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Modeling and Optimization of Biological Nutrients Removal in Wastewater Treatment Processes Considering Advanced Kinetic Modeling Techniques

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United Arab Emirates University
Deanship of Graduate Studies
M.Sc. Program in Water Resources

MODELING AND OPTIMIZATION OF BIOLOGICAL NUTRIENTS REMOVAL IN WASTEWATER TREATMENT PROCESSES CONSIDERING ADVANCED KINETIC MODELING TECHNIQUES

By

Nawras Nabil Al Ghazaly

A Thesis submitted to the Deanship of Graduate Studies in Partial Fulfillment of the Requirements of the Degree of Master of Science in Water Resources

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M.Sc. Program in Water Resources

Thesis Title: **Modeling and Optimization of Biological Nutrients Removal In Wastewater Treatment Processes Considering Advanced Kinetic Modeling Techniques**

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GLOSSARY

ASM	Activated sludge model
A^2O	Anaerobic – Anoxic – Oxic
A	Surface area of clarifier
AFR	Air Flow Rate
BOD	5-day biochemical oxygen demand
BNR	Biological Nutrients Removal
BPR	Biological Phosphorus Removal
COD	chemical oxygen demand
CAPEX	Capital Cost Investments
DO	dissolved oxygen
DNPAO	Denitrifying Phosphate Accumulating Organisms
EBPR	Enhanced Biological Phosphorus Removal
EAWAG	Swiss Federal Institute for Environmental Science and Technology
ENR	Engineering News Record
GRG	Generalized Reduced Gradient
HRT	Hydraulic Retention Time
IAWPRC	International Association on Water Pollution Research and Control
IAWQ	International Association on Water Quality
IWA	International Water Association
ir	Internal recirculation ratio
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed liquor Volatile Suspended Solids
OPEX	Operation Cost Investments
O&M	Operation and maintenance
PAO	Phosphorus Accumulating Organisms
PHA	Poly-Hydroxy Alkanoates
PP	Poly-Phosphate
Q	Process stream flow rate
q	Tank Overflow rate
RO_H	Oxygen required for organic matter removal
RO_A	Oxygen required for nitrification requirement
r	Sludge circulation ratio
SCOD	soluble COD
SRT	Solids Retention Time
SVI	Sludge Volume Index
$S_{\text{subscript}}$	Soluble matter
SBR	Sequencing Batch Reactor
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TSS	Total Suspended Solids
UCT	University of Cape Town
VFA	Volatile Fatty Acids
VSS	Volatile Suspended Solids
V	Reactor / Tank Volume
WWTP	Waste Water Treatment Plant
$X_{\text{subscript}}$	Particulate matter

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ABSTRACT

In the field of wastewater treatment, there is an increasing demand to improve the effluent quality especially if it is going to be discharged to surface water. Effluent discharged to surface water should have minimum nutrients level (nitrogen and phosphorus) in order to avoid eutrophication and the resulting algal blooms which deplete the water from the oxygen needed by other plant and animal species. Moreover, there is a demand to reduce the chemical consumption in the treatment processes and to depend as much as we can on the biological treatment methods in achieving the required effluent quality in terms of BOD and nutrients concentration. This thesis implements an extended and more comprehensive analysis in order to accomplish an optimal sizing that achieve minimum capital and operation costs for the biological nutrients removal (BNR) activated sludge processes using ASM kinetic models. An existing model that optimally sizes the activated sludge processes will be further developed and refined to incorporate and consider new components; mainly denitrification and phosphorus removal. The study has revealed the strengths and practicality of using ASM kinetic models in a more sophisticated activated sludge system. It has been found that the internal recirculation ratio (ir) is an important design parameter that can contribute significantly in achieving an economical BNR design, thus, imposing a maximum upper limit for the internal recirculation ratio (like what have been suggested by Metcalf & Eddy 1991) could form a real obstacle against the optimal economical design. The study has proposed a new design philosophy that considers the life cycle cost analysis of the BNR system (CAPEX & OPEX). The model results have shown that more economical design for the BNR system might be achieved if the highest influent temperature is considered rather than the lowest temperature. The higher organisms' growth rate at higher temperatures will generate higher amounts of sludge and therefore a considerable increase in the disposal cost. The study illustrates that the BNR system design can be more economical in terms of life cycle cost if consideration is given to minimize the amount of the sludge generated from the system.

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CHAPTER I

INTRODUCTION

The biological treatment process, which is an essential part of any wastewater treatment plant (WWTP), can be considered as one of the largest industries that deal with the treatment of raw material. The two main objectives of the biological wastewater treatment process are to coagulate and remove the non-settleable colloidal solids and to stabilize the organic matter. Moreover, WWTPs can be designed to reduce the nutrients content (i.e., nitrogen and phosphorus) of the plant effluent.

The activated sludge process, first developed in England in 1914, has been used widely in municipal and industrial wastewater treatment. It is defined as a biological wastewater treatment process in which a mixture of wastewater and activated sludge is agitated and aerated. The activated sludge is subsequently separated from the treated wastewater (mixed liquor) by sedimentation and wasted or returned to the process as needed. The basic scheme of this process is performed by a variable and mixed community of microorganisms in an aerobic aquatic environment. These microorganisms derive energy from carbonaceous organic matter in aerated wastewater for the production of new cells in a process known as synthesis, while simultaneously releasing energy through the conversion of this organic matter into compounds that contain lower energy, such as carbon dioxide and water, in a process called respiration. In addition, a number of microorganisms in the system obtain energy by converting ammonia-nitrogen to nitrate-nitrogen in a process called nitrification.

The activated sludge process has been subjected to many variations developed for specific applications such as incorporating anaerobic and anoxic reactors in order to achieve better biological nutrients removal. Nutrients removal from wastewater is considered an effective approach for the prevention of eutrophication in closed or semi-closed water systems. Biological phosphorus and nitrogen removal is usually considered in WWTPs whenever the treated effluent is to be discharged to a sensitive receiving water body or the treated effluent is to be exploited for reuse.

The main objective of any WWTP design process in general is to have an optimized cost effective design that can meet the effluent quality limits fixed by certain regulations. Such an objective is not easy to achieve using published guidelines or trial and error approaches because of, first: the complexity of the biological treatment process, and second: the high interrelation between the different treatment processes (i.e., physical and biological). However, the recent advancement in the mathematical characterization of the different WWTP processes in general, and the biological wastewater treatment in particular has contributed significantly in strengthening the role of computer models, which assist the process designers to understand better the behavior of the different treatment processes and the way they are interrelated. The most popular and widely used mathematical models in the field of biological wastewater treatment are the activated sludge models (ASMs), which were developed in 1983 by the International Association on Water Pollution Research and Control (IAWPRC).

1.1 Research Objectives

The main objective of this study is to explore the way how to formulate a mathematical model to optimize the cost of the Biological Nutrients Removal (BNR) process using: (i) advanced ASMs, (ii) mathematical models of primary and secondary clarifiers and (iii) capital and plant operation cost functions. The above mentioned sub-models are incorporated together in one model using the operation research methodology after defining the problem objective function, which is achieving the minimal possible cost considering the system constraint functions. The sensitivity of the model results to different operating parameters and to variable operating conditions will be analyzed and evaluated.

1.2 Methodology

The methodology followed in this research to achieve its objective is summarized in the following points:

1. Identifying the recent approaches available in modeling the biological treatment processes in general and the BNR systems in particular.
2. Incorporating the cost functions of the BNR System considering the required capital and system operation investments.
3. Selecting the appropriate performance equations relating the process design variables to influent and effluent wastewater parameters and making the necessary refinements for their incorporation in the optimization model.
4. Incorporating the above components in a pre-developed optimization model in GAMS language.
5. Solving the model for different sets of parameters describing the reaction kinetics of viable biomass, the influent conditions, the project life, the economical inflation rates, etc.

