



THE UNIVERSITY OF QUEENSLAND

Bachelor of Engineering Thesis

**DENITRIFICATION IN FIXED FILM DOMESTIC WASTEWATER
TREATMENT SYSTEMS WITHOUT AN ADDITIONAL CARBON
SOURCE – A MODELING APPROACH**

Student Name: **REBECCA ANNE SMITH**

Course Code: **CHEE4006**

Supervisor: **DR BILL CLARKE**

Submission date: **26 May 2004**

A thesis submitted in partial fulfillment of the requirements of the Bachelor of Engineering degree program in the Division of Chemical Engineering

School of Engineering

Faculty of Engineering, Physical Sciences and Architecture

Miss Rebecca A. Smith
5/136 Miskin Street
TOOWONG QLD 4066

26 May 2004

Prof. J. M. Simmons
Head of School
School of Engineering
University of Queensland
BRISBANE QUEENSLAND 4072

Dear Sir,

I hereby submit my Thesis titled ‘Denitrification in fixed film domestic wastewater treatment systems without an additional carbon source – A modeling approach’ for consideration as partial fulfillment of the Bachelor of Engineering degree.

All the work contained within this Thesis is my original work except where otherwise acknowledged.

I understand that this thesis may be made publicly available and reproduced by the University of Queensland unless a limited term embargo on publication has been negotiated with a sponsor.

Yours sincerely

Rebecca Smith

ABSTRACT

Fixed film biological systems have been used for the treatment of wastewater for many years. These systems have been extensively and generally effectively used for the removal of carbon from wastewater sources. In recent years the legislative demands for nutrient removal, both in Australia and overseas, has seen a move away for biological fixed film systems to activated sludge (suspended growth) systems because of the perceived inability of fixed film systems to provide appropriate nutrient removal. However extensive research has been conducted into this field.

The most common approach to biological denitrification in fixed film treatment systems has been to place an anoxic zone either before (pre-anoxic) or after (post-anoxic) the aeration system (i.e. Trickling Filter, Rotating Biological Contactor, etc.). However this previous research has focused on the use of an external carbon source in the post anoxic zones to provide the carbon requirements for the biological denitrification reaction. This project was aimed at determining the nitrogen removal potential of fixed film biological treatment systems without the need for an additional carbon source.

Following a literature survey and mathematical modelling of three different trickling filter – anoxic vessel configurations, the pre-anoxic system was determined as the best system for denitrification in fixed film domestic wastewater treatment systems without an additional carbon source.

It is however recommended that the models created in this project be applied to an experimental system to determine their accuracy. This experimental verification of the modelling performed is expected to be undertaken in the second half of this year.

ACKNOWLEDGEMENTS

I would like to offer my thanks to my academic supervisor Dr Bill Clarke and my industrial supervisor Mr David Bristow for their advice during the preparation of this thesis. David, without your guidance I would never have gotten this project off the ground and Bill, for giving me perspective on my topic which has enabled me to clarify my understanding of this project.

I would also like to personally thank the following people individually:

Thomas, thank you for all of your support and patience and for believing that I could do this,

Samantha, for patting me on the shoulder periodically and answering any questions that I asked,

Joe, for giving me the inspiration for the topic and organising the reallocation of my work when I couldn't come in because I was working on this, and finally

I would like to give a special thanks to my parents and siblings for being wonderfully supportive throughout my university degree and always believing in me.

TABLE OF CONTENTS

Abstract	i
Acknowledgements	ii
Table of Contents	iii
List of Figures	iv
List of Tables	v
Glossary.....	v
1 INTRODUCTION.....	1
1.1 Introduction	1
1.2 Background	1
1.3 Scope	2
1.4 Objectives	3
2 LITERATURE REVIEW.....	4
2.1 Introduction	4
2.2 History of Fixed Film Systems	4
2.3 Denitrification in Fixed Film Anoxic Zones.....	5
2.4 Biological Denitrification	7
3 METHODOLOGY	9
3.1 Introduction	9
3.2 Basis for Unit Design	9
3.3 Trickling Filter Design	11
3.4 Anoxic Tank Design.....	14
4 MODELS	17
4.1 Introduction	17
4.2 Pre-Anoxic System Model.....	17
4.3 Post Anoxic System (Option 1).....	21
4.4 Post-Anoxic System (Option 2)	25
5 DISCUSSION	29
6 CONCLUSIONS and RECOMMENDATIONS	30
7 REFERENCES.....	31
APPENDIX A – Trickling Filter Design Calculations	A-1
APPENDIX B – Anoxic Tank Design Calculations	B-1
APPENDIX C – Pre-Anoxic System Design Calculations.....	C-1
APPENDIX D – Post-Anoxic System (option 1) Design Calculations	D-1
APPENDIX E – Post-Anoxic System (option 2) Design Calculations	E-1

LIST OF FIGURES

Figure 1.1 – Pre-Anoxic Configuration.....	3
Figure 1.2 – Post-Anoxic Configuration (Option 1).....	3
Figure 1.3 – Post-Anoxic Configuration (Option 2).....	3
Figure 2.1 – Nitrogen transformations in biological treatment processes (Metcalf and Eddy, 2003)	7
Figure 3.1 – Laboratory Trickling Filter that design is based on (Ho et al.,2003)	10
Figure 3.2 – BOD concentration profile within the trickling filter.....	13
Figure 3.3 – NH ₄ -N concentration profile within the trickling filter	14
Figure 3.4 – NO ₃ -N Concentration profile through anoxic tank	15
Figure 3.5 – BOD Concentration profile through anoxic tank.....	16
Figure 4.1 – Pre-anoxic system configuration	17
Figure 4.2 – BOD concentration profile within Trickling filter (Pre-Anoxic).....	19
Figure 4.3 – NH ₄ -N concentration profile within Trickling filter (Pre -Anoxic)	19
Figure 4.4 – BOD concentration profile within Anoxic filter (Pre-Anoxic)	19
Figure 4.5 – NO ₃ -N concentration profile within Anoxic filter (Pre-Anoxic).....	20
Figure 4.6 – Post anoxic system (option 1) configuration.....	21
Figure 4.7 - BOD concentration profile within Trickling filter (Post Anoxic (Option 1))	23
Figure 4.8 – NH ₄ -N concentration profile within Trickling filter (Post Anoxic (Option 1)).....	23
Figure 4.9 – BOD concentration profile within Anoxic vessel (Post Anoxic (Option 1))	24
Figure 4.10 – NO ₃ -N concentration profile within Anoxic vessel (Post Anoxic (Option 1)).....	24
Figure 4.11 –Post Anoxic (Option 2) configuration.....	25
Figure 4.12 – BOD concentration profile within Trickling Filter (Post Anoxic (Option 2)).....	27
Figure 4.13 – NH ₄ -N concentration profile within Trickling filter (Post Anoxic (Option 2))	27
Figure 4.14 – BOD concentration profile within Anoxic vessel (Post Anoxic (Option 2))	27
Figure 4.15 – NO ₃ -N concentration profile within Anoxic vessel (Post Anoxic (Option 2)).....	28

LIST OF TABLES

Table 4.1 – Effluent Quality of Pre-Anoxic System Model	18
Table 4.2 – Effluent Quality obtained from Post-Anoxic (option 1) System Model.....	22
Table 4.3 – Effluent Quality obtained from Post-Anoxic (option 2) System Model.....	26

GLOSSARY

AT	Anoxic vessel/tank
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
COHNS	Represents the Organic Matter in the Wastewater
NH ₄ -N	Ammonia nitrogen
NO ₃ -N	Nitrate nitrogen
RBC	Rotating Biological Contactor
TF	Trickling Filter

1 INTRODUCTION

1.1 INTRODUCTION

This thesis outlines the research that has been undertaken to determine the optimal treatment system design - incorporating a trickling filter, anoxic zone and clarifier – for the nitrogen removal from domestic wastewater. This research has been undertaken from a theoretical viewpoint as a basis for identifying, at least theoretically, the critical parameters in the plants.

This is the first thesis in a series of two (2), to research the optimal treatment system design using fixed film systems for nitrogen removal from domestic wastewater. This thesis (a modelling approach) outlines the previous research that has been undertaken into the field of biological nitrification and denitrification in fixed film treatment systems and determines, using computerised modelling techniques, the optimal fixed film treatment system. The second thesis (an experimental approach) will determine the optimal fixed film treatment system from an experimental viewpoint and provide a comparison and validation of the computerised model provided in this thesis.

1.2 BACKGROUND

Fixed film biological systems have been used for the treatment of wastewater for many years. These systems have been extensively and generally effectively used for the removal of carbon from wastewater sources. In recent years the legislative demands for nutrient removal, both in Australia and overseas, has seen a move away for biological fixed film systems to activated sludge (suspended growth) systems because of the perceived inability of fixed film systems to provide appropriate nutrient removal

These suspended growth processes are generally more expensive, due to pumping and aeration requirements, and are also a lot more operator intensive than fixed film systems. This makes suspended growth systems unattainable for small communities. Therefore, there is a need for nutrient removal in fixed film wastewater treatment systems.

Extensive research has been conducted in the past into nutrient removal (especially biological denitrification) in fixed film systems. The most common approach to biological denitrification has been to place an anoxic zone either before (pre-anoxic) or after (post-anoxic) the aeration system (i.e. Trickling Filter, Rotating Biological Contactor, etc.).

However this previous research has focused on the use of an external carbon source in the post anoxic zones to provide the carbon requirements for the biological denitrification reaction. The most common carbon source used is methanol, but research has also been conducted into alternative sources such as volatile fatty acids (VFA) from hydrolysed sludge (Æsøy and Ødegaard, 1994). These external carbon sources are generally expensive, thus reducing the viability of such systems.

The following thesis will discuss the nitrogen removal potential of fixed film biological treatment systems without the need for an additional carbon source.

1.3 SCOPE

This thesis focuses on the design of fixed film biological treatment systems for optimal nitrogen removal capability. The system boundary for the design of the treatment systems and associated analysis is confined to two operational units – the trickling filter and a submerged biofilm anoxic reactor. Therefore, it is assumed that the influent to the system is in the form of settled raw domestic sewage and the effluent is secondary treated with nutrient removal.

1.4 OBJECTIVES

This thesis aims to investigate the denitrification potential of a submersed biofilm anoxic zone without an external carbon source in a trickling filter wastewater treatment system from a theoretical viewpoint. The research aims to determine whether it is possible to achieve adequate denitrification in post-anoxic zones without the use of a carbon source not already available in the wastewater and how this compares to the denitrification capability of a pre-anoxic zone for the same trickling filter.

Specifically, this thesis aims to:

- ? Conduct extensive research into the processes of biological nitrification and denitrification in fixed film systems.
- ? Design and Construct a computerised model to perform a process design of the three alternative treatment systems which may be used for biological nitrogen removal without the use of an additional carbon source. The three alternatives include:
 - o Pre-Anoxic Denitrification with recycled Trickling Filter effluent (see *Figure 1.1*)

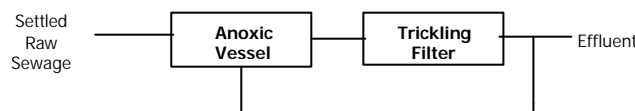


Figure 1.1 – Pre-Anoxic Configuration

- o Post-Anoxic Denitrification without any recycles (see *Figure 1.2*)

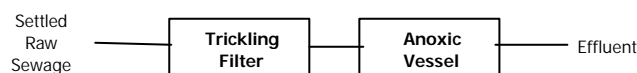


Figure 1.2 – Post-Anoxic Configuration (Option 1)

- o Post-Anoxic Denitrification with Raw Sewage feed and internal recycle (see *Figure 1.3*)

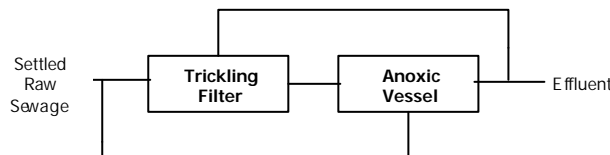


Figure 1.3 – Post-Anoxic Configuration (Option 2)

- ? Run these models to determine the nitrogen removal capability of each system and the optimal fixed film system design, for biological nitrogen removal.

2 LITERATURE REVIEW

2.1 INTRODUCTION

The use of fixed film biological treatment systems for the treatment of domestic wastewater is not a new concept. Beginning with the demonstration by Dr. Alexander Mueller in 1865, where he showed that sewage could be purified by living organisms in a filtration column (Peters and Alleman, 1982), the science and technology associated with the treatment of sewage has been extensively researched.

This review of the literature aims to provide a brief history of the technological advances to the process of fixed film wastewater treatment, discuss recent advances in the field of denitrification in fixed film anoxic zones and explain the process of biological nitrogen removal

2.2 HISTORY OF FIXED FILM SYSTEMS

Mueller's development of the first fixed film system in 1865 occurred in a period of history where the western world was in the midst of the industrial revolution and with the urbanisation of cities came the spread of disease due to poor sanitation (Peters and Alleman, 1982). Between 1865 and 1908 the method of fixed film biological treatment was further advanced and implemented with the emergence of the trickling filter and contact bed (The Dow Chemical Company, 1971).

Between 1925 and 1950 extensive efforts were made to improve and upgrade trickling filter performance, including the development and adoption of technical standards for design loading, bed construction and system operation (Peters and Alleman, 1982). High-rate designs were also developed to increase the hydraulic capacity of trickling filters (Peters and Alleman, 1982). Early Rotating Biological Contactors (RBCs) were also developed during this period (Peters and Alleman, 1982).

