net P Removal	mg/day-P	1267

APPENDIX D: EXAMPLE CALCULATIONS

The following are sample mass balance calculations used in analyzing the pilot test and computer model systems. These calculations are based on Figure D.1 and are similar in nature to the other system configurations used in the study.

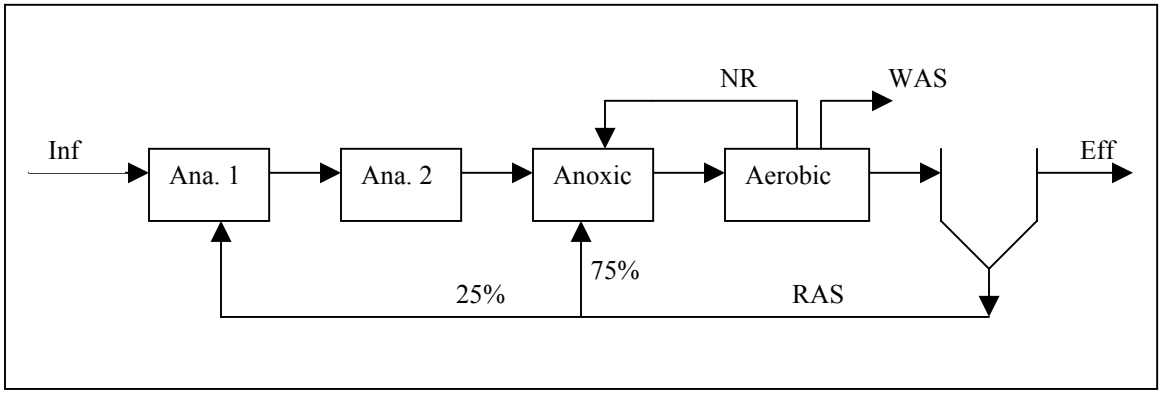

Figure D.1 – Sample System for Sample Calculations

Total P Loading

(INF L/day)(INF TP mg/L) = Total P Loading mg/day

Mass of P Removed due to EBPR

[(Inf L/day)(Inf TP mg/L) – (Eff L/day)(Eff SOP mg/L) – (WAS L/day)(WAS SOP mg/L)] – 0.023[(Eff L/day)(Eff TSS mg/L) + (WAS L/day)(Aerobic MLSS mg/L)] = Mass of P Removed due to EBPR mg/day

Total Anaerobic P Release

(Ana2 SOP mg/L)(0.25 x RAS + Inf L/day) – (0.25 x RAS L/day)(eff SOP mg/L) – (Inf TP mg/L)(Inf L/day) = Total Anaerobic P Release mg/day

Anoxic P Uptake

(Ana2 SOP mg/L)(0.25 x RAS + Inf L/day) + (Aero SOP mg/L)(NR L/day) + (0.75 x RAS L/day)(Eff SOP mg/L) – (Anox SOP mg/L)(RAS + Inf + NR L/day) = Anoxic P Uptake mg/day

Aerobic P Uptake

(Anox SOP mg/L)(RAS + Inf + NR L/day) – (Aero SOP mg/L)(NR + WAS + EFF + RAS L/day) = Aerobic P Uptake mg/day

P Uptake/Release Ratio

(Total P Uptake mg/day) / (Total P Release mg/day) = P Up/Rel Ratio

Net P Removal

(Total P Uptake mg/day) – (Total P Release mg/day) = Net P Removal mg/day

LIST OF REFERENCES

1) Barker, P.S.; Dold, P.L., General model for biological nutrient removal activated-sludge systems: model presentation, Water Environment Research, Vol 69, No. 5, pg 969, August 1997.

2) Haas DW de; Wentzel, MC; Ekama, GA, Comparison Between Combined Biological N & P Removal in the UCT and BIOWIN Models for Activated Sludge Systems, University of Cape Town, Rondebosch, Cape Town, 2001a.

3) Haas DW de; Wentzel, MC; Ekama, GA, A Comparison Between Denitrification in the UCT and BIOWIN Models for Activated Sludge Systems Without Biological Excess Phosphorous Removal, University of Cape Town, Rondebosch, Cape Town, 2001b.

4) Haas, DW de; Wentzel, MC, Calibration of the BIOWIN Model for N removal: part 1, desktop study, Water, pg 37, September 2002a.

5) Haas, DW de; Wentzel, MC, Calibration of the BIOWIN Model for N removal: part 2, full-scale study, Water, pg 65, November 2002b.

6) Leslie Grady, Jr., C.P.; Daigger, Glen T.; Lim, Henry C., Biological Wastewater Treatment, 2nd ed, Marcel Dekker, New York, 1999.

7) McCue, T.; Naik, R; Zepeda, M.; Liu, Y-H; Vasilliev, I.; Randall, A.A. (accepted, in press) Changes in Anoxic Denitrification Rate Due to Prefermentation of a Septic, Phosphorous Limited Wastewater, *Water Environment Research*.

8) Randall, C.W.; Barnard, J.L.; Stensel, H.D., Design and Retrofit of Wastewater Treatment Plants for Biological Nutrient Removal, Technomic Publishing Co., Lancaster, Pa., 1992.

9) Randall, A.A.; Benefield, L.D.; Hill, W.E.; Nicol, J-P.N.; Boman, G.K.; Jing, S-R (1997) The Effect of Volatile Fatty Acids On Enhanced Biological Phosphorus Removal and Population Structure In Anaerobic/Aerobic Sequencing Batch Reactors, *Water, Science, and Technology*, **35**(1), 153-160.

10) *Standard Methods for the Examination of Water and Wastewater*, 19th ed. (1995). American Public Health Association (APHA), Washington, DC.