1.3 Thesis Outline

Throughout the chapters of this thesis, a systematic research approach is introduced to the reader to illustrate the methodology followed in formulating the optimization model of the BNR system, in particular, the anaerobic-anoxic-aerobic system, abbreviated as (A^2O) system. Chapter 2 of this thesis provides the reader with the necessary background information on the biological nutrients removal system. In Chapter 3, an overview is presented to the reader on the main currently existing modelling platforms for the activated sludge systems; their development history, main differences between them and capabilities of each one. The cost functions together with the mathematical model of A^2O activated sludge system combined with a primary clarifier are formulated in Chapter 4. In Chapter 5, the usefulness of the developed model is illustrated through an illustrative problem where a typical BNR / A^2O system is designed. Chapter 6 is devoted to examine the model performance at varying input data in order to have better understanding for the system response considering different design conditions. Finally, in Chapter 7, the study conclusions are presented and areas of future research are highlighted.

CHAPTER II

BACKGROUND

2.1 Biological Nutrient Removal

The BNR processes, which were first developed during the 1960's, have been used for decades to treat wastewater containing nitrogen and phosphorus, as well as organic compounds due to their economic advantage compared with the chemical treatment methods. BNR systems are considered a modification of the original activated sludge process by incorporating anoxic and/or anaerobic zones to provide nitrogen and/or phosphorus removal.

Grady et al. (1999) presented an elaborate review on the history of the BNR systems. One of the first schemes of a BNR system used a series of three separate suspended growth systems where the organic matter removal is accomplished in the first one, nitrification in the second and denitrification in the third one. This scheme was studied extensively by the researchers but found little attention from the industry because of its high capital and operating costs. Another approach, called the single sludge nitrogen removal system, incorporated both aerobic zones for nitrification and anoxic zones for denitrification in a single system, with carbon oxidation occurring in both zones. The system included an internal recirculation for the nitrates from the aerobic zones to the front anoxic zones in order to allow the use of the readily biodegradable substrates (S_s) by the denitrifying organisms. In addition, a second anoxic zone after the aerobic zone is proposed in order to achieve additional de-nitrification using the slowly biodegradable substrates (X_s) and the biomass decay (endogenous respiration).

Biological phosphorus removal (BPR) was first observed at certain full scale activated sludge plants that have a bioreactor of a plug flow type with uniform aeration along its length. Such type of bioreactors usually results in low concentrations of dissolved oxygen (DO) especially in the initial sections. These initial sections of the plug-flow bioreactor behaved as anaerobic environment which is actually necessary for the phosphate accumulating organisms (X_{PAO}) to form the internal storage products they need to perform the phosphorus uptake. The research during the 1960s resulted in the first commercial BPR process which was known at that time as the Phostrip Process. In this process, a side-stream flow is diverted to an anaerobic phosphorus stripper tank at an approximate ratio between 10 to 30% of the influent flow (Plaza et al., 1997). Refer to Figure 2-1.

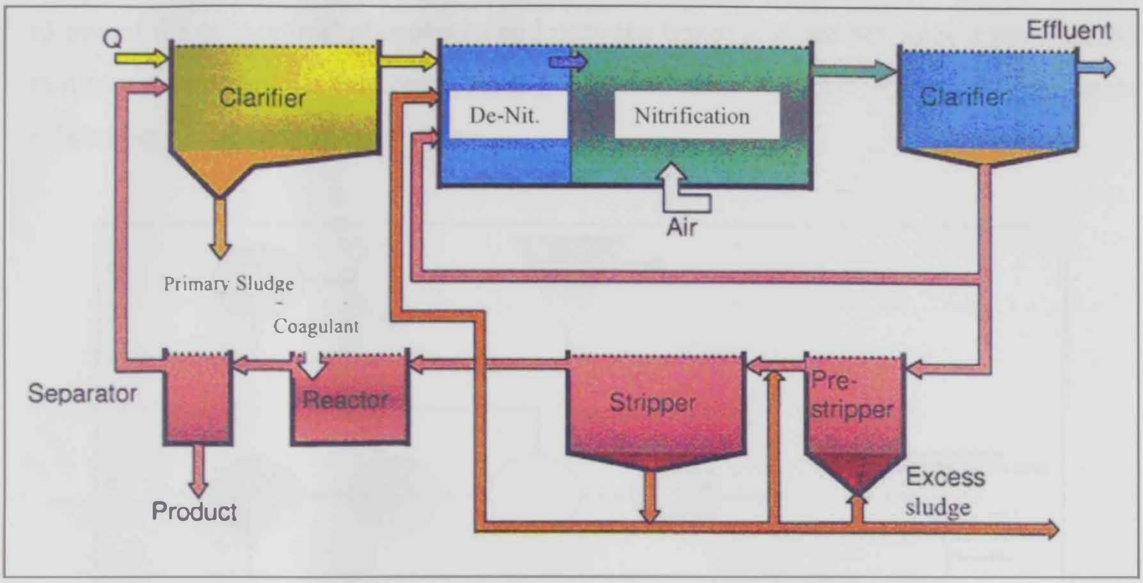


Figure 2-1 Phostrip side-stream process.

Bernard (1975, 1982 and 1983) carried out an important research contribution to this field by proposing two significant conceptual advancements to the BNR system. The first was by integrating the anaerobic and anoxic zones, along with the nitrate re-circulation, in order to create an effective and cost competitive single sludge nitrogen removal system currently known as the four-stage Bardenpho process. The second was his observation that BPR would occur if nitrate was sufficiently depleted in the initial anoxic zone; this observation led him to add an initial anaerobic zone to his nitrogen removal system to become five stages instead of four.

In general, a biological nitrogen and phosphorus removal system shall be divided into anaerobic, anoxic and aerobic zones with provision of internal recirculation from the aerobic to the front anoxic zone. The BNR system zones are distinguished by the electron acceptor utilized in each one (i.e., oxygen in the aerobic zones and nitrate-N in the anoxic zones) except the anaerobic zone which has to be maintained free of any electron acceptor. The way the BNR system bioreactor is divided between the anaerobic, anoxic and aerobic zones is the distinguishing feature of any BNR system. In this regard, several BNR schemes have been developed such as the sequencing batch reactor (SBR), the University of Cape Town (UCT) system, the Bardenpho process and the Phoredox process. The three stage Phoredox Anaerobic-Anoxic-Oxic (A^2O) process is considered as one of the economical phosphorus and nitrogen removal processes since it requires the minimum number of the recalculating streams and reactors. Figure 2-2 presents schematics for several BNR systems.