However with the emergence of the activated sludge process and rapid advancements in the field of suspended growth biological treatment, the popularity of fixed film systems diminished (Peters and Alleman, 1982). Yet, the past 50 years has seen the emergence of plastic packing for trickling filters, advancements to RBC technology and the development of submersed fixed film systems (Peters and Alleman, 1982).

2.3 DENITRIFICATION IN FIXED FILM ANOXIC ZONES

During the last 50 years, increased environmental awareness has led to an increased demand for not only the removal of biochemically oxidisable material, as has been the focus in the past, but also the removal of nutrients (particularly Nitrogen). This has led to a rethink of the process of wastewater treatment worldwide and renewed interest in fixed film bioreactors.

As discussed in Dee *et al.* (1994), in the 1970s WRc plc performed extensive tests on parallel pilot, submersed fixed film filters operating in single filtration mode (without recirculation) at loading rates of about 0.1 kgBOD/m³.d to evaluate the performance of different types of media. The results of these tests indicated that single-filtration was only capable of removing up to 50% of the total nitrogen (Dee *et al.*, 1994). This research however only looked at single pass treatment of the wastewater and the filters were not maintained in an anoxic environment.

WRc plc also demonstrated that nitrogen could be removed from effluent in pilot flooded pebble or sand beds using methanol as the carbon source (Bailey and Thomas, 1975). The use of Methanol as the carbon source for post-anoxic submersed fixed film systems has also been researched by Hawkins *et al.* (1976). Although the use of methanol as a carbon source for post-anoxic systems have had proven success in the biological removal of nitrogen, the operating costs associated with this methanol dosing makes it an expensive process (Dee *et al.*, 1994).

Due to the expense associated with methanol dosing in post-anoxic systems, extensive research has also been conducted into the denitrification ability of pre-anoxic systems. Submerged mineral-media reactors, comprising an upstream anoxic unit which treats a mixture of settled sewage and nitrified effluent recycled from a downstream aerobic stage, have been used to remove total nitrogen with removal rates between 70% and 80% recorded (Dee *et al.*, 1994). However in order to achieve these removal rates large recycles (often 5-10 times raw sewage inflow) are required. This increases capital and operating costs due to the pumping requirements.

Dee *et al.* (1994) conducted a case study to evaluate the use of pre-denitrification versus post-denitrification (using a methanol dosed deep-bed sand filter) for nitrogen removal at a low-rate biological filter works. The findings of this study indicated that pre-denitrification was effective for the removal of nitrogen and were cost-competitive with the tertiary denitrification process involving methanol dosing (Dee *et al.*, 1994). Therefore the costs associated with pre-denitrification are comparative to post-denitrifying sand filters with methanol dosing.

The high costs associated with pre-anoxic systems are mainly due to the extra capital requirements and operating costs of the pumps. Pre-anoxic systems usually require large recycle streams which need to be pumped back to the trickling filter feed. This recycle stream can be up to ten (10) times the raw effluent flowrate. Therefore the costs associated with pumping and the extra capital costs associated with these pumps results in the pre-anoxic system costing about the same as a post-anoxic system which has methanol dosing.

The recent challenge for researches in this field has been to develop a post-anoxic system, capable of effective denitrification, without the need for methanol dosing. Researchers have conducted studies into the use various internal carbon sources such as activated sludge (Schreff and Wilderer, 1998 and Sekoulov *et al.*, 1990) or biologically hydrolysed sludge (Æsøy and Ødegaard, 1994). However the use of these carbon sources requires extra infrastructure as the sludge has to be either degraded anaerobically or aerobically or hydrolysed. This increases the initial capital outlay associated with the plant.

This thesis aims to determine whether effective denitrification can occur within a submersed fixed film post anoxic reactor using in internal carbon source which doesn't require pre-treatment. However in order to determine this it is necessary to understand the process of biological denitrification.

2.4 BIOLOGICAL DENITRIFICATION

Denitrification is the term used to describe the biological reduction of nitrate to nitric oxide, nitrous oxide and nitrogen gas (Metcalf and Eddy, 2003). Metcalf and Eddy (2003) report that there are two modes of nitrate removal that can occur in biological processes – assimilating and dissimilating nitrate reduction (see *figure 2.1*).

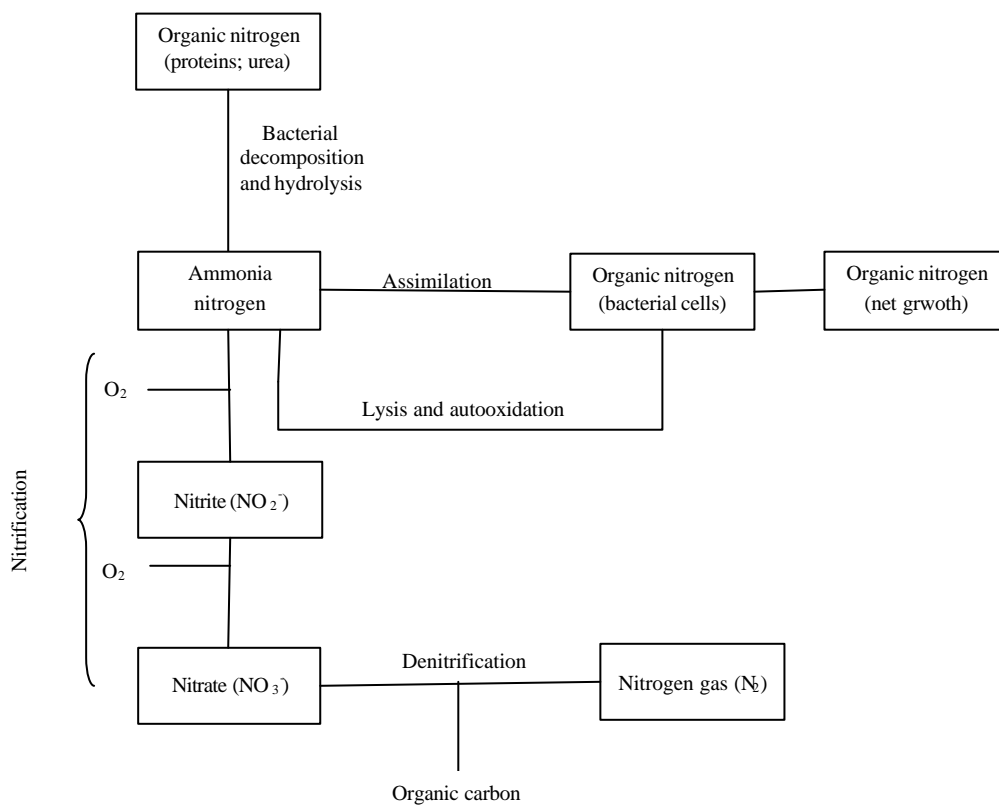
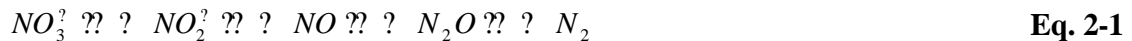


Figure 2.1 Nitrogen transformations in biological treatment processes (Metcalf and Eddy, 2003)

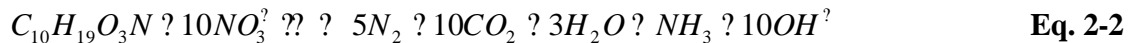
As *figure 2.1* illustrates, assimilating nitrogen reduction involves the reduction of nitrate to ammonia for use in cell synthesis (Metcalf and Eddy, 2003). This process is not involved in the scope of this thesis and therefore has not been thoroughly researched.

The process of biological denitrification or dissimilating nitrate reduction involves the biological oxidation of many organic substrates in wastewater treatment using nitrate and nitrite as the electron acceptor instead of oxygen (Metcalf and Eddy, 2003). Under anoxic (no free dissolved oxygen or limited dissolved oxygen) conditions bacteria use the nitrate and nitrite as their oxygen source. The reactions for biological denitrification, given in Metcalf and Eddy (2003), are expressed in equations **Eq 2-1**, **Eq 2-2** and **Eq 2-3**:

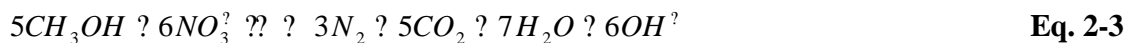


The last three components of **Eq. 2-1** (ie NO, N₂O and N₂) are gaseous and can be released into the atmosphere. The reaction stoichiometry for biological denitrification using wastewater or methanol as the carbon source (electron donator) is given in the following equations:

Wastewater:



Methanol:



The carbon source requirements for the reduction of nitrate to nitrite and nitrite to nitrogen gas are given by Pochana (1999) as 1.14 mgCOD/mgNO₃⁻-N and 2.28 mgCOD/mgNO₂⁻-N, respectively. Therefore, according to Pochana (1999), the total carbon requirement for complete biological denitrification to occur is 3.42 mgCOD/mgNO₃⁻-N. Barth *et al.* (1968) estimated that, as a general approximation, 4 grams of BOD is needed per gram of NO₃ reduced.

The background modelling literature, which forms the basis of the simulations performed in this thesis, is discussed in **Chapter 3**.

3 METHODOLOGY

3.1 INTRODUCTION

Following the literature review it was decided that in order to effectively compare the denitrification effectiveness of submersed fixed film pre and post anoxic zones around a trickling filter, without laboratory experiments, was to develop a computerised model to simulate the performance of the various systems. This involved the computerised design of the two biologically active operational units (trickling filter and anoxic tank) and the development of models to predict the performance of these units when placed in different configurations.

3.2 BASIS FOR UNIT DESIGN

The operational units that were required to model the various systems included a trickling filter, an anoxic tank and a clarifier. As this thesis is the first thesis in a series of two (2), with the experimental thesis validating the results of the modelling performed in this thesis, the design of the operational units was based on the practical limitations associated with the experiments.

The trickling filter and anoxic tank required for the experimentation aspect of this research (discussed in the experimental thesis) were provided by the Environmental Engineering Division of the University of Queensland. The reactors to be used in the experimental phase of this project in second semester will be modifications of existing reactors. Therefore the design of the systems, including the mechanisms within the systems, is constrained by dimensions of these reactors.

The trickling filter unit, as described by Ho *et al* (2003), is Acrylic with a diameter and height of 0.24m and 1.00m respectively. The column has feeding ports, aeration ports, liquid sampling ports, and solid sampling ports, as shown in *Figure 3.1*.

Acrylic Retort Water Treatment Column

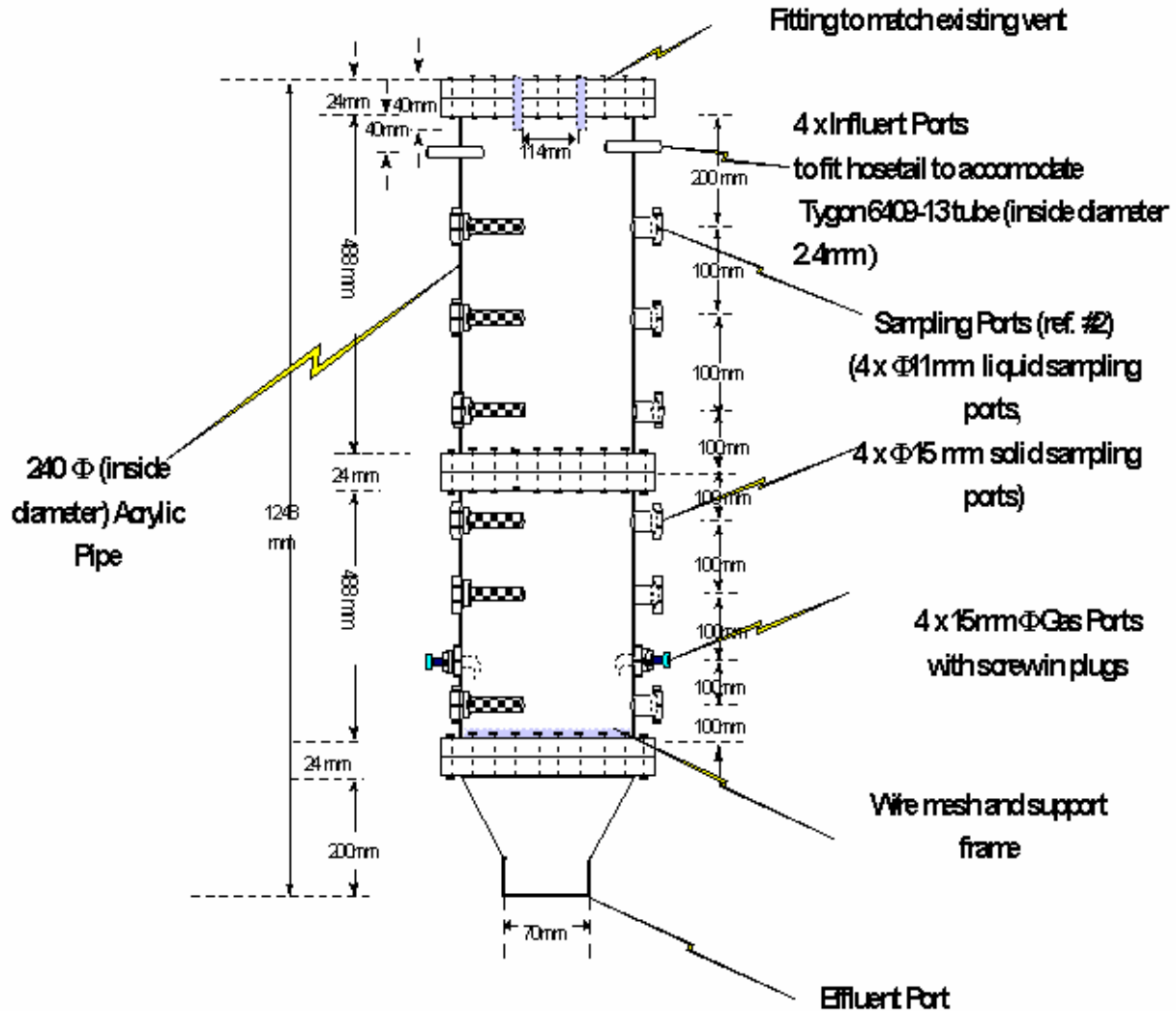


Figure 3.1 – Laboratory Trickling Filter that design is based on

Source: Ho et al (2003)

The trickling filter unit to be used in the experiments has a forced aeration system with air being drawn up through the filter bottom by a 114mm diameter 12V fan, centrally positioned 0.2m above the filter surface. It is assumed for modelling purposes that this system is sufficient to provide oxygen in excess within the trickling filter.

The anoxic tank to be used in the experimental analysis is to be a carbon copy of the trickling filter system except with out an aeration system (fan) and with the influent being fed from the bottom of the plant with the anoxic tank effluent being drawn off the top. The dimensions of the anoxic tank are the same as the trickling filter with the height and diameter of the system being 1.00m and 0.24m respectively.

As this thesis is focused on the computerised modelling of the nitrogen removal capacity of differently configured fixed film wastewater treatment systems, all calculations will be based on dissolved substrates (ie BOD, NH₄-N and NO₃-N). Consequently, the suspended solids within the system are disregarded and all BOD is considered to be soluble BOD. This assumption removes the requirement for a clarifier and simplifies the modelling. The clarifier will be designed during the experimental phase of this project.

Due to the size constraints of the units to be designed, a filtered sewage flow rate of 0.1m³/day has been assumed to be an appropriate flow rate. This flowrate has been used as the basis for the operational unit design and the base flowrate for the modelling of the different treatment systems.

3.3 TRICKLING FILTER DESIGN

As discussed previously trickling filters have been used for many years, therefore extensive research has been conducted into the mechanisms which occur within trickling filters and different ways of designing such systems. The approach used for this design is based on predominately empirical relationships used to determine the variation of substrate concentration with filter depth.

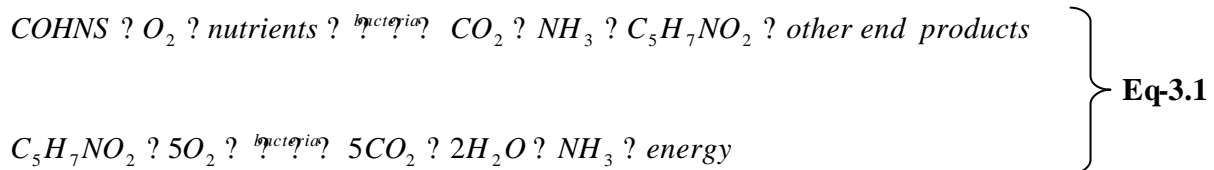
Due to the constraints of the design, conventional plastic packing was taken to be the packing used within the system as this form of packing provides a high specific surface area, which enables efficient contaminant removal, and is light which reduces the risk of damaging the unit and enables a tall tower trickling filter, rather than a traditional shallow trickling filter.

According to Metcalf and Eddy (2003) conventional plastic packing is characterised by the following physical properties:

? Nominal Size (mm)	61 x 61 x 122
? Approximate unit weight (kg/m ³)	30-80
? Approximate specific surface area (m ² /m ³)	90
? Void Space (%)	>95

The trickling filter has two roles – to biologically oxidise BOD and to biologically nitrify NH₄-N. The biological oxidation occurs due to the growth of heterotrophic bacterial while the biological nitrification involves autotrophic bacteria. Metcalf and Eddy (2003) state that both the biological oxidation of BOD and the biological nitrification of NH₄-N occur under oxygen rich conditions as expressed in the stoichiometric expressions **Eq-3.1** and **Eq-3.2** below:

Total biological oxidation reaction:



Total Biological Nitrification reaction:



In order to determine the variation of the concentration of the BOD and NH₄-N over the depth of the trickling filter the Schulze equation and the Okey and Anderson nitrification rate equation respectively were used. These equations with their associated nomenclature are provided in **Appendix A**.

Due to competition within the trickling filter's biofilm these two mechanisms do not occur in the same areas. The carbon oxidation reaction occurs in the upper portion of the trickling filter due to the higher specific growth rate of heterotrophic bacteria than the autotrophic nitrifying bacteria when the substrates for both are not present in rate limiting concentrations (Wanner and Gujer, 1985).

According to Daigger *et al* (1994), the transition from biological oxidation to biological nitrification occurs at a soluble BOD concentration of 20 mg/L. Therefore the system has been designed to reflect this (see **Appendix A**).

When assuming an influent flowrate of $0.1\text{m}^3/\text{day}$, influent BOD and $\text{NH}_4\text{-N}$ concentrations of 150mg/L and 25mg/L respectively, and a one pass system; the concentration gradients within the trickling filter, according to calculations given in **Appendix A**, are shown in *figure 3.2* and *figure 3.3*.

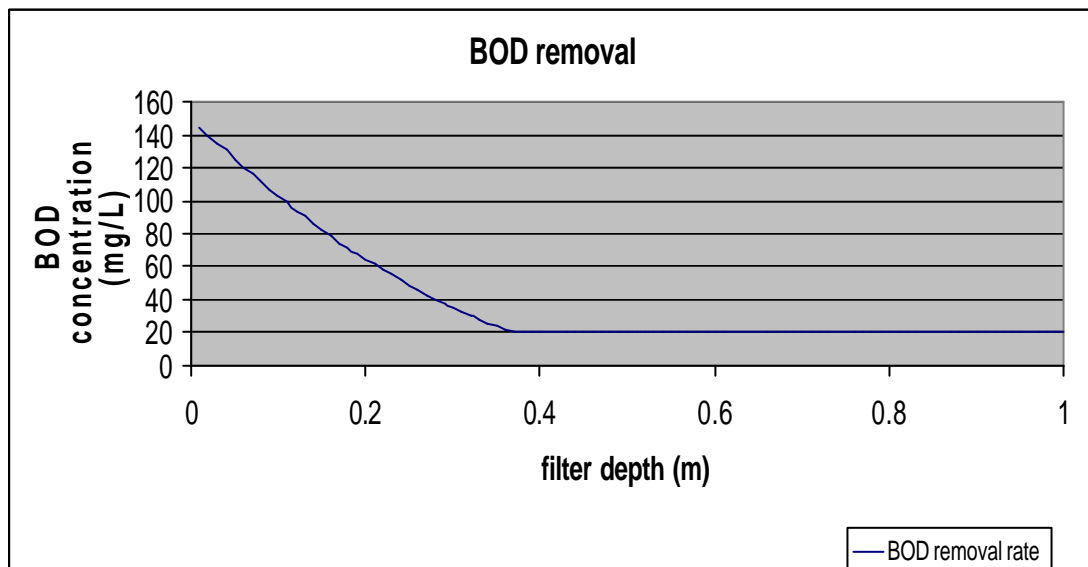


Figure 3.2 – BOD concentration profile within the trickling filter

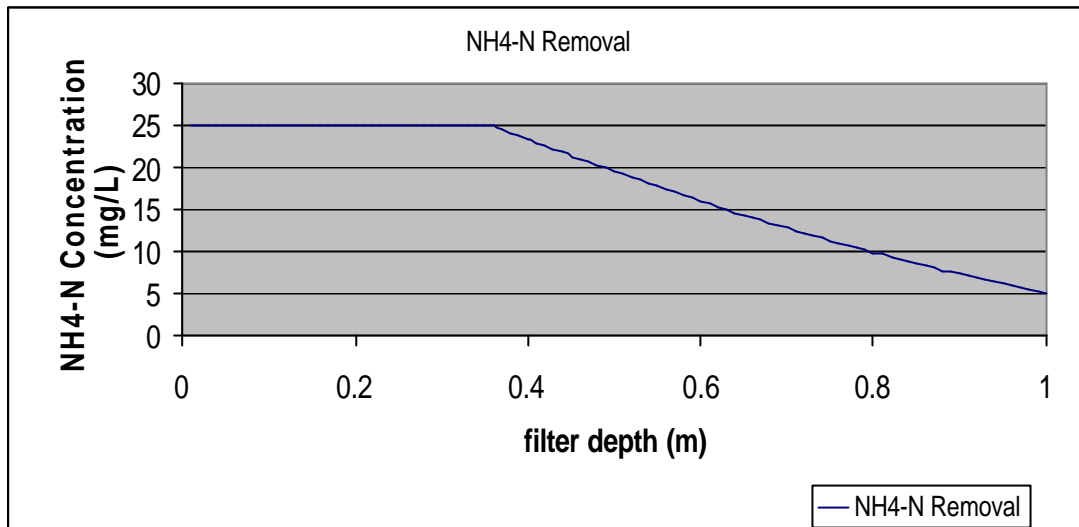


Figure 3.3 – NH₄-N concentration profile within the trickling filter

3.4 ANOXIC TANK DESIGN

In contrast to the trickling filter, limited research has been conducted into the concentration profiles within submersed fixed film anoxic systems. To date, the research undertaken into determining the concentration profiles within submersed fixed film/packed anoxic systems has taken a mass transfer approach derived from first principles. This approach has been used in the anoxic tank design.

Due to the constraints of the experimental equipment, the reactor height is set to be 1m with a diameter of 0.24m. The existing experimental equipment will be modified so that the anoxic zone operates as a packed upflow fixed film reactor. The packing to be used in the anoxic zone will be glass beads of diameter 0.01m and a density of 2900kg/m³ (Eramo *et al*, 1994).

The purpose of the anoxic zone is to enable biological denitrification to occur. This process, and the recent research conducted into it, has been discussed previously in **Section 2.4**.

The basis for this project's anoxic zone design was the mathematical model constructed by Eramo *et al* (1994). The equations and parameters supplied in this model were entered into the Matlab v(see **Appendix B**). It has been assuming that the inlet soluble BOD concentration and NO₃-N concentration are 20mg/L and 20mg/L respectively (taken from outlet of trickling filter design).

Using these initial conditions and the calculations provided in **Appendix B**, the concentration gradient of each substrate through the anoxic tank bed is provided in *figure 3.4* and *figure 3.5*.