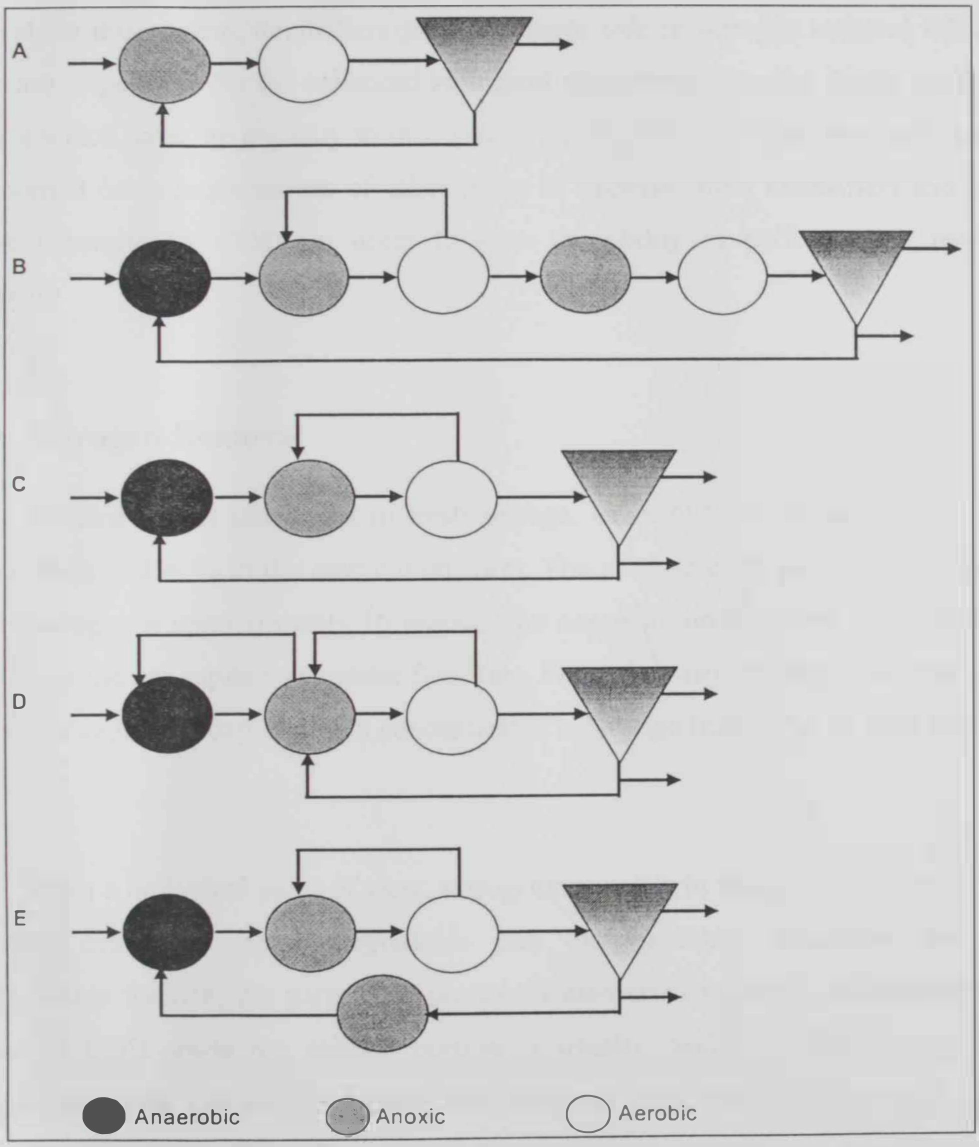


Figure 2-2 Schematics of different BNR systems (Source: Meijer, 2004)

where

A is two stage phoredox
B is five stage phoredox (modified Bardenpho)
C is Three Stage Phoredox (A^2O)
D is UCT Process
E is Johannesburg Process.

The A^2O system basically consists of anaerobic compartment which is necessary beside other reactors, to accomplish phosphorus removal, anoxic compartment to accomplish total nitrogen removal and aerobic compartment to accomplish organic matter removal. In this system, denitrifiers play the major role in nitrogen removal while the PAOs are responsible for the enhanced biological phosphorus removal. PAOs are certain bacteria which have the capacity to incorporate more phosphorus into their cell material than normal basic requirements of other types of bacteria. Both denitrifiers and PAOs require substrate (or COD) in order to have the ability to perform their reactions efficiently.

2.1.1 Nitrogen Removal

Richard (1991) stated that in fresh sewage, about 60% of the nitrogen is in the organic form and 40% in the ammonium form. The average daily per capita production rate of nitrogen is approximately 16 grams. The nitrogen concentration in a wastewater depends on the per capita wastewater flow rate. For a flow rate ranging from 100 to 200 gallons per capita per day, nitrogen concentration will range from 42 to 21 mg/l (Richard, 1991).

From a biological point of view, nitrogenous matter in wastewater can be divided into two categories: non-biodegradable and biodegradable. Regarding the non-biodegradable fraction, the particulate portion is associated with the non-biodegradable particulate COD while the soluble portion is usually neglected. The biodegradable nitrogenous matter can be sub-divided into ammonia (both the free compound and its salts); the soluble organic nitrogen and the particulate organic nitrogen. Particulate organic nitrogen is hydrolyzed to soluble organic nitrogen through a hydrolysis process.

The soluble organic nitrogen is acted on by the heterotrophic bacteria and converted to ammonia nitrogen in a process called ammonification (Henze et al., 2000).

Currently, there are several methods available to control the concentration of the total nitrogen such as break-point chlorination, ion exchange, air stripping of ammonia, and biological nitrification and denitrification. The biological nitrification and denitrification processes are the most economic and widely used processes in controlling the concentration of total nitrogen in the wastewater treatment plants effluent.

2.1.1.1 Nitrification

The nitrification process can be described as the conversion of ammonia to nitrate. This conversion process generally involves two oxidation reactions: (1) oxidation of ammonia to nitrite (equation 2-1) and (2) oxidation of nitrite to nitrate (equation 2-2).

$$NH_4^+ + \frac{3}{2}O_2 \xrightarrow{Nitrosomonas} NO_2^- + 2H^+ + H_2O \qquad (2\text{-}1)$$

$$NO_2^- + \frac{1}{2}O_2 \xrightarrow{Nitrobacter} NO_3^- \qquad (2\text{-}2)$$

In the nitrification process, the oxidation reactions are carried out by autotrophic organisms (X_A) (also called nitrifiers). The nitrifiers consist of two distinctive organisms which are Nitrosomonas and Nitrobacter. The Nitrosomonas type of autotrophs is involved in the process of oxidizing the ammonia to nitrite while the Nitrobacter type of autotrophs is involved in the process of oxidizing nitrite to nitrate. Nitrification process is usually accomplished in wastewater treatment plants in conjunction with the carbonaceous BOD removal process. However, additional oxygen would be required to oxidize ammonia to nitrate. From equations 2-1 and 2-2, the stoichiometric oxygen requirement for oxidation of ammonia to nitrate is $2*32/14 = 4.57$ gO_2/g NH_4-N.

Since the concentration of the Total Kjeldahl Nitrogen TKN (sum of organic nitrogen and ammonia) in the influent is significantly lower than that of organic substances, the cell mass produced due to ammonia oxidation is also smaller than that produced due to BOD removal. As a result, the fraction of nitrifiers in the total population of the mixed liquor volatile suspended solids (MLVSS) typically ranges between 2 to 5 percent. The activity of nitrifiers in a single stage reactor depends upon the ratio of BOD_5 to TKN in the influent. At a ratio of 5 or higher, the activity of nitrifiers is limited (Syed, 1999).

The concentration of DO in the aerobic zone may also impact the nitrification process. The growth rate of nitrifiers at a DO level in the range of 0.3-0.5 mg/l may be insufficient and nitrification may not occur. The nitrification rate increases with an increase in DO in the range of 1.0 – 3.0 mg/l. A minimum DO level of 2.0 mg/l is recommended for the process design (Syed , 1999).

It is important to also highlight that many organic and inorganic compounds at different concentrations and under different environmental conditions may have inhibitory effects on the nitrification process.

2.1.1.2 Denitrification

Denitrification is the conversion of nitrate to nitrogen gas. This conversion process is accomplished by microorganisms through a sequence of reduction reactions. These reactions are developed using an organic source like methanol (CH_3OH) as (Equations 2-3 and 2-4).

$$6NO_3^- + 2CH_3OH \longrightarrow 6NO_2^- + 2CO_2 + 4H_2O \tag{2-3}$$

$$6NO_2^- + 3CH_3OH \longrightarrow 3N_2 + 3CO_2 + 3H_2O + 6OH^- \tag{2-4}$$

Denitrification is an anoxic process that requires the absence of oxygen and presence of suitable organic carbon source as electron donor. This process is usually carried out by heterotrophic bacteria that are able to grow under anoxic condition; such type of bacteria is termed as denitrifiers. The source of the organic carbon required for the denitrification process is either from the incoming raw wastewater (single sludge system) or from an external organic source such as methanol (separate sludge system). In a BNR single sludge system with internal recirculation, the heterotrophic population is altered between anoxic and aerobic conditions resulting in a lower denitrification capacity when compared to the separate sludge system.