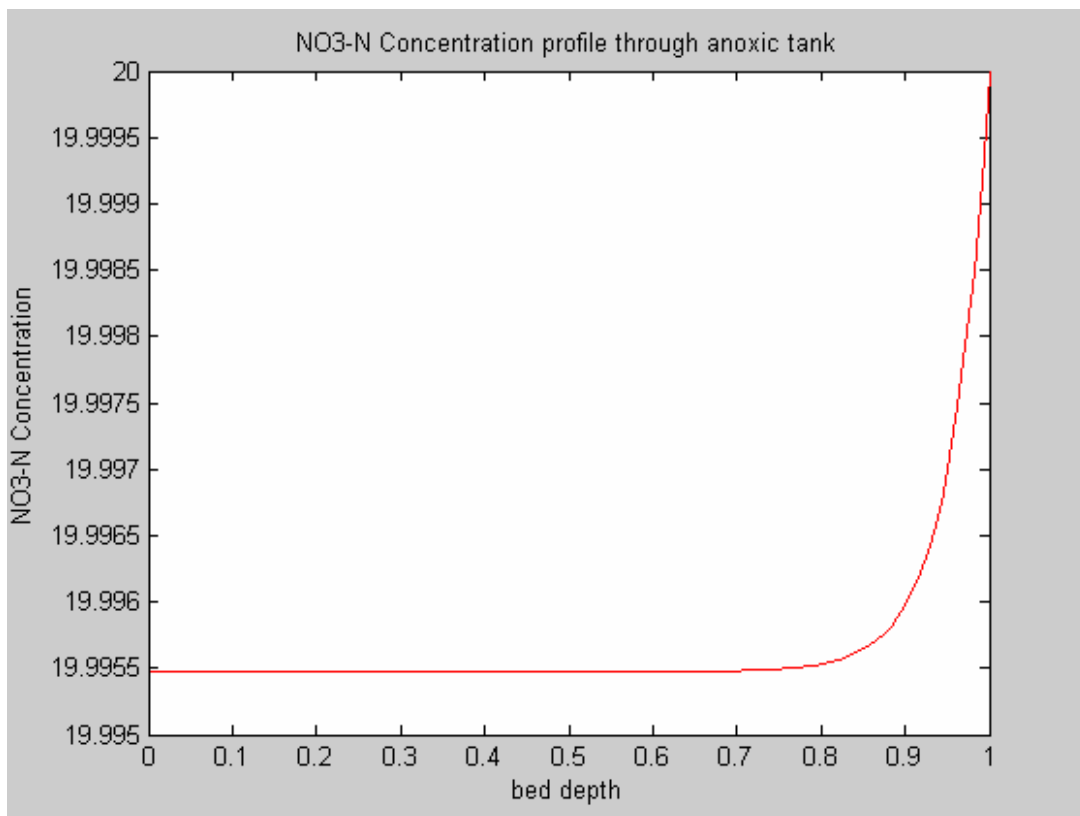


Figure 3.4 – NO₃-N Concentration profile through anoxic tank

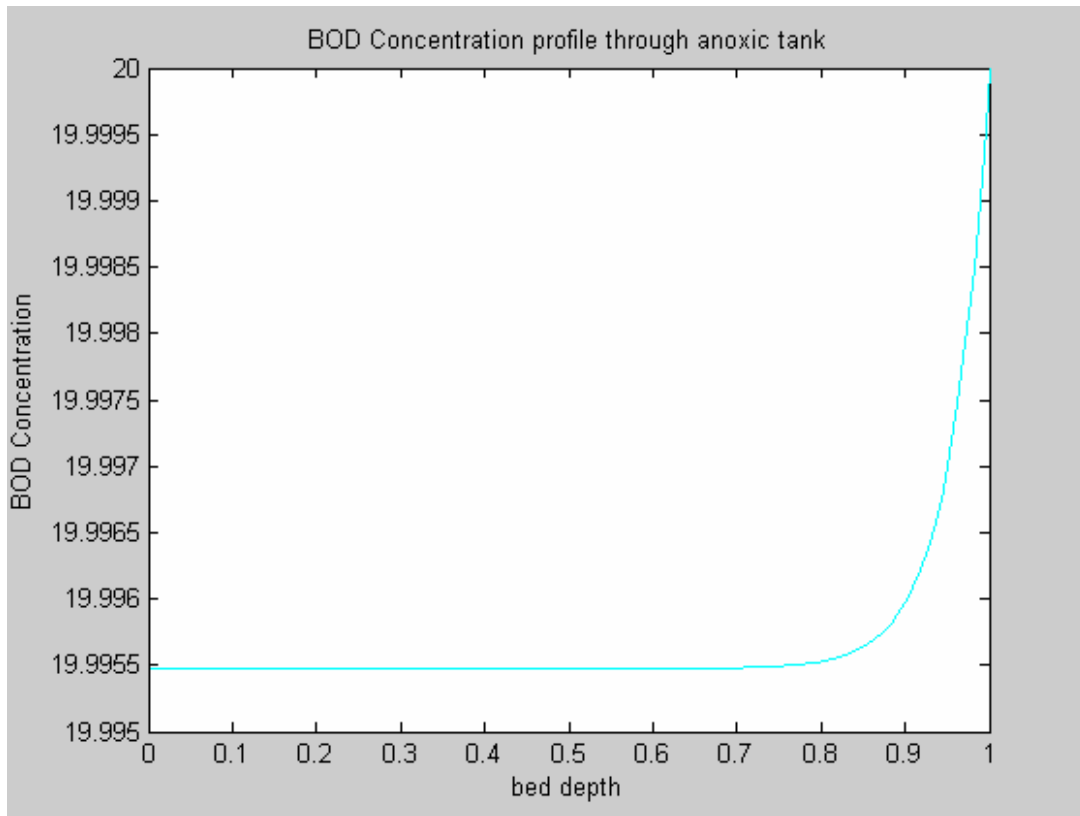


Figure 3.5 – BOD Concentration profile through anoxic tank

Figures 3.4 and 3.5 illustrate that the anoxic vessel as described by the model has very limited substrate removal (denitrification) capacity. The $\text{NO}_3\text{-N}$ and BOD concentrations were only reduced by approximately 0.0045mg/L , and this only occurred within the first 20cm of the filter height. This is a very poor denitrification rate and leads to a questioning of the mathematical model based on that by Eramo *et al* (1994).

Although this anoxic vessel model does not appear to be an accurate representation of the expected denitrification within an anoxic vessel, it has been used purely to enable a comparison between the nitrogen removal capacities of the different configurations of a trickling filter-anoxic tank system.

4 MODELS

4.1 INTRODUCTION

As the aim of this project was to determine whether it was possible and viable to achieve denitrification in fixed film domestic wastewater treatment systems without an additional carbon source, three (3) models have been created to determine the nitrogen removal capability of a trickling filter and an anoxic zone in different configurations. These models utilise the design calculations as described in **Chapter 3** and **Appendix A and B** to determine the expected effluent quality, in terms of BOD, $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$.

4.2 PRE-ANOXIC SYSTEM MODEL

The pre-anoxic system configuration, as shown in *figure 4.1* (also *figure 1.1*) is the first configuration to be analysed. This system is commonly used in industry as it does not require an external carbon source. The soluble carbon required in the denitrification process is sourced from the incoming raw sewage.

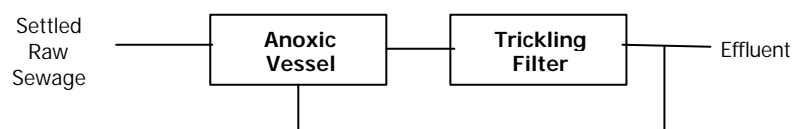


Figure 4.1 Pre-anoxic system configuration

4.2.1 Modelling Assumptions and Parameters

The basic assumptions used to develop the pre-anoxic system model are given below:

- ? The system is in steady state
- ? The composition of the settled raw sewage is constant
- ? Ammonia nitrogen ($\text{NH}_4\text{-N}$) is reduced to Nitrate nitrogen ($\text{NO}_3\text{-N}$) only.

The trickling filter and the anoxic tank have been designed separately in accordance with the procedure outlined in **Chapter 3** and the models developed in **Appendix A** and **Appendix B** respectively.

The inlet raw sewage flowrate of $0.1\text{m}^3/\text{day}$ is assumed to be constant. The contaminant concentration in the raw sewage has a BOD: NH_4 ratio of 150:25 mg/L. For the purpose of this modelling a one (1) times recycle ratio has been used.

4.2.2 Pre-Anoxic System Model Results

The pre-anoxic system model was developed by using the anoxic tank model and trickling filter model, developed in Chapter 3 to determine the concentration of contaminants everywhere within the system. The result of this modelling was a final effluent quality as given in Table 4.1 below:

Table 4.1 – Effluent Quality of Pre-Anoxic System Model

Effluent Quality Parameter	Effluent Concentration (mg/L)
BOD	20
$\text{NH}_4\text{-N}$	<0.1
$\text{NO}_3\text{-N}$	12.5

From this table it is possible to infer that the trickling filter is working to achieve satisfactory biological carbon removal and biological nitrification.

The concentration gradient of the substrates within the modelled trickling filter and the modelled anoxic filter are illustrated in *figures 4.2-4.5*. These concentration profiles further express the inadequacy of the modelled pre-anoxic filter in performing biological denitrification.

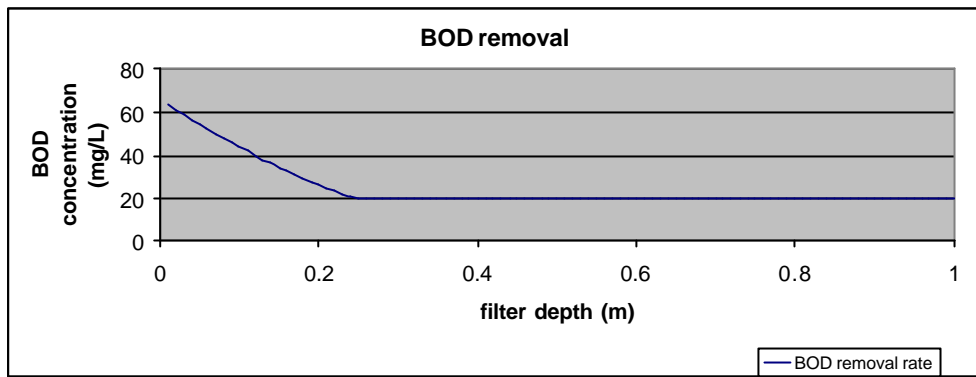


Figure 4.2 – BOD concentration profile within Trickling filter (Pre-Anoxic)

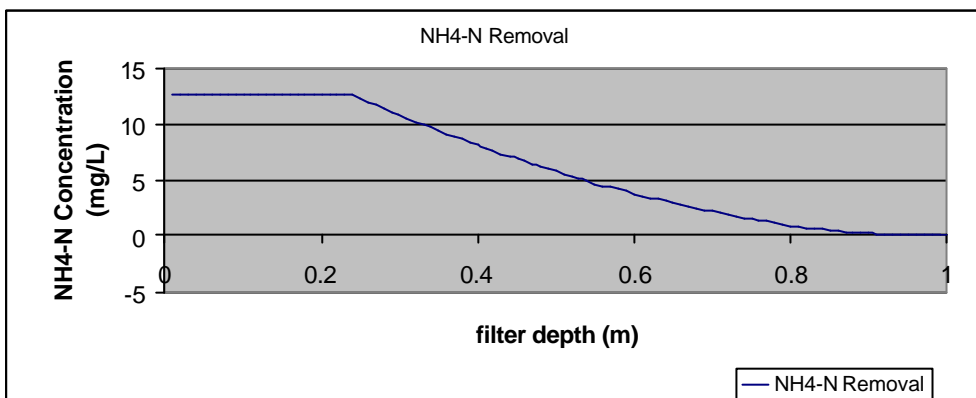


Figure 4.3 – NH₄-N concentration profile within Trickling filter (Pre-Anoxic)

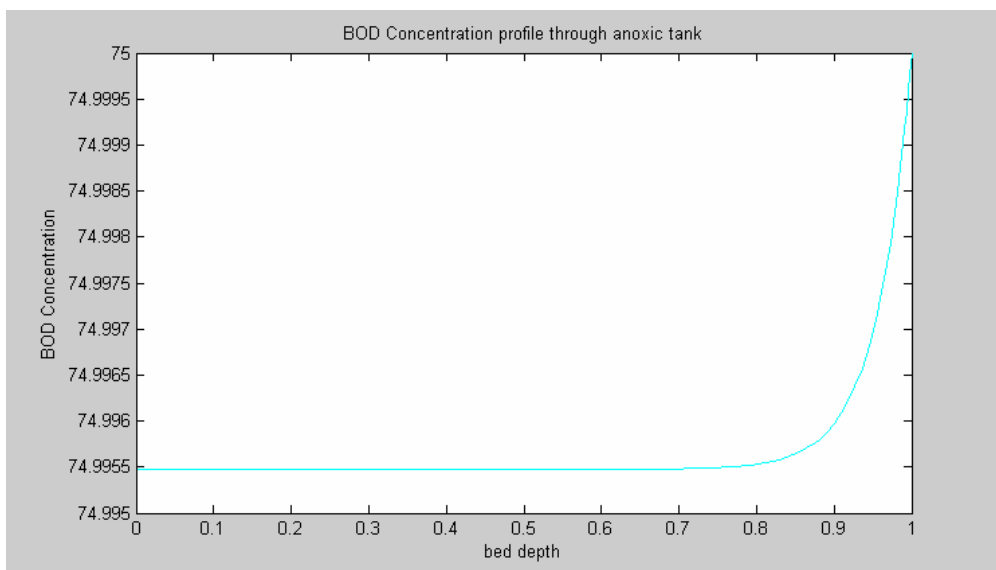


Figure 4.4 – BOD concentration profile within Anoxic filter (Pre-Anoxic)

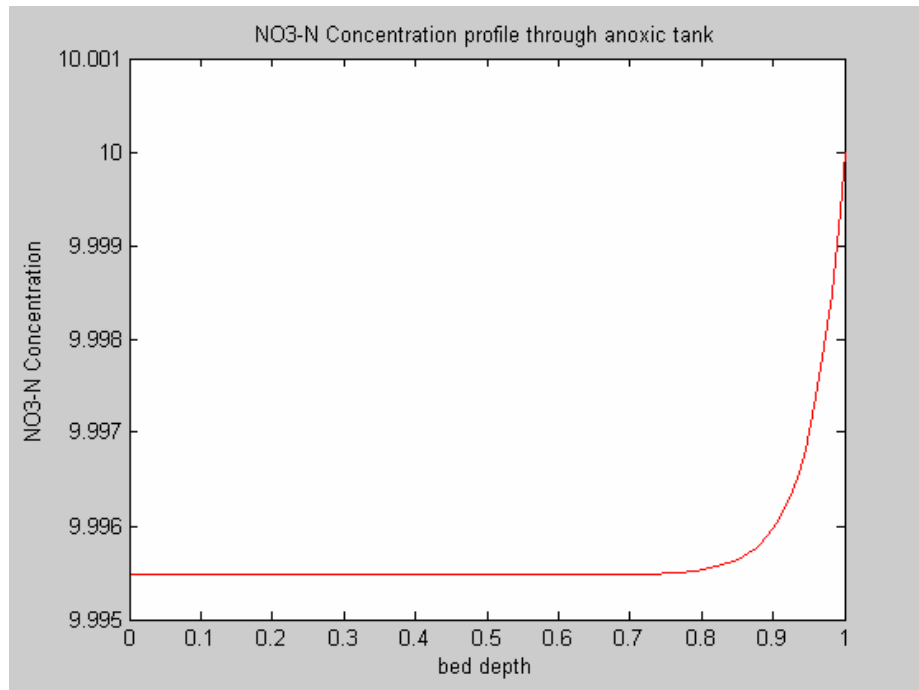


Figure 4.5 – $\text{NO}_3\text{-N}$ concentration profile within Anoxic filter (Pre-Anoxic)

The substrate concentrations at each point in the modelled pre-anoxic system are provided in **Appendix C**. The effluent substrate concentrations from the trickling filter and anoxic filter have been determined using the Trickling filter design model (**Appendix A**) and Anoxic zone design model (**Appendix B**) using the inlet concentrations determined by the pre-anoxic system model (**Appendix C**).