The denitrification rate is very sensitive to the DO level in the anoxic zone. Researchers reported that the denitrification process might stop entirely at a DO concentration of 0.1 to 0.2 mg/l. A maximum DO level of 0.1 mg/l is generally assumed in the design of the anoxic denitrification process (Syed , 1999).

2.1.2 Phosphorus Removal

The discharge of phosphorus to surface water causes accelerated eutrophication of lakes, reservoirs and ponds. Municipal and industrial wastewater has been identified as one of the principal sources of phosphorus readily available for uptake by aquatic micro-organisms (algae). Since 1970s, phosphorus has been identified as the most important rate-limiting factor for algal growth in freshwater systems, and its removal from these wastewaters has therefore become increasingly important.

Phosphorus removal from wastewater effluents can be achieved in two fundamentally different ways: physical-chemical precipitation and enhanced biological removal.

Several researchers have shown that the biological process has a lower overall operating cost, when compared with the chemical precipitation (Jiang F. et al, 2004). In biological phosphorus removal, phosphorus is removed by means of incorporating the polyphosphate (Poly P) and the organically bound phosphorus into the cell tissue. The organically bound phosphorus is sequestrated from the wastewater to satisfy the growth requirements of the biomass.

The actual phosphorus content of the cell tissue may vary from one-seventh to one-third of the nitrogen value, depending on specific environmental conditions. In average, 10 to 30 percent of the influent phosphorus is removed during the normal secondary treatment process by sludge wasting. However, higher percentages can be further achieved if an enhanced biological phosphorus removal (EBPR) process is implemented. The idea of EBPR is to stress the microorganisms by exposing them to altering an-aerobic and aerobic conditions so that their uptake for phosphorus is above normal levels (Metcalf & Eddy, 1991).

Droste (1997) mentioned that there are certain bacteria with the ability to accumulate phosphorus in the form of poly-phosphate well in excess of the phosphorus requirements for growth of microorganisms. The operation of the activated sludge process with the anaerobic – aerobic sequencing provides favorable conditions for enrichment of the sludge with bio-P microorganisms. The initial anaerobic phase is required to produce short chain acids which are used by the bio-P microorganisms in the aerobic conditions to store the poly-phosphate and achieve phosphorus removal. Phosphorus is released from the microorganisms in the anaerobic phase but it is taken up again during the process.

Basically, there are two main processes occurring in the anaerobic zone, these are the accumulation of the readily biodegradable carbon substrates (i.e. Cell internal stored organic materials X_{PHA}) and the hydrolysis of intracellular polyphosphate (X_{pp}) which is released in the bulk liquid in the form of orthophosphate (S_{PO4}). In the aerobic phase, phosphate is taken by the poly-phosphate accumulating organisms (X_{PAO}) in the form of intracellular polyphosphate using the internally stored organic materials (X_{PHA}) as energy source. In the aerobic phase, the PAOs take up more phosphate than that released in the anaerobic phase and therefore resulting in an achievement of a net phosphorus uptake (Joel et al., 2003).

Serralta et al. (2004) have studied the effect of pH on the EBPR process and concluded that operating the anaerobic phase of the system in elevated pH mode offers a strategy for controlling competition between the different organisms' types in accumulating readily biodegradable carbon substrates. They also showed that pH values lower than 7 or greater than 9 greatly inhibit bacterial activity in the biological treatment system.

2.1.2.1 Denitrifying Phosphate Accumulating Organisms (DNPAOs)

Researchers have studied in depth the behavior of the PAOs in terms of their ability to accept different electron acceptors other than oxygen, and in terms of their interaction with the nitrification / denitrification process in the biological treatment system of wastewater treatment plants. Comeau Y. et al. (1987) were among the first few researchers who stated that biological phosphorus uptake can be achieved under anoxic conditions. It was discovered that some PAOs are capable to use the nitrate / nitrite rather than the oxygen as electron acceptors during the phosphate uptake process. This type of organisms is called Denitrifying Phosphate Accumulating Organisms (DNPAOs).

If DNPAOs were present in the A^2O system, they could counteract the negative impact of poly-P substrate uptake (which occurs in the anaerobic compartment) on nitrate removal by the ordinary heterotrophic organisms (denitrifiers) Yong et al. (2006). This is because the DNPAOs will perform denitrification and phosphorus removal simultaneously.

A review of some literature published in early nineties revealed that intermediate products of biological nitrogen removal process, nitrate and nitrite, could become inhibitory or toxic substances to phosphorus removal, on the other hand, several recent publications have reported occurrence of phosphorus removal with the presence of nitrate in activated sludge system. From the basic microbiological point of view, there is no reason why nitrate or nitrite could not be used as an electron acceptor for phosphorus removal (Hu et al., 2003).

Although nitrite may not be as good as nitrate in replacing the oxygen as electron acceptor, Hu et al., (2003), in their research to validate and study the role of nitrite in phosphorus removal process, suggested the possibility of using the nitrite as an electron acceptor as long as its concentration does not exceed the inhibition concentration (> 115 mg /l). They also classified the phosphorus removal bacteria into three groups, one is capable of utilizing only oxygen as electron acceptor, the second is capable of utilizing both oxygen and nitrate as electron acceptors and the third is capable of utilizing oxygen, nitrate and nitrite as electron acceptors.

CHAPTER III

MODELING OF BNR SYSTEMS

The development of mathematical models describing the BNR with a study on EBPR in activated sludge processes was started in 1976 by Barnard J. L. in South Africa. Very few models were developed at that time but were not widely used because of the lack of confidence in their results. (Meijer, 2004).

A model is defined as a description of reality, used to understand and predict certain aspects of reality. Usually, natural processes are difficult to understand in full details because of their complexity (i.e. activated sludge process). Therefore, for the sake of understanding, process simplification is required. In activated sludge process, several organisms are responsible for conversion of pollutants. A comprehensive model that intends to describe all processes will be complicated and impractical to use. A well known method for functional model design is based on the "Black Box" concept. In the black box concept, the system is described in terms of what is observed from the process in terms of exchange of compounds without going into the internal details of the actual process. If the internal details are to be studied (i.e., cell internal metabolism) then a "Grey Box" model is developed.

The International Association on Water Pollution Research and Control, which become the International Water Association "IWA" in year 2000, has presented its first ASM for carbon and nitrogen removal in 1986. The BPR processes have been included in the IWA model in a later version presented in 1995 which was upgraded again in 1999 to account for the phosphorus removal under anoxic conditions.

With knowledge increase in the cell internal biochemistry of the PAOs, a metabolic model that describes the EBPR has been developed in 1994 by the technical university of Delft in the Netherlands. This model is referred to as the Technical

University of Delft Phosphorus Model (TUPD). The most recent version of this model was integrated with the heterotrophic, hydrolytic and autotrophic reactions of the ASM2d and referred to as the TUD model. The literature research has revealed that both ASM and TUD models are currently the most comprehensive modeling structures for activated sludge processes. Bradjanovic et al. (1999) used a combination between ASM No. 2 and Delft BPR model to describe the performance of a full scale wastewater treatment plant (Phostrip-like process) in terms of COD, nitrogen and phosphorus removal. Koch et al. (2000) developed an ASM3-based steady state model which can be used for estimating the average nitrogen removal, sludge production and phosphorus removal rates of different biological phosphorus removing systems such as A^2O and UCT systems. The author could not find any work done previously where the three Stage Phoredox (A^2O) process is modeled using optimization approach.

This section provides an overview on both modeling structures and tracks their development process till they reached their final shape. A detailed description is provided for the ASM3 model since it is selected in this thesis for solving the WWTP optimization problem formulated in the subsequent chapters.

3.1 Activated Sludge Models of IWA Task Group (ASMs)

As stated earlier, ASMs are considered as one of the most famous models which have the capability to depict the performance of the wastewater treatment systems receiving both soluble and particulate substrates in which organic substrate removal , nitrification , denitrification and phosphorus removal are all occurring.