4.3 POST ANOXIC SYSTEM (OPTION 1)

The post-anoxic system model (see *figure 4.6*) is a slightly simplified version of the pre-anoxic system model. The purpose of this model is to determine the approximated nitrogen removal capacity of a post anoxic vessel without an additional carbon source whether that be internal or external.

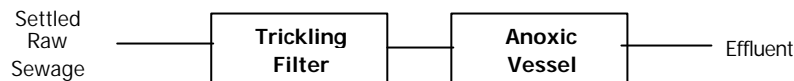


Figure 4.6 – Post anoxic system (option 1) configuration

This system, if viable, is the simplest trickling filter-anoxic vessel configuration. It should also have the best nitrogen removal capacity of all configurations as it follows the natural nitrogen cycle with nitrification followed by denitrification. The major problem however is that the soluble BOD which is removed in the trickling filter is required to enable biological denitrification to occur.

4.3.1 Modelling Assumptions and Parameters

As with the pre-anoxic model, this post anoxic system (option 1) has been modelled by determining the substrate concentrations at each point in the process. The substrate concentration profiles are determined by initial value substitution into the trickling filter design model and anoxic vessel design model developed in **Chapter 3** and given in **Appendix A** and **B** respectively.

The settled raw sewage parameters used are the same as those used in the pre-anoxic system model with the inlet settled raw sewage flowrate being constant at $0.1\text{m}^3/\text{day}$ and the raw sewage contaminant concentration, BOD: NH_4 ratio of 150:25 mg/L.

To simplify the model it is assumed that:

- ? The system is in steady state
- ? The ammonia nitrogen is completely reduced to nitrate nitrogen (ie nitrite not considered)
- ? All assumptions required for the trickling filter and anoxic vessel designs are also applicable to this situation.
- ? Only denitrification occurs in the anoxic filter

4.3.2 Post-Anoxic System (Option 1) Results

After developing a model to describe the system, using the trickling filter and anoxic vessel designs to calculate the concentration profiles, the effluent quality of this post anoxic system is given in **Table 4.2**:

Table 4.2 – Effluent Quality obtained from Post-Anoxic (option 1) System Model

Effluent Quality Parameter	Effluent Concentration (mg/L)
BOD	20
NH ₄ -N	4.5
NO ₃ -N	20.5

From **Table 4.2** it is possible to observe that while the trickling filter appears to be operating effectively in biologically oxidising the carbon material and reducing the ammonia nitrogen to nitrate nitrogen, the effluent nitrogen concentration is still high. This figure is much higher than that obtained from the pre-anoxic system model.

As this system does not contain a recycle, this effluent ammonia concentration is the best that may be obtained using the physical system defined. This figure may only be reduced in theory by increasing the trickling filter depth, thus increasing the autotrophic zone.

The concentration profiles in the trickling filter have been graphed in *figures 4.7 and 4.8*.

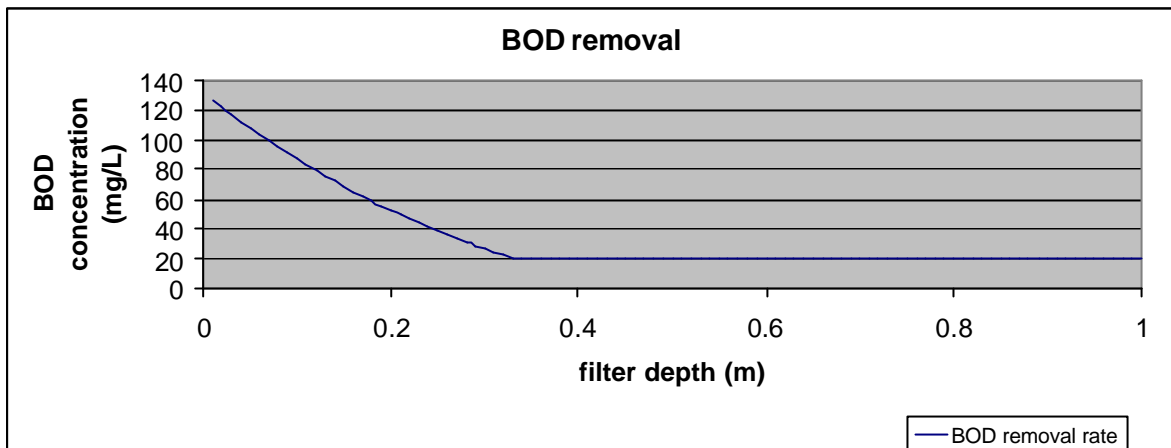


Figure 4.7 - BOD concentration profile within Trickling filter (Post Anoxic (Option 1))

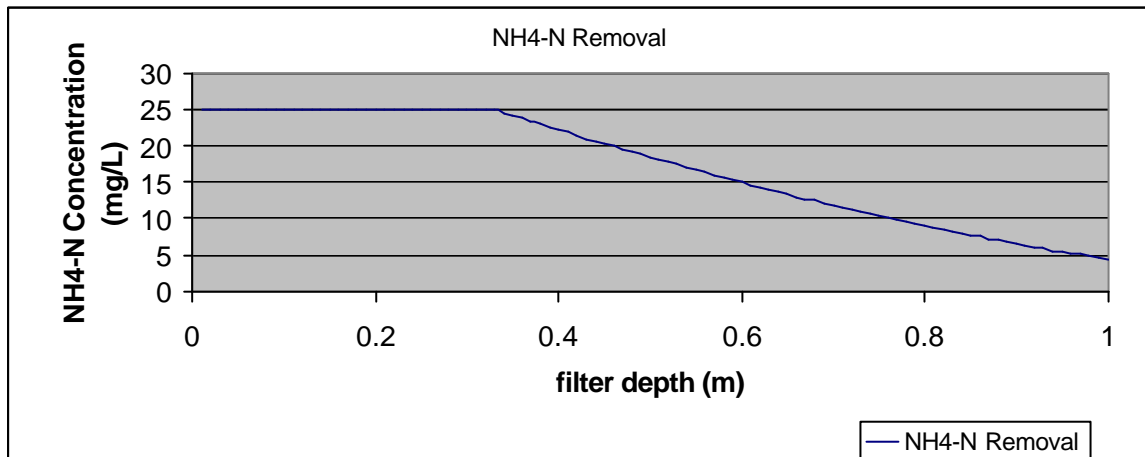


Figure 4.8 – NH₄-N concentration profile within Trickling filter (Post Anoxic (Option 1))

Table 4.2 also further illustrates the inadequacy of the designed anoxic vessel in achieving effective denitrification. This has led to a high effluent nitrate nitrogen concentration in the effluent. The substrate concentration profiles within the designed anoxic vessel are given in *Figures 4.9 and 4.10*.

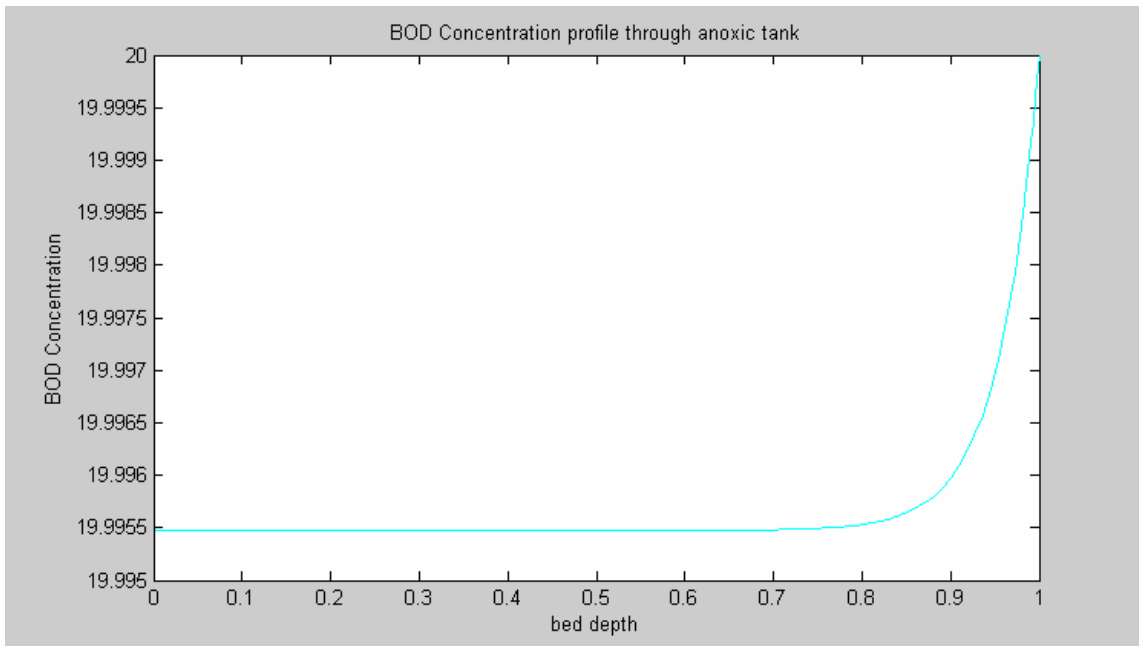


Figure 4.9 – BOD concentration profile within Anoxic vessel (Post Anoxic (Option 1))

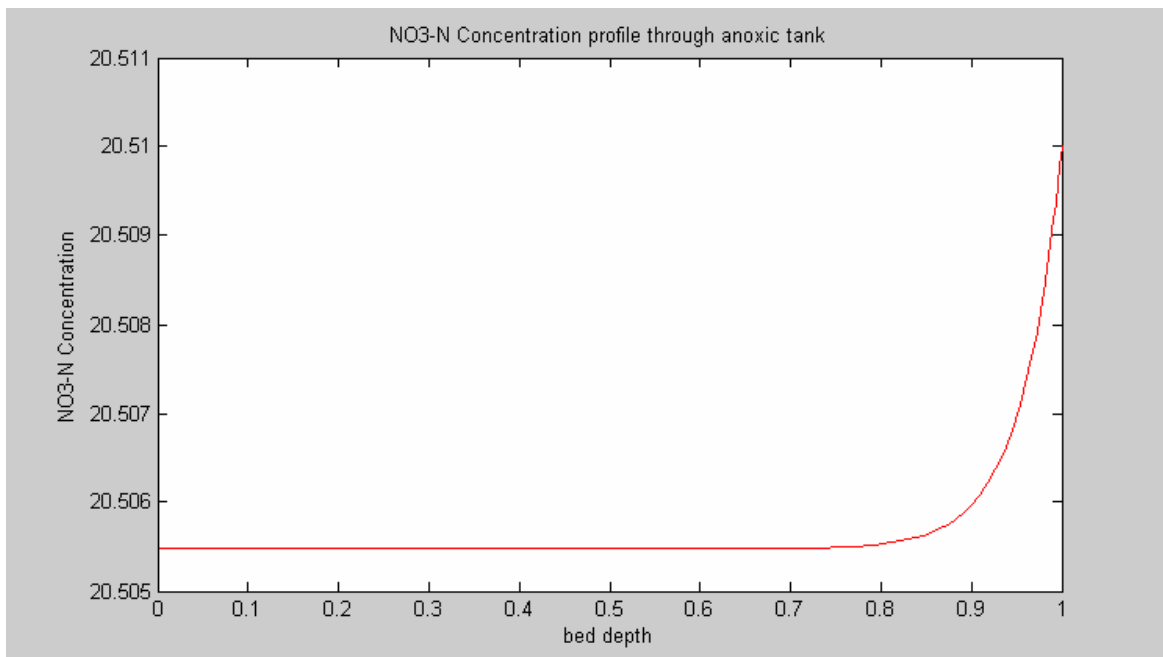


Figure 4.10 – NO₃-N concentration profile within Anoxic vessel (Post Anoxic (Option 1))

The substrate concentrations at each point in the modelled post-anoxic system (Option 1) are provided in **Appendix D**. The effluent substrate concentrations from the trickling filter and anoxic filter have been determined using the Trickling filter design model (**Appendix A**) and Anoxic zone design model (**Appendix B**) using the inlet concentrations determined by the post-anoxic system (option 1) model (**Appendix D**).

As this post anoxic system is greatly constrained by the physical size of the units, due to the absence of internal recycle streams, the nitrogen removal capacity is limited. Therefore, a post anoxic system with internal recycles was also modelled.

4.4 POST-ANOXIC SYSTEM (OPTION 2)

This post-anoxic system arrangement (see *figure 4.11*) is a combination of the pre-anoxic configuration and the simple post-anoxic configuration. This system has been designed as an alternative to the pre-anoxic system without the need for an additional carbon source.

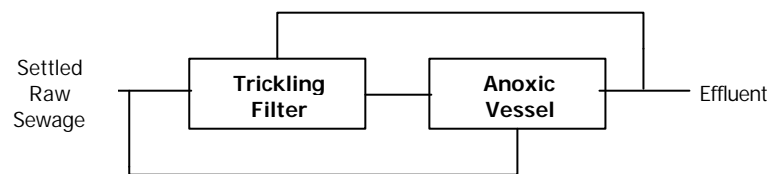


Figure 4.11 –Post Anoxic (Option 2) configuration

This system theoretically optimises the nitrogen removal by providing a raw sewage feed into the anoxic zone to provide a carbon source and an internal recycle to reduce the final effluent ammonia nitrogen and nitrate nitrogen concentrations.

4.4.1 Modelling Assumptions and Parameters

The system was modelled using the same assumptions and parameters as those used in the post-anoxic system (option 1). The only additional parameters for this system are the recycle ratio and the raw sewage split.

The recycle ratio is one (1) times the raw sewage flowrate which is the same as the recycle ratio used in the pre-anoxic system. The raw sewage split is assumed to be 80:20 with 80% of the raw sewage entering the trickling filter while the remaining 20% is diverted straight to the post-anoxic vessel.

4.4.2 Post Anoxic System (Option 2) Results

After running the post anoxic system (option 2) model, the effluent quality (as shown in Table 4.3) was achieved.

Table 4.3 – Effluent Quality obtained from Post-Anoxic (option 2) System Model

Effluent Quality Parameter	Effluent Concentration (mg/L)
BOD	46
NH ₄ -N	12.57
NO ₃ -N	20

From **Table 4.3** it is possible to determine that this system **is not** the optimal system for nitrogen removal. This system has the highest effluent BOD and ammonia nitrogen concentration out of the three systems modelled. This may be attributed to the fact that 20% of the BOD and total ammonia in the raw sewage effectively bypasses the treatment units. This also indicates that the one (1) times recycle may not be adequate for this system.

The concentration profiles for the BOD, NH₄-N and NO₃-N concentrations within the trickling filter and the anoxic zone are provided in *figures 4.12-4.15*.

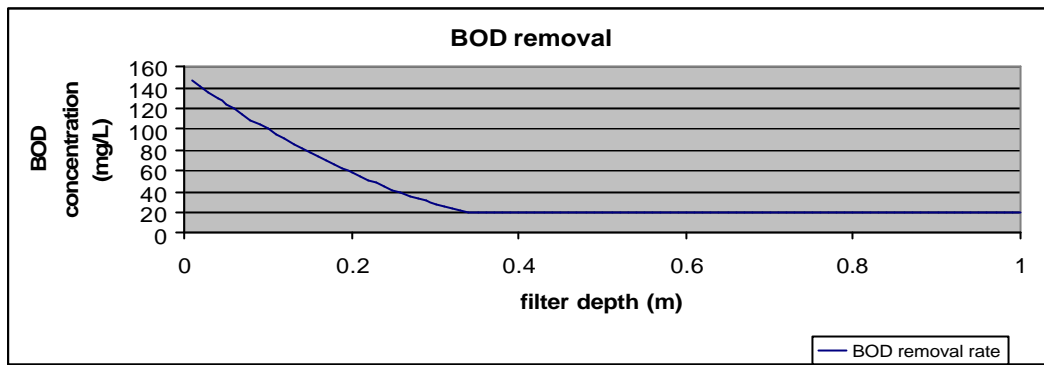


Figure 4.12 – BOD concentration profile within Trickling Filter (Post Anoxic (Option 2))

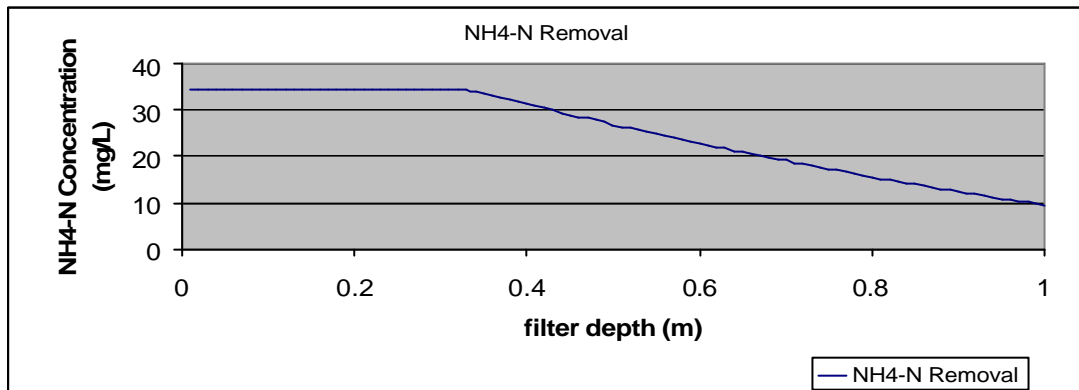


Figure 4.13 – NH₄-N concentration profile within Trickling filter (Post Anoxic (Option 2))

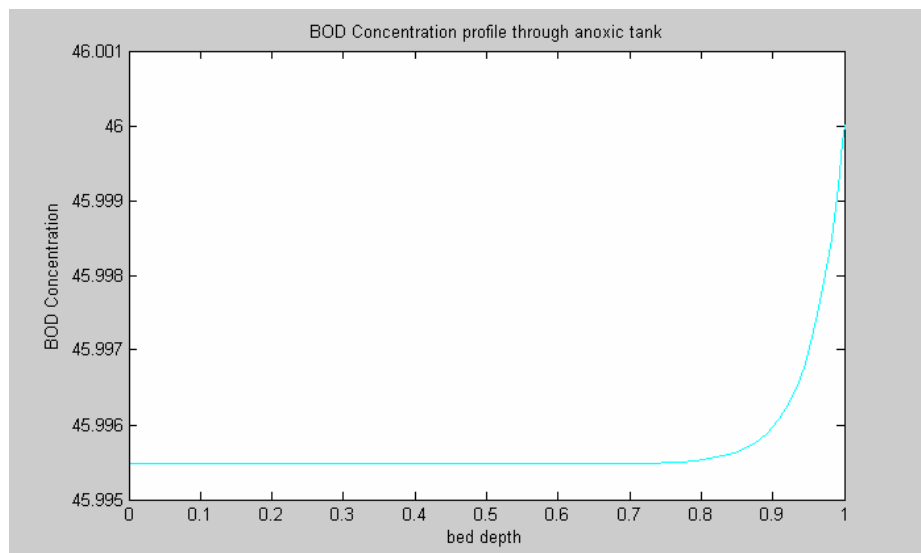


Figure 4.14 – BOD concentration profile within Anoxic vessel (Post Anoxic (Option 2))

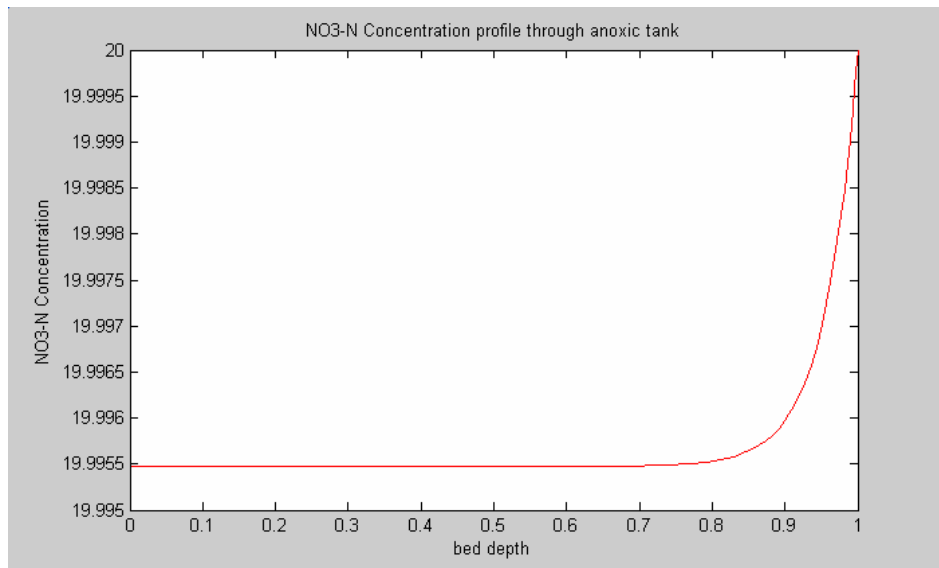


Figure 4.15 – NO₃-N concentration profile within Anoxic vessel (Post Anoxic (Option 2))

The substrate concentrations at each point in the modelled post-anoxic system (Option 2) are provided in **Appendix E**. The effluent substrate concentrations from the trickling filter and anoxic filter have been determined using the Trickling filter design model (**Appendix A**) and Anoxic zone design model (**Appendix B**) using the inlet concentrations determined by the post-anoxic system (option 2) model (**Appendix E**).

5 DISCUSSION

The trickling filter model developed in Chapter 3 is based on a combination of industrially and scientifically accepted empirical relations and differential balances. This model accurately follows the constraints listed in literature to not only provide concentration profiles for the substrates (ie BOD and $\text{NH}_4\text{-N}$) through the depth of the filter, it also clearly identifies the depth of the heterotrophic/autotrophic bacterial interface. This model has been accurately applied in the system designs.

Due to the complexity of the mass transport mechanisms within the anoxic vessel a complicated second order differential system of equations was used to develop models that describe the BOD and $\text{NO}_3\text{-N}$ concentrations through the depth of the vessel. These relations (based on the work by Eramo et al (1994)) were successfully solved using an ordinary differential equation (ODE) solver in Matlab. Although the resulting graphs had the expected profile, the amount of removal provided by the modelled system appeared inaccurate. The removal rates were less than expected which leads to the conclusion that either the model is not accurate or the model doesn't accurately describe the system. This model however was used in the system designs.

The three (3) trickling filter – anoxic vessel system configurations were modelled using a mass balance approach. The models took data from the trickling filter model and the anoxic vessel model (solved using the appropriate initial conditions) and utilized mass balances to determine the expected effluent quality. From this analysis the pre-anoxic system was the clear winner with the best effluent quality. The post-anoxic system with a raw sewage feed into the anoxic vessel (option 2) had the worst effluent quality. This can be attributed to the fact that the raw sewage feed to the post anoxic system effectively bypassed all treatment units. The three system models appeared to provide an accurate representation of the expected treatment.

6 CONCLUSIONS AND RECOMMENDATIONS

Therefore according to a literature survey the mathematical modelling, the pre-anoxic system is the best system for denitrification in fixed film domestic wastewater treatment systems without an additional carbon source.

The pre anoxic system comprises of an anoxic vessel placed in front of a trickling filter and a recycle from the trickling filter effluent to the anoxic vessel (see *figure 4.1*). This system, based on the mathematical modelling conducted provides 100% removal of Ammonia, approximately 87% removal of BOD and an effluent Nitrate concentration of 12.5mg/L.

Although the nitrate concentration in the pre-anoxic system effluent is a little high, this can be put down to the possible inaccuracy of the anoxic vessel design model as discussed in **Chapter 5**.

Therefore the pre-anoxic system is, from a modelling viewpoint, the best system for denitrification in fixed film domestic wastewater treatment systems without an additional carbon source.

It is however recommended that the models created in this project be applied to an experimental system to determine their accuracy. This experimental verification of the modelling performed is expected to be undertaken in the second half of this year.

7 REFERENCES

Æsøy, A. and Ødegaard, H. (1994) Denitrification in biofilms with biologically hydrolysed sludge as carbon source, *Wat. Sci. Tech.*, **29**(10-11), 93-100.

Bailey, D.A. and Thomas, E.V. (1975) The removal of inorganic nitrogen from sewage effluents by biological denitrification, *Journal of the Institute of Water Pollution Control*, **74**(5), 497-515.

Barth, E.F. *et al.* (1968) Chemical Biological Control of Nitrogen and Phosphorus in Wastewater Effluent, *Water Research Journal*, **33**.

Daigger, G.T. *et al.* (1994) Practical Experience with Combined Carbon Oxidation and Nitrification in Plastic Media Trickling Filters, *Wat. Sci. Tech.*, **29**(10-11), 189-196.

Dee A. *et al.* (1994) Pre- or Post-Denitrification at Biological Filter Works? A Case Study, *Wat. Sci. Tech.*, **29**(10-11), 145-155.

Do D. (2004) *CHEE4009 - Transport Phenomena: Lecture Notes*, [online]. Brisbane, University of Queensland. Available from: <http://www.eng.uq.edu.au/cpb/file.asp?ID=171> [Accessed 14th May 2004]

Eramo, B. *et al.* (1994) Validation of a multisubstrate mathematical model for the simulation of the denitrification process in fluidized bed biofilm reactors, *Wat. Sci. Tech.*, **29**(10-11), 401-408.

Ho, N.M. *et al.* (2003) Development of a Waste Water Treatment Process for the Stuart Oil Shale Project, *Proceedings of AWA 20th Convention - Ozwater: Innovations in Water*, Perth, Australia.

Metcalf and Eddy Inc. (2003) *Wastewater Engineering: Treatment and Reuse*, Fourth Edition, New York, McGraw-Hill.

Peters, R.W. and Alleman, J.E. (1982) The History of Fixed Film Wastewater Treatment Systems, *Proceedings of the 1st International Conference on Fixed-Film Systems*, Kings Island, Ohio, p. 60 – 88.

Pochana, K. (1999) *Simultaneous nitrification and denitrification in wastewater treatment process*, Unpublished M.Eng. thesis, University of Queensland.