In 1982, the International Association on water pollution Research and Control (IAWPRC or IAWQ) established a task group on mathematical modeling for design and operation of activated sludge processes. The aim for the task group was to create a common platform that could be used for future developments. The ASM models were developed gradually and published in a series started with ASM no. 1 which included the nitrogen removal processes, then ASM no. 2 which included the BPR processes and then ASM no. 2d which included the DNPAOs. In year 1998 the Task Group decided to develop a new modeling platform, based on recent developments in the understanding of the activated sludge processes, named as ASM no. 3 (Henze et al., 2000). All ASM models are presented in a matrix format in order to overcome the difficulties in tracing the interactions between all model components. Following is a summarized description for each model.

3.1.1 Activated Sludge Model No. 1

When it was offered in 1987 by the IAWQ, ASM No. 1 was considered a new trend in the mathematical modeling of the activated sludge systems. The model has adapted many basic concepts from the earlier UCT model such as the bisubstrate hypothesis and the death regeneration hypothesis. The bisubstrate hypothesis classifies the biodegradable COD in the wastewater into readily and slowly biodegradable COD. The readily biodegradable COD (S_S) can pass through the cell and immediately used for the synthesis process while the slowly biodegradable COD (Xs), which consists of larger and more complex molecules, has to be hydrolyzed prior to its transformation through the cell wall.

The death-regeneration hypothesis was introduced in an attempt to model the different reactions that take place when organisms die. In this concept the decay of the organism will result in two fractions. One fraction is slowly biodegradable substrate, which is recycled back to soluble substrate through hydrolysis, and used for more cell growth. The other fraction is non-biodegradable and will remain as an inert residue (X_p). Because of the fact that organisms yield is less than unity, the amount of the new biomass grown from released substrate must always be less than the amount of biomass lost. The ASM1 model incorporates 8 processes and 13 components to simulate the COD and nitrogen removal. Phosphorus removal is not introduced in this model.

Detailed description of the model components and the main processes considered can be found in Henze et al. (2000) and Jeppsson (1996). Table 3-1 shows the process kinetics and the stoichiometry considered in ASM1.

Table 3-1 Process Kinetics and Stoichiometry for Activated Sludge Model No.1

Component →	i	1	2	3	4	5	6	7	8	9	10	11	12	13^a	
j	Process ↓	S_I	S_S	X_I	X_S	X_H	X_A	S_O	S_{NOX}	S_{NH}	S_{No}	X_{No}	S_{ALK}	X_{NI}	Process Rate, ρ_j $[ML^{-3}T^{-1}]$
1	Aerobic growth of heterotrophs		$-\frac{1}{Y_H}$			1		$-\frac{1-Y_H}{Y_H}$		$-i_{NBM}$			$-\frac{i_{NBM}}{14}$		$\mu_{Hm}\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{OH}+S_O}\right)X_H$
2	Anoxic growth of heterotrophs		$-\frac{1}{Y_H}$			1			$-\frac{1-Y_H}{2.86Y_H}$	$-i_{NBM}$			$\frac{1-Y_H}{14\cdot 2.86Y_H}$ $-i_{NBM}/14$		$\mu_{Hm}\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{K_{OH}}{K_{OH}+S_O}\right)$ $\times\left(\frac{S_{NOX}}{K_{NOX}+S_{NOX}}\right)\eta_g X_H$
3	Aerobic growth of autotrophs						1	$-\frac{4.57-Y_A}{Y_A}$	$\frac{1}{Y_A}$	$-i_{NBM}-\frac{1}{Y_A}$			$-\frac{i_{NBM}}{14}-\frac{1}{7Y_A}$		$\mu_{Am}\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_O}{K_{OA}+S_O}\right)X_A$
4	Decay of heterotrophs			f_{XI}	$1-f_{XI}$	-1						$i_{NBM}-f_{XI}i_{NX}$ I		$f_{XI}i_{NX}$ I	$b_H X_H$
5	Decay of autotrophs			f_{XI}	$1-f_{XI}$		-1					$i_{NBM}-f_{XI}i_{NX}$ I		$f_{XI}i_{NX}$ I	$b_A X_A$
6	Ammonification of soluble org. nitrogen									1	-1		$\frac{1}{14}$		$k_a S_{No} X_H$
7	Hydrolysis of entrapped organics		1		-1										$k_h\left(\frac{X_S/X_H}{K_X+(X_S/X_H)}\right)\left[\left(\frac{S_O}{K_{OH}+S_O}\right)\right.$ $\left.+\eta_h\left(\frac{K_{OH}}{K_{OH}+S_O}\right)\left(\frac{S_{NOX}}{K_{NOX}+S_{NOX}}\right)\right]X_H$
8	Hydrolysis of entrapped organic nitrogen										1	-1			$\rho_7(X_{No}/X_S)$
Observed conversion rates $[ML^{-3}T^{-1}]$					$r_i=\sum_j \nu_{ij}\rho_j$										

3.1.2 Activated Sludge Model No. 2

Activated Sludge Model No. 2 (ASM2) which was published in 1995 considered an extension to ASM1 as it includes many more components required to characterize the activated sludge process. The most significant change from ASM1 to ASM2 is that in ASM2 the biomass cell internal structure has been modeled in order to include the BPR processes.

In ASM2 model, additional biological processes were added to model the BPR process. Moreover, two chemical processes were added to model the chemical precipitation of phosphorus.

In ASM1 model, all particulate organic components where accounted as part of the total COD value. However, ASM2 model includes the poly-phosphate, which is of a prime importance for the BPR process, as a fraction of the activated sludge. The problem with introducing the poly-phosphate is that it does not exert any additional COD in the system. For that reason, the TSS was introduced for the first time in ASM2. The introduction of the TSS will allow also for the generation of solids formed during the chemical precipitation of phosphorus. The ASM2 model incorporates 19 processes and 19 components to simulate the COD, nitrogen and phosphorus removal. No consideration has been given to the DNPAOs in ASM2 model as the PAO (X_{PAO}) grows under aerobic conditions only.

3.1.3 Activated Sludge Model No. 2d

As stated earlier, Comeau Y. et al. (1987) were from the first few researchers who stated that biological phosphorus uptake can be achieved under anoxic conditions. In ASM2 model, no consideration was given to the anoxic growth of the PAOs which was considered a weak point in it. Therefore, the IWA Task group has avoided this weakness in the ASM2 model by issuing an amended version in 1999 named as ASM2d.

The ASM2d is actually a minor extension of ASM2 model by including two additional processes to account for the DNPAOs. These two processes are process no. 12 which is the anoxic storage of the poly-phosphate (X_{pp}) and process no.14 which is the anoxic growth of the PAOs. The ASM2d model incorporates 21 processes and 19 components to simulate the COD, nitrogen and phosphorus removal.

Serralta J. et al. (2004) have presented an extension to the ASM2d by including a chemical model able to calculate the pH value in the biological processes. The model allows predicting the pH variations due to biochemical processes and takes into account the pH inhibition for each group of bacteria considered in the biological model. Table 3-2 shows the process kinetics and the stoichiometry considered in ASM2d.

Table 3-2 Process Kinetics and Stoichiometry for Activated Sludge Model No.2d

Component →	i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
j	Process ↓	S_O	S_S	S_A	S_{NH}	S_{N2}	S_{NOX}	S_{PO4}	S_I	S_{ALK}	X_I	X_S	X_H	X_{TSS}	X_{PAO}	X_{PP}	X_{PHA}	X_A	X_{MOH}	X_{MP}
Hydrolysis Processes																				
1	Aer. hydrolysis		$1-f_{SI}$		$v_{1,NH4}$			$v_{1,PO4}$	f_{SI}	$v_{1,ALK}$		-1		$-i_{TSSXS}$						
2	Anox. hydrol.		$1-f_{SI}$		$v_{2,NH4}$			$v_{2,PO4}$	f_{SI}	$v_{2,ALK}$		-1		$-i_{TSSXS}$						
3	Anaer. hydrol.		$1-f_{SI}$		$v_{3,NH4}$			$v_{3,PO4}$	f_{SI}	$v_{3,ALK}$		-1		$-i_{TSSXS}$						
Facultative Heterotrophic Organisms																				
4	Aerobic growth on S_S	$1-\frac{1}{Y_H}$	$-\frac{1}{Y_H}$		$\frac{i_{NSS}}{Y_H}-i_{NBM}$			$\frac{i_{PSS}}{Y_H}-i_{PBM}$		$v_{4,ALK}$			1	i_{TSSBM}						
5	Aerobic growth on S_A	$1-\frac{1}{Y_H}$		$-\frac{1}{Y_H}$	$-i_{NBM}$			$-i_{PBM}$		$v_{5,ALK}$			1	i_{TSSBM}						
6	Anoxic growth on S_S (denitrification)		$-\frac{1}{Y_H}$		$\frac{i_{NSS}}{Y_H}-i_{NBM}$	$\frac{1-Y_H}{2.86 \cdot Y_H}$	$\frac{Y_H-1}{2.86 \bullet Y_H}$	$\frac{i_{PSS}}{Y_H}-i_{PBM}$		$v_{6,ALK}$			1	i_{TSSBM}						
7	Anoxic growth on S_A (denitrification)			$-\frac{1}{Y_H}$	$-i_{NBM}$	$\frac{1-Y_H}{2.86 \cdot Y_H}$	$\frac{Y_H-1}{2.86 \cdot Y_H}$	$-i_{PBM}$		$v_{7,ALK}$			1	i_{TSSBM}						
8	Fermentation		-1	1	i_{NSS}			i_{PSS}		$v_{8,ALK}$										
9	Lysis				$v_{9,NH4}$			$v_{9,PO4}$		$v_{9,ALK}$	f_{XIH}	$1-f_{XIH}$	-1	$v_{9,TSS}$						
Phosphorus-Accumulating Organisms																				
10	Storage of X_{PHA}			-1				Y_{PO4}		$v_{10,ALK}$				$v_{10,TSS}$		$-Y_{PO4}$	1			
11	Aerobic storage of X_{PP}	$-Y_{PHA}$						-1		$v_{11,ALK}$				$v_{11,TSS}$		1	$-Y_{PHA}$			
12	Anoxic storage of X_{PP}					$\frac{Y_{PHA}}{2.86}$	$-\frac{Y_{PHA}}{2.86}$	-1		$v_{12,ALK}$				$v_{12,TSS}$		1	$-Y_{PHA}$			
13	Aerobic growth of X_{PAO}	$1-\frac{1}{Y_{PAO}}$			$-i_{NBM}$			$-i_{PBM}$		$v_{13,ALK}$				$v_{13,TSS}$	1		$-\frac{1}{Y_{PAO}}$			
14	Anoxic growth of X_{PAO}				$-i_{NBM}$	$\frac{1-Y_{PAO}}{2.86 \bullet Y_{PAO}}$	$\frac{Y_{PAO}-1}{2.86 \bullet Y_{PAO}}$	$-i_{PBM}$		$v_{14,ALK}$				$v_{14,TSS}$	1		$-\frac{1}{Y_{PAO}}$			
15	Lysis of X_{PAO}				$v_{15,NH4}$			$v_{15,PO4}$		$v_{15,ALK}$	f_{XIP}	$1-f_{XIP}$		$v_{15,TSS}$	-1					
16	Lysis of X_{PP}							1		$v_{16,ALK}$				-3.23		-1				
17	Lysis of X_{PHA}			1						$v_{17,ALK}$				-0.6			-1			
Growth and Decay of Nitrifying Organisms																				
18	Aer. growth of X_A	$-\frac{4.57-Y}{Y_A}$			$-i_{NBM}-\frac{1}{Y_A}$		$\frac{1}{Y_A}$	$-i_{PBM}$		$v_{18,ALK}$				i_{TSSBM}				1		
19	Lysis of X_A				$v_{19,NH4}$			$v_{19,PO4}$		$v_{19,ALK}$	f_{XIA}	$1-f_{XIA}$		$v_{19,TSS}$				-1		
Processes Describing Simultaneous Precipitation of Phosphorus																				
20	Precipitation							-1		$v_{20,ALK}$				1.42					-3.45	4.87
21	Redissolution							1		$v_{21,ALK}$				-1.42					3.45	-4.87

3.1.4 Activated Sludge Model No. 3

With more than ten years of experience with ASM1 modeling platform which was upgraded twice to ASM2 and ASM2d, Some defects of this platform were identified by the IWA task group researchers such as:

1. The ASM1 model does not include the kinetic expressions that can deal with the nitrogen and alkalinity limitations of heterotrophic organisms.
2. The ASM1 model considers both the particulate and soluble nitrogen components (X_{ND} & S_{ND}) which cannot be easily measured and added un-necessary complication to the ASM1 model.
3. Kinetics of ammonification in ASM1 cannot be easily quantified. Moreover, ammonification is a fast process that will hardly affect the model results.
4. The ASM1 model differentiates between two types of inert particulates based on their origin, which is either from the influent (X_I) or from the biomass decay (Xp). However, it is impossible to differentiate between these two fractions in reality.
5. In the ASM1 model, the decay-regeneration cycles of heterotrophs and autotrophs are strongly interrelated although the two decay processes differ significantly in their details.
6. In ASM1, the hydrolysis process has a significant impact on the oxygen consumption and the denitrification by heterotrophic organisms. This is found to be not very accurate since some other coupled processes are involved in it.
7. The storage of PHA and sometimes lipids or glycogen in aerobic or anoxic conditions is not included in ASM1.

Considering the above defects in the ASM1 model platform, the IWA task group has proposed in 1998 the Activated Sludge Model no. 3 (ASM3) as a new modeling platform. In ASM3, a more realistic description of decay processes based on the endogenous respiration hypothesis rather than the death regeneration hypothesis, which was followed in ASM1 model, is adapted. Unlike the ASM1 model, in ASM3, the decay processes of heterotrophs and nitrifiers are clearly separated. Moreover, larger emphasis has been given in ASM3 to the process of organic substrates storage which has been postulated and observed by many researchers. The ASM3 model includes the cell internal storage compounds by modeling the cell internal storage structure. Modeling of the cell internal storage structure was already considered in ASM2 model in order to incorporate the BPR processes. However, the ASM3 model published by the IWA task group does not include the BPR processes. It consists of 12 processes and 13 components. The following table presents a summary for the ASM3 model components:

Table 3-3 Summary of ASM3 Model Components

Component	**Description**
Soluble Compounds	
SO_2 ($M(O_2)L^{-3}$)	Dissolved oxygen. It can be measured directly and it is subject to gas exchange.
S_I ($M(COD)L^{-3}$)	Inert soluble organic material. These compounds are either part of the influent or they are produced during the hydrolysis process of the slowly biodegradable substrates (X_s). No further treatment is possible for these compounds.
Ss ($M(COD)L^{-3}$)	Readily biodegradable organic substrates. This fraction of substrate is directly available for consumption by heterotrophic organisms. ASM3 model assumes that all these substrates are first taken up by heterotrophic organisms and stored in the form of storage compounds (X_{STO})
S_{NH4} ($M(N)L^{-3}$)	Ammonium plus ammonia nitrogen (NH_4 + NH_3)
S_{N2} ($M(N)L^{-3}$)	Nitrogen (N_2). This compound is assumed to be the only product of the denitrification process.
S_{NOX} ($M(N)L^{-3}$)	Nitrate plus nitrite nitrogen (NO_3 + NO_2)
S_{ALK} ($mole(HCO_3)L^{-3}$)	Alkalinity of the wastewater. This compound is introduced in order to have an early indication of possible low pH conditions, which might inhibit some biological processes.
Particulate Compounds	
X_I ($M(COD)L^{-3}$)	Inert particulate organic material. This compound could be a fraction of the influent and is produced in the context of the biomass decay process.