Schreff, D. and Wilderer, P.A. (1998) Nitrogen Removal in Multi-Stage Wastewater Treatment Plants by using a modified Post-Denitrification System, *Wat. Sci, Tech.*, **37**(9), 151-158.

Sekoulov, I. *et al.* (1990) Post-Denitrification with Controlled Feeding of Activated Sludge as H Donator, *Wat. Sci, Tech.*, **22**(7/8), 161-170.

The Dow Chemical Company (1971) *A Literature search and critical analysis of biological trickling filter studies*, Midland, Michigan, Environmental Protection Agency.

Treybal, R.E. (1981) *Mass-Transfer Operations*, Third Edition, Singapore, McGraw-Hill.

Viotti, P. *et al* (2002) Development and calibration of a mathematical model for the simulation of the biofiltration process, *Advances in Environmental Research*, **7**, 11-33.

Wanner, O. and Gujer, W. (1985) Competition in Biofilms. *Wat. Sci, Tech.*, **17**(2/3), 27-39.

APPENDIX A – TRICKLING FILTER DESIGN CALCULATIONS

DESIGN CONDITIONS

Influent Characteristics

Item	Unit	Primary Effluent
Flow	m ³ /d	0.10
BOD (soluble)	mg/L	150.00
TSS	mg/L	80.00
NH ₄ -N	mg/L	25.00
TKN	mg/L	25.00

Packing Characteristics

Constant characteristic of packing used	n	0.5
Approx. specific surface area of packing (m ² /m ³)	As	90 (plastic - conventional)

Trickling Filter Characteristics

Filter height (m)	1.00
Filter diameter (m)	0.24
Filter cross section area (m ²)	0.05

EQUATIONS

1. Concentration of BOD in trickling filter with respect to depth

$$S_e = S_o e^{-kD/Q^n} \quad \text{where } k = k_1 \frac{D_1^{0.5} S_1^{0.5}}{D_2 S_2} \quad (\text{Metcalf and Eddy, 2003})$$

Nomenclature:

S_e = BOD concentration in settled filter effluent, mg/L (g/m^3)

S_o = influent BOD concentration, mg/L (g/m^3)

k = normalised value of k for the site-specific packing depth and influent BOD concentration

D = depth of packing, m

Q = hydraulic application rate, $\text{m}^3/\text{m}^2 \cdot \text{d}$

n = constant, characteristic of packing used

k_1 = k value at depth of 6.1m and influent BOD of 150 mg/L (g/m^3)

S_1 = 150 g BOD/ m^3

S_2 = site specific influent BOD concentration, g BOD/ m^3

D_1 = 6.1m packing depth, m

D_2 = site specific packing depth, m

From Metcalf and Eddy (2003):

$k_1 = 0.210 (\text{L}/\text{s})^{0.5}/\text{m}^2$ (for Domestic Sewage)

$n = 0.50$ for conventional plastic packing

2. Concentration of Ammonia nitrogen in trickling filter with respect to depth

$$R_n = 0.82 \left(\frac{\text{BOD}}{\text{TKN}} \right)^{0.44} \quad (\text{Metcalf and Eddy, 2003})$$

Nomenclature:

R_n = nitrification rate, g N/ $\text{m}^2 \cdot \text{d}$

$\frac{\text{BOD}}{\text{TKN}}$ = influent BOD to TKN ratio, g/g

LIMITING FACTORS

Carbon oxidation occurs in the upper portion of the trickling filter due to the higher specific growth rate of heterotrophic bacteria than the autotrophic nitrifying bacteria when the substrates for both are not present in rate limiting concentrations (Wanner and Gujer, 1985).

The transition from biological oxidation to biological nitrification occurs at a soluble BOD concentration of 20 mg/L (Daigger *et al*, 1994).

Therefore if:

BOD concentration > 20 mg/L	No nitrification occurs
BOD concentration < 20 mg/L	No BOD oxidation occurs

This has been modelled in excel (see following pages).

Depth of Trickling filter (m)	TF BOD concentration (mg/L)	TF NH4-N Concentration (mg/L)
0.01	144.8574507	25
0.02	139.8053646	25
0.03	134.8437271	25
0.04	129.9725234	25
0.05	125.1917377	25
0.06	120.501354	25
0.07	115.9013555	25
0.08	111.3917246	25
0.09	106.9724435	25
0.1	102.643493	25
0.11	98.40485365	25
0.12	94.25650492	25
0.13	90.19842546	25
0.14	86.23059294	25
0.15	82.35298406	25
0.16	78.56557443	25
0.17	74.86833849	25
0.18	71.26124947	25
0.19	67.74427925	25
0.2	64.31739829	25
0.21	60.98057551	25
0.22	57.73377817	25
0.23	54.57697172	25
0.24	51.51011966	25
0.25	48.53318337	25
0.26	45.64612192	25
0.27	42.84889186	25
0.28	40.14144698	25
0.29	37.52373802	25
0.3	34.99571239	25
0.31	32.55731383	25
0.32	30.20848196	25
0.33	27.94915188	25
0.34	25.7792536	25

0.35	23.69871144	25
0.36	21.70744333	25
0.37	20	24.60525921
0.38	20	24.19888577
0.39	20	23.79547919
0.4	20	23.39504553
0.41	20	22.99759092
0.42	20	22.60312158
0.43	20	22.2116438
0.44	20	21.82316392
0.45	20	21.43768839
0.46	20	21.05522373
0.47	20	20.67577652
0.48	20	20.29935346
0.49	20	19.9259613
0.5	20	19.55560691
0.51	20	19.18829721
0.52	20	18.82403925
0.53	20	18.46284015
0.54	20	18.10470713
0.55	20	17.74964752
0.56	20	17.39766872
0.57	20	17.04877827
0.58	20	16.70298379
0.59	20	16.36029302
0.6	20	16.02071381
0.61	20	15.68425412
0.62	20	15.35092204
0.63	20	15.02072575
0.64	20	14.69367359
0.65	20	14.36977401
0.66	20	14.04903558
0.67	20	13.73146703
0.68	20	13.41707721
0.69	20	13.10587513
0.7	20	12.79786991
0.71	20	12.49307086
0.72	20	12.19148744
0.73	20	11.89312925
0.74	20	11.59800607
0.75	20	11.30612785
0.76	20	11.01750472
0.77	20	10.73214699
0.78	20	10.45006515
0.79	20	10.17126989
0.8	20	9.895772118
0.81	20	9.623582923
0.82	20	9.354713628
0.83	20	9.089175776
0.84	20	8.826981142

0.85	20	8.56814174
0.86	20	8.312669838
0.87	20	8.060577961
0.88	20	7.811878903
0.89	20	7.566585742
0.9	20	7.324711846
0.91	20	7.086270887
0.92	20	6.851276857
0.93	20	6.619744077
0.94	20	6.391687214
0.95	20	6.167121296
0.96	20	5.946061729
0.97	20	5.728524315
0.98	20	5.514525271
0.99	20	5.304081247
1	20	5.097209352

APPENDIX B – ANOXIC TANK DESIGN CALCULATIONS

The following Matlab code is based predominately on the equations supplied by Eramo et al (1994). Two different Matlab models were created to model the depth varying behaviour of both the NO₃-N and BOD concentrations within the anoxic tank packing. The output of these models is provided in figure 3.4 and 3.5.

This code forms the basis of the anoxic tank design calculations. In modelling the different configurations of the system these models will be used and altered by changing the initial conditions.

In order to develop these models some basic assumptions were used. These include:

- ? Substrates (BOD and NO₃-N) are dissolved in the liquid phase and do not influence the fluid motion;
- ? Biomass is attached to the support medium particles, the quantity of biomass is negligible, and consequently no biodegradation occurs in the liquid phase;
- ? Movement in the filter is monodimensional;
- ? Liquid phase moves through the reactor by convection and turbulent diffusion;
- ? The support medium characteristics are uniform through the bed height;
- ? Initial porosity is assumed constant through the bed height;
- ? There are steady-state conditions;
- ? Removal kinetics of each NO₃-N is limited by the concentration of the substrate itself and soluble BOD;
- ? The bulk liquid within the filter has an association factor of 2.26 (ie same as for water)
- ? The diffusivity of substrates through the bulk liquid in the filter follows the Wilke and Chang empirical correlation (Treybal, 1981).

NO3-N Function File

```
function dydz = Anoxicanf(z,y)
```

```
%-----
```

```
% Function file for the NO3-N concentration in the Anoxic Tank
```

```
%
```

```
% Driver is Anoxicand.m
```

```
%
```

```
% States:    y(1) Concentration of NO3-N in anoxic tank
```

```
%          y(2) Concentration gradient of NO3-N in anoxic tank (f(1))
```

```
%-----
```

```
% set parameters and constants
```

```
rhobd = 102; % Concentration of the biomass in the biofilm (kg/m3)      (Eramo et al, 1994)
```

```
K = 6.0;    % Maximum velocity of substrate use (kgBOD/kgVSS.d)      (Eramo et al, 1994)
```

```
Ksn = 0.005; % NO3-N Saturation Constant (kg NO3-N/m3)      (Eramo et al, 1994)
```

```
Dz = 0.01; % Axial Dispersion coefficient (m2/s)      (Eramo et al, 1994)
```

```
Db = 0.24; % Diameter of the anoxic tank (m)
```

```
V = 0.01; % Volumetric influent flowrate (m3/s)
```

```
phi = 2.26; % Association factor for solvent (water)      (Treybal, 1981)
```

```
Mb = 18.0; % Molecular weight of solvent (water) (kg/kmol)
```

```
T = 293; % Temperature (K)
```

```
mu = 0.001005; % Solution viscosity (kg/m.s)      (Viotti et al, 2002)
```

```
dp = 0.02; % Bioparticle diameter (m)
```

```
rho = 1122 ; % Density of the liquid phase (kg/m3)      (Eramo et al, 1994)
```

```
epsilon = 0.97; % porosity of bed      (Metcalf and Eddy, 1991)
```

```
Nbi = 20; % influent NO3-N concentration (mg/L)
```

```
Hb = 1; %Height of filter bed
```

% solve the algebraics sequentially (check order must be sequential)

$$A_b = \pi \cdot (D_b/2)^2; \quad \% \text{ Cross sectional area of anoxic tank (m}^2\text{)}$$

$$u = V/A_b; \quad \% \text{ Influent velocity (m/s)}$$

$$V_m = (D_b/d_m) \cdot (H_b/d_m) \cdot ((4/3) \cdot \pi \cdot (d_m/2)^3); \quad \% \text{ Volume of support media (m}^3\text{)}$$

$$v_{an} = 15.6 + (3 \cdot 7.4); \quad \% \text{ NO}_3\text{-N molal volume at normal boiling point (m}^3\text{/kmol)}$$

(Treybal, 1981)

$$D_{sln} = ((117.3 \cdot 10^{-18}) \cdot (\phi \cdot M_b)^{0.5} \cdot T) / (\mu \cdot v_{an})^{0.6};$$

% Diffusivity of NO₃-N in bulk liquid (m²/s)
(Treybal, 1981)

$$D_{sbn} = D_{sln} \cdot 0.8; \quad \% \text{ Diffusivity of NO}_3\text{-N in biofilm (m}^2\text{/s)} \quad (\text{Viotti et al, 2002})$$

$$Sc_n = \mu / (D_{sln} \cdot \rho); \quad \% \text{ Schmidt number for NO}_3\text{-N substrate} \quad (\text{Viotti et al, 2002})$$

$$Re = (u \cdot \rho \cdot d_p) / \mu; \quad \% \text{ Reynolds number} \quad (\text{Viotti et al, 2002})$$

$$K_{cn} = (109/\epsilon) \cdot Re^{1/3} \cdot Sc_n^{1/3} \cdot (D_{sln}/d_p);$$

% Mass exchange coefficient for NO₃-N (Viotti et al, 2002)

$$R_{ln} = (y(1) / (K_{sn} + y(1))) \cdot K_{cn}; \quad \% \text{ Consumption rate of the substrates}$$

$$R_{vn} = (R_{ln} \cdot (1 - \epsilon - (V_m / (H_b \cdot A_b))));$$

% Removal rate of NO₃-N per unit bed volume
(Eramo et al, 1994)

% evaluate the differential equation

$$dy/dz = [y(2); (R_{vn} + (u \cdot y(2))) / D_z];$$

NO₃-N Driver File

```
%-----  
% Driver for NO3-N concentration profile  
% through the biofilm depth  
%  
% Non-stiff solver: ODE45  
%-----  
  
% set parameters for the solvers  
toler = input('What local error tolerance do you want? (eg. 1e-3) ');  
tt=cputime ;  
  
% call the solvers  
opts=odeset('AbsTol',toler,'RelTol',toler);  
[z,y] = ode45(@Anoxicanf, [1.0 0], [20; 0.1]);  
elap = cputime - tt ;  
fprintf('Execution time = %5.3f seconds\n',elap)  
  
% analyze results  
steps = length(z) ;  
fprintf('Number of steps = %4.0f\n',steps)  
fprintf('Local error tolerance = %g\n',toler)  
  
% plot results  
plot(z,y(:,1),'r')  
xlabel('bed depth')  
ylabel('NO3-N Concentration')  
title('NO3-N Concentration profile through anoxic tank')
```