Component	Description
X_S $(M(COD)L^{-3})$	Slowly biodegradable substrates. These compounds must go through the hydrolysis process before they are available for degradation by the biomass. It is assumed that the products of hydrolysis are either readily biodegradable substrate (S_s) or inert soluble organics (S_I)
X_H $(M(COD)L^{-3})$	Heterotrophic organisms. These organisms can grow aerobically, many of them also anoxically (denitrification) but they are assumed to be inactive anaerobically. They are responsible for the hydrolysis of the particulate substrate X_s and they can metabolize all degradable substrate (S_s). X_H are assumed to have no anaerobic activity except cell external hydrolysis which is the only anaerobic process in ASM3.
X_{STO} $(M(COD)L^{-3})$	A cell internal storage product of heterotrophic organisms such as PHA and glycogen.
X_A $(M(COD)L^{-3})$	Autotrophic nitrifying organisms which are responsible for the nitrification process by oxidizing the ammonium S_{NH4} to nitrate S_{NOX}. Nitrite (NO_2) as an intermediate product of nitrification is not considered in ASM3 model.
T_{SS} $(M(SS)L^{-3})$	Total suspended solids. This parameter is usually monitored on daily basis by the WWTP's operators as a reflection of the plant performance.

The following are the transformation processes considered in the ASM3 model:

1. Hydrolysis: Conversion of the slowly biodegradable substrates (X_s) into readily biodegradable substrates (S_s). Hydrolysis is assumed to be active independently from the electron acceptor.
2. Aerobic storage of the readily biodegradable substrates (S_s): It describes the storage of the readily biodegradable substrate (S_s) into a cell internal storage

product (X_{STO}). In ASM3, It is assumed that all substrates shall first become a stored material and later assimilated into the biomass (heterotrophs). Energy is obtained for this process from the aerobic respiration of the biomass.

3. Anoxic Storage of readily biodegradable substrate (Ss): It is identical to the aerobic storage process except that the energy for this process is obtained from the denitrification instead of the aerobic respiration. A fraction of the heterotrophic organisms is capable of growing anoxically (denitrification).
4. Aerobic growth of heterotrophs: For simplification purposes, the substrate for this process is assumed to consist entirely of storage compounds (X_{STO}).
5. Anoxic growth of heterotrophs: It is similar to the aerobic growth except that growth here is done through denitrification instead of the aerobic respiration.
6. Aerobic endogenous respiration: It describes all forms of biomass loss under aerobic conditions. The process consumes oxygen and produces mainly inert particulate (X_I).
7. Anoxic endogenous respiration: It is similar to the aerobic endogenous respiration but usually slower. This process participates in achieving part of the denitrification capacity of the system (Koch et al. 2001).
8. Aerobic Respiration of storage products: This process assures that storage products (X_{STO}) decay together with the biomass.
9. Anoxic Respiration of storage products: similar to the aerobic respiration of storage products except that it happens under anoxic conditions. This process participates in achieving part of the denitrification capacity of the system (Koch et al. 2001).
10. Aerobic growth of autotrophs: This process achieves the nitrification in the system. It has the highest oxygen consumption when compared with other processes.

In the ASM3 formulation, it is assumed that the aerobic endogenous respiration and anoxic endogenous respiration processes are identical for all biomass types.

3.1.5 EAWAG Bio-P Module

Rieger et al. (2001) have published the EAWAG Bio-P module which adds the biological phosphorus removal processes to the Activated Sludge Model No. 3 (ASM3). In contrast to the ASM2d module developed by the IWA task group, the EAWAG Bio-P module is based on the following "Simplification" assumptions:

1. Based on the statistic model analysis and research results, it is assumed that there is no limitation on the P-release due to the fermentation process. Therefore, the fermentation process considered in the ASM2d model is neglected in the EAWAG Bio-P module.
2. To keep the mode simple, only one internal substrate pool is modelled (Ss) unlike the ASM2d model where fermentable readily biodegradable substrates (SF) and fermentation products (SA) were considered.
3. Use of endogenous respiration hypothesis to simulate the PAO loss.
4. Lower rates of anoxic decay when compared with the aerobic decay

The EAWAG Bio-P module has considered four (4) additional components in addition to the (13) components defined in the ASM3 model. These four additional components are identical to the components used in the ASM2d model. The following table summarizes each of them:

Table 3-4 Additional Components of the EAWAG Bio-P module

Component	Description
S_{PO4} ($M(P)L^{-3}$)	Inorganic soluble phosphorus, mainly ortho-Phosphate.
X_{PAO} ($M(COD)L^{-3}$)	Phosphorus Accumulating Organisms (PAOs). These organisms are assumed to grow aerobically and some of them anoxically. Their concentration does not include the internal cell storage product Xpp and X_{PHA}.
X_{PHA} ($M(COD)L^{-3}$)	This is the cell internal storage products of the PAOs. It mainly includes PHA and glycogen.
X_{PP} ($M(P)L^{-3}$)	Polyphosphate. This is the cell internal storage products of the PAOs. It forms part of the particulate phosphorus.

The EAWAG Bio-P module considers both the physiological phosphorus uptake during the growth of the organisms as well as the EBPR of the PAO. For the physiological phosphorus uptake, the growth processes of the organisms are completed to account for the phosphorus limitation. The anaerobic decay is neglected in the EAWAG Bio-P module; as this was confirmed by batch experiments done under starvation conditions (Siegrist et al., 1999). Another assumption is that the model does not consider the biologically induced but inorganic calcium phosphate precipitation in the anaerobic tank. Koch et al. (2001) have emphasized that the biologically induced inorganic calcium phosphate precipitation is only supported at high pH values, high temperatures, and high concentrations of PAO. The EBPR is described by eleven (11) processes in addition to the twelve (12) processes of the ASM3 model. Following is a description for the biological phosphorus removal processes described in the EAWAG Bio-P module:

1. Storage of X_{PHA}: This process occurs mainly under anaerobic conditions but is also observed under aerobic and anoxic zones. In this process, the readily biodegradable substrate (S_s) is stored in the form of X_{PHA}. This storage process is connected directly to the P-release by the stoichiometric parameter Y_{PO4}.
2. Aerobic and anoxic storage of X_{PP}: The PAO will require energy in order to uptake orthophosphate (S_{PO4}) and store it in the form of poly-phosphate (X_{PP}). This energy is obtained from the aerobic or anoxic respiration of the X_{PHA}. The PAO has a maximum P-content to uptake, for that reason, an inhibition term (K_{max}) is implemented to maintain the X_{PP}/X_{PAO} ratio below the maximum permissible value. During the anoxic P-Storage where nitrate is respired instead of the oxygen, A reduction factor ($\eta_{NO,PAO}$) is introduced because only fraction of the PAO (i.e., DNPAO) is capable of denitrification which will proceed at a reduced rate when compared with aerobic storage.
3. Aerobic and anoxic growth of X_{PAO}: EAWAG Bio-P module assumes that PAO grow only on the cell internal storage products (X_{PHA}). For anoxic growth, a reduction factor ($\eta_{NO,PAO}$) is applied.
4. Aerobic and anoxic endogenous respiration: These processes describe all forms of biomass loss. The anoxic endogenous respiration is similar to the aerobic process, but includes the reduction factor $\eta_{NO,end,PAO}$.

5. Aerobic and anoxic respiration (for X_{PHA}) and lysis (for X_{PP}) of internal storage products: These processes ensure that storage products will decay together with the biomass. The anoxic processes are reduced by the factors $\eta_{NO,resp,PAO}$ and $\eta_{NO,lys,PAO}$.

The tables below present the stoichiometric matrix for the soluble and particulate components of the ASM3 and the EAWAG Bio-P module.

Table 3-5 Stoichiometric matrix of soluble components in ASM3 & EAWAG Bio-P module.