BOD function file

```
function dydz = Anoxicacf(z,y)
```

```
%-----
```

```
% Function file for the BOD concentration in the Anoxic Tank Model
```

```
%
```

```
% Driver is Anoxicnd.m
```

```
%
```

```
% States:    y(1) Concentration of BOD in anoxic tank
```

```
%          y(2) Concentration Gradient of BOD in anoxic tank
```

```
%-----
```

```
% set parameters and constants
```

```
rhobd = 102; % Concentration of the biomass in the biofilm (kg/m3)      (Eramo et al, 1994)
```

```
K = 6.0;    % Maximum velocity of substrate use (kgBOD/kgVSS.d)      (Eramo et al, 1994)
```

```
Cs = 5.98; % Consumption ratio between the two substrates            (Eramo et al, 1994)
```

```
Ksc = 0.03; % BOD Saturation Constant (kg BOD/m3)                   (Eramo et al, 1994)
```

```
Dz = 0.01; % Axial Dispersion coefficient (m2/s)                     (Eramo et al, 1994)
```

```
Db = 0.24; % Diameter of the anoxic tank (m)
```

```
V = 0.01; % Volumetric influent flowrate (m3/s)
```

```
phi = 2.26; % Association factor for solvent (water)                 (Treybal, 1981)
```

```
Mb = 18.0; % Molecular weight of solvent (water) (kg/kmol)
```

```
T = 293;   % Temperature (K)
```

```
mu = 0.001005; % Solution viscosity (kg/m.s)                         (Viotti et al, 2002)
```

```
dp = 0.02;    % Bioparticle diameter (m)
```

```
rho = 1122 ;  % Density of the liquid phase (kg/m3)                 (Eramo et al, 1994)
```

```
epsilon = 0.97; % porosity of bed                                    (Metcalf and Eddy, 1991)
```

```
Cbi = 20;    % influent BOD concentration (mg/L)
```

```
Hb = 1;     % height of filter bed (m)
```

% solve the algebraics sequentially (check order must be sequential)

$Ab = \pi * (Db/2)^2;$ % Cross sectional area of anoxic tank (m²)

$Vm = (Db/dm) * (Hb/dm) * ((4/3) * \pi * (dm/2)^3);$ % Volume of support media (m³)

$u = V/Ab;$ % Influent velocity (m/s)

$vac = (10 * 14.8) + (19 * 3.7) + (3 * 7.4) + 15.6;$

% BOD molal volume at normal boiling point (m³/kmol) (Treybal, 1981)

$Dslc = ((117.3 * 10^{(-18)}) * (\phi * Mb)^{0.5} * T) / (\mu * vac)^{0.6};$

% Diffusivity of BOD in bulk liquid (m²/s) (Treybal, 1981)

$Dsbc = Dslc * 0.5;$ % Diffusivity of BOD in biofilm (m²/s) (Viotti et al, 2002)

$Sc = \mu / (Dslc * \rho);$ % Schmidt number for BOD substrate (Viotti et al, 2002)

$Re = (u * \rho * dp) / \mu;$ % Reynolds number (Viotti et al, 2002)

$Kcc = (109 / \epsilon) * Re^{(1/3)} * Sc^{(1/3)} * (Dslc / dp);$

% Mass exchange coefficient for BOD (Viotti et al, 2002)

$Rlc = (y(1) / (Ksc + y(1))) * Kcc;$ % Consumption rate of the substrates

$Rvc = (Rlc * (1 - \epsilon - (Vm / (Hb * Ab))));$ % Removal rate of BOD per unit bed volume
(Eramo et al, 1994)

% evaluate the differential equations

$dy/dz = [y(2); ((Cs * Rvc) + (u * y(2))) / Dz];$

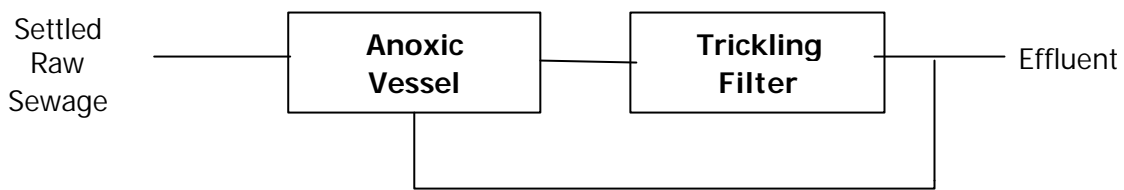
BOD driver file

```
%-----  
% Driver for determination of concentration profile  
% through the biofilm depth  
%  
% Non-stiff solver: ODE45  
%-----  
  
% set parameters for the solvers  
toler = input('What local error tolerance do you want? (eg. 1e-3) ');  
tt=cputime ;  
  
% call the solvers  
opts=odeset('AbsTol',toler,'RelTol',toler);  
[z,y] = ode45(@Anoxicacf, [0 1.00], [20; 0.1]);  
elap = cputime - tt ;  
fprintf('Execution time = %5.3f seconds\n',elap)  
  
% analyze results  
steps = length(z) ;  
fprintf('Number of steps = %4.0f\n',steps)  
fprintf('Local error tolerance = %g\n',toler)  
  
% plot results  
plot(z,y(:,1),'c')  
xlabel('bed height')  
ylabel('BOD Concentration')  
title('BOD Concentration profile through anoxic tank')
```

APPENDIX C – PRE-ANOXIC SYSTEM

DESIGN CALCULATIONS

The Pre-Anoxic system is described by the following block diagram:



The Settled Raw Sewage characteristics

Item	Unit	Primary Effluent
Flow	m ³ /d	0.10
BOD	mg/L	150.00
TSS	mg/L	80.00
NH ₄ -N	mg/L	25.00

Assumptions

- ? The system is in steady state
- ? The composition of the settled raw sewage is constant
- ? Ammonia nitrogen (NH₄-N) is reduced to Nitrate nitrogen (NO₃-N) only.

Controlling Factors

The substrate removal capacity of the anoxic vessel and trickling filter are determined using the models formulated in Appendix B and Appendix A respectively.

The Pre-Anoxic system model

Settled Raw Sewage Inflow (m3/hr)	Inflow BOD (g/m3)	Inflow BOD (g/hr)	Inflow NH4-N (g/m3)	Inflow NH4-N (g/hr)			
0.00	150.00	0.63	25.00	0.10			
Recycle Flow (m3/hr)	Recycle BOD (g/m3)	Recycle BOD (g/hr)	Recycle NH4-N (g/m3)	Recycle NH4-N (g/hr)	Recycle NO3-N (g/m3)	Recycle NO3-N (g/hr)	
0.00	40.00	0.17	0.00	0.00	25.00	0.10	
Anoxic Tank (AT) influent flow (m3/hr)	AT influent BOD (g/m3)	AT influent BOD (g/hr)	AT influent NO3-N (g/m3)	AT influent NO3-N (g/hr)	AT Influent NH4-N (g/m3)	AT Influent NH4-N (g/hr)	
0.01	95	0.79	12.5	0.10	12.5	0.10	
Anoxic Tank (AT) effluent flow (m3/hr)	AT effluent BOD (g/m3)	AT effluent NO3-N (g/m3)	AT effluent NH4-N (g/m3)				
0.01	75.00	9.9955	12.50				
Total Trickling Filter (TF) inflow (m3/hr)	TF Inflow BOD (g/hr)	TF Inflow BOD (g/m3)	TF Inflow NH4-N (g/hr)	TF Inflow NH4-N (g/m3)	TF Inflow NO3-N (g/hr)	TF Inflow NO3-N (g/m3)	
0.01	0.62	74.9955	0.10	12.5	0.08	9.9955	
Trickling Filter (TF) effluent flow (m3/hr)	TF effluent BOD (g/m3)	TF effluent BOD (g/hr)	TF effluent NH4-N (g/m3)	TF effluent NH4-N (g/hr)	TF effluent NO3-N (g/m3)	TF effluent NO3-N (g/hr)	
0.01	20.00	0.166666667	0.00	0	12.50	0.104167	

APPENDIX D – POST-ANOXIC SYSTEM (OPTION 1) DESIGN CALCULATIONS

The post-anoxic system (option1) is illustrated by the following flow diagram:



The Settled Raw Sewage characteristics

Item	Unit	Primary Effluent
Flow	m ³ /d	0.10
BOD	mg/L	150.00
TSS	mg/L	80.00
NH ₄ -N	mg/L	25.00

Assumptions

- ? The system is in steady state
- ? The composition of the settled raw sewage is constant
- ? Ammonia nitrogen (NH₄-N) is reduced to Nitrate nitrogen (NO₃-N) only.
- ? Nitrification only occurs within the trickling filter
- ? Denitrification only occurs within the anoxic vessel

Controlling Factors

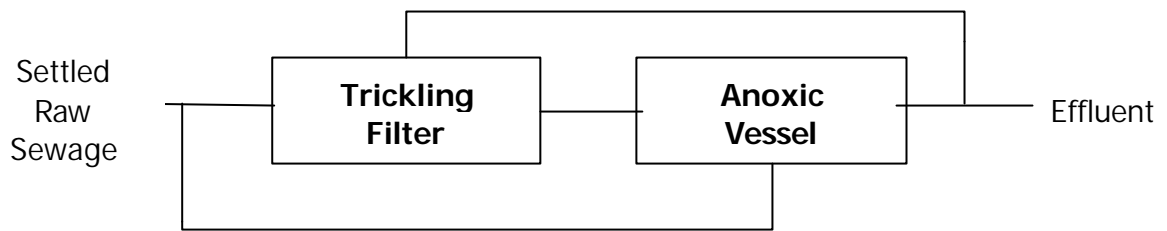
The substrate removal capacity of the anoxic vessel and trickling filter are determined using the models formulated in Appendix B and Appendix A respectively.

The Post-Anoxic system (Option 1) model

Settled Raw Sewage Inflow (m3/hr)	Inflow BOD (g/m3)	Inflow BOD (g/hr)	Inflow NH4- N (g/m3)	Inflow NH4-N (g/hr)
0.00	150.00	0.63	25.00	0.10
Trickling Filter (TF) effluent flow (m3/hr)	TF effluent BOD (g/m3)	TF effluent NH4-N (g/m3)	TF effluent NO3-N (g/m3)	
0.00	20.00	4.49	20.51	
Anoxic Tank (AT) effluent flow (m3/hr)	AT effluent BOD (g/m3)	AT effluent NO3-N	AT effluent NH4-N	
0.00	20.00	20.5055	4.49	

APPENDIX E – POST-ANOXIC SYSTEM (OPTION 2) DESIGN CALCULATIONS

The post-anoxic system (option 2) is illustrated by the following flow diagram:



The Settled Raw Sewage characteristics

Item	Unit	Primary Effluent
Flow	m ³ /d	0.10
BOD	mg/L	150.00
TSS	mg/L	80.00
NH ₄ -N	mg/L	25.00

Assumptions

- ? The system is in steady state
- ? The composition of the settled raw sewage is constant
- ? Ammonia nitrogen (NH₄-N) is reduced to Nitrate nitrogen (NO₃-N) only.
- ? Nitrification only occurs within the trickling filter
- ? Denitrification only occurs within the anoxic vessel
- ? Recycle ratio: Recycle/Raw Inflow = 1
- ? Raw Sewage to Trickling filter:Raw sewage to anoxic vessel = 80:20

Controlling Factors

The substrate removal capacity of the anoxic vessel and trickling filter are determined using the models formulated in Appendix B and Appendix A respectively.

The Post-Anoxic system (Option 1) model

Settled Raw Sewage Inflow (m3/hr)	Inflow BOD (g/m3)	Inflow BOD (g/hr)	Inflow NH4-N (g/m3)	Inflow NH4-N (g/hr)		
0.00	150.00	0.63	25.00	0.10		
Recycle Flow (m3/hr)	Recycle BOD (g/m3)	Recycle BOD (g/hr)	Recycle NH4-N (g/m3)	Recycle NH4-N (g/hr)	Recycle NO3-N (g/m3)	Recycle NO3-N (g/hr)
0.00	20.00	0.08	7.57	0.03	20.00	0.08
Total Trickling Filter (TF) inflow (m3/hr)	TF Inflow BOD (g/hr)	TF Inflow BOD (g/m3)	TF Inflow NH4-N (g/hr)	TF Inflow NH4-N (g/m3)	TF Inflow NO3-N (g/hr)	TF Inflow NO3-N (g/m3)
0.0033333333	0.58	174.994375	0.11	34.4595495	0.08	25
Trickling Filter (TF) effluent flow (m3/hr)	TF effluent BOD (g/m3)	TF effluent BOD (g/hr)	TF effluent NH4-N (g/m3)	TF effluent NH4-N (g/hr)	TF effluent NO3-N (g/m3)	TF effluent NO3-N (g/hr)
0.00	20.00	0.066666667	9.46	0.031531832	25.00	0.0833333333
Anoxic Tank (AT) influent flow (m3/hr)	AT influent BOD (g/m3)	AT influent BOD (g/hr)	AT influent NO3-N (g/m3)	AT influent NO3-N (g/hr)	AT Influent NH4-N (g/m3)	AT Influent NH4-N (g/hr)
0.004166667	46	0.191666667	20	0.0833333333	12.5676396	0.052365165
Anoxic Tank (AT) effluent flow (m3/hr)	AT effluent BOD (g/m3)	AT effluent NO3-N	AT effluent NH4-N			
0.00	20.00	19.9955	12.57			