	Model components i	1	2	3	4	5	6	7	8
j	Processes	S_O ($gO_2 m^{-3}$)	S_S ($gCOD m^{-3}$)	S_I ($gCOD m^{-3}$)	S_{NH} ($gN m^{-3}$)	S_{NO} ($gN m^{-3}$)	S_{N_2} ($gN m^{-3}$)	S_{PO_4} ($gP m^{-3}$)	S_{HCO} ($mol m^{-3}$)
1	Hydrolysis		$1-f_{SI}$		$i_{N,XS} - i_{N,SS}(f_{SI}-1) - i_{N,SI} f_{SI}$			$i_{P,XS} - i_{P,SS}$	$\nu_{1,HCO}$
	Heterotrophic organisms X_H								
2	Aer. Storage of X_{STO}	Y_{STO,O_2}^{-1}	-1		$i_{N,SS}$			$i_{P,SS}$	$\nu_{2,HCO}$
3	Anox. Storage of X_{STO}		-1		$i_{N,SS}$	$-(1-Y_{STO,NO})/2.86$	$(1-Y_{STO,NO})/2.86$	$i_{P,SS}$	$\nu_{3,HCO}$
4	Aerobic growth	$1 - 1/Y_{H,O_2}$			$-i_{N,BM}$			$-i_{P,BM}$	$\nu_{4,HCO}$
5	Anoxic growth				$-i_{N,BM}$	$-(1/Y_{H,NO}^{-1})/2.86$	$(1/Y_{H,NO}^{-1})/2.86$	$-i_{P,BM}$	$\nu_{5,HCO}$
6	Aer. endog. respiration	$-(1-f_{XI})$			$i_{N,BM} - f_{XI} i_{N,XI}$			$i_{P,BM} - f_{XI} i_{P,XI}$	$\nu_{6,HCO}$
7	Anox. endog. respiration				$i_{N,BM} - f_{XI} i_{N,XI}$	$-(1-f_{XI})/2.86$	$(1-f_{XI})/2.86$	$i_{P,BM} - f_{XI} i_{P,XI}$	$\nu_{7,HCO}$
8	Aer. respiration of X_{STO}	-1							
9	Anox. resp. of X_{STO}					$-1/2.86$	$1/2.86$		$\nu_{9,HCO}$
	Autotrophic organisms X_A								
10	Growth	$1-4.57/Y_A$			$-1/Y_A - i_{N,BM}$	$1/Y_A$		$-i_{P,BM}$	$\nu_{10,HCO}$
11	Aer. endog. respiration	$-(1-f_{XI})$			$i_{N,BM} - f_{XI} i_{N,XI}$			$i_{P,BM} - f_{XI} i_{P,XI}$	$\nu_{11,HCO}$
12	Anox. endog. respiration				$i_{N,BM} - f_{XI} i_{N,XI}$	$-(1-f_{XI})/2.86$	$(1-f_{XI})/2.86$	$i_{P,BM} - f_{XI} i_{P,XI}$	$\nu_{12,HCO}$
	Phosphorus accumulating organisms X_{PAO}								
P1	Storage of X_{PHA}		-1		$i_{N,SS}$			$Y_{PO4} + i_{P,SS}$	$\nu_{P1,HCO}$
P2	Aerobic storage of X_{PP}	$-Y_{PHA}$						-1	$\nu_{P2,HCO}$
P3	Anox. storage X_{PP}					$-Y_{PHA}/2.86$	$Y_{PHA}/2.86$	-1	$\nu_{P3,HCO}$
P4	Aerobic growth	$1-(1/Y_{PAO,O_2})$			$-i_{N,BM}$			$-i_{P,BM}$	$\nu_{P4,HCO}$
P5	Anox. growth				$-i_{N,BM}$	$(1-(1/Y_{PAO,NO}))/2.86$	$-(1-(1/Y_{PAO,NO}))/2.86$	$-i_{P,BM}$	$\nu_{P5,HCO}$
P6	Aer. endog. respiration	$-(1-f_{XI})$			$i_{N,BM} - f_{XI} i_{N,XI}$			$i_{P,BM} - f_{XI} i_{P,XI}$	$\nu_{P6,HCO}$
P7	Anox. endog. respiration				$i_{N,BM} - f_{XI} i_{N,XI}$	$(f_{XI}-1)/2.86$	$-(f_{XI}-1)/2.86$	$i_{P,BM} - f_{XI} i_{P,XI}$	$\nu_{P7,HCO}$
P8	Aerobic lysis of X_{PP}							1	$\nu_{P8,HCO}$
P9	Anox. lysis of X_{PP}							1	$\nu_{P9,HCO}$
P10	Aer. respiration of X_{PHA}	-1							
P11	Anox. resp. of X_{PHA}					$-1/2.86$	$1/2.86$		$\nu_{P11,HCO}$
	Composition matrix								
	Conservatives								
1	ThOD[a] g ThOD	-1	1	1		$-64/14$	$-24/14$		
2	Nitrogen g N		$i_{N,SS}$	$i_{N,SI}$	1	1	1		
3	Phosphorus g P		$i_{P,SS}$	$i_{P,SI}$				1	
4	Ionic charge Mole+				$1/14$	$-1/14$		$-1.5/31$	-1
	Observables								
5	SS g SS								

[a] In this model, it is assumed that ThOD is identical to the measured COD. Definition: 1 g S_O = −1 g ThOD, 1 g S_{NH} = 0 g ThOD, 1 g S_{NO} = −64/14 g ThOD and 1 g S_{N_2} = −24/14 g ThOD

Table 3-6 **Stoichiometric matrix of particulate components in ASM3 & EAWAG Bio-P module**

	Model components *i*	9	10	11	12	13	14	15	16	17
j	Processes	X_I (gCODm^{-3})	X_S (gCODm^{-3})	X_H (gCODm^{-3})	X_{STO} (gCODm^{-3})	X_{PAO} (gCODm^{-3})	X_{PP} (gPm^{-3})	X_{PHA} (gCODm^{-3})	X_A (gCODm^{-3})	X_{TSS} (gTSSm^{-3})
1	Hydrolysis		-1							$\nu_{1,TSS}$
	Heterotrophic organisms X_H									
2	Aer. storage of X_{STO}				Y_{STO,O_2}					$\nu_{2,TSS}$
3	Anox. storage of X_{STO}				$Y_{STO,NO}$					$\nu_{3,TSS}$
4	Aerobic growth			1	$-1/Y_{H,O_2}$					$\nu_{4,TSS}$
5	Anoxic growth			1	$-1/Y_{H,NO}$					$\nu_{5,TSS}$
6	Aer. endog. respiration	f_{XI}		-1						$\nu_{6,TSS}$
7	Anox. endog. respiration	f_{XI}		-1						$\nu_{7,TSS}$
8	Aer. respiration of X_{STO}				-1					$\nu_{8,TSS}$
9	Anox. resp. of X_{STO}				-1					$\nu_{9,TSS}$
	Autotrophic organisms X_A									
10	Growth								1	$\nu_{10,TSS}$
11	Aer. endog. respiration	f_{XI}							-1	$\nu_{11,TSS}$
12	Anox. endog. respiration	f_{XI}							-1	$\nu_{12,TSS}$
	Phosphorus accumulating organisms X_{PAO}									
P1	Storage of X_{PHA}						Y_{PO_4}	1		$\nu_{P1,TSS}$
P2	Aerobic storage of X_{PP}						1	$-Y_{PHA}$		$\nu_{P2,TSS}$
P3	Anox. storage X_{PP}						1	$-Y_{PHA}$		$\nu_{P3,TSS}$
P4	Aerobic growth					1		$-1/Y_{PAO,O_2}$		$\nu_{P4,TSS}$
P5	Anox. growth					1		$1/Y_{PAO,NO}$		$\nu_{P5,TSS}$
P6	Aer. endog. respiration	f_{XI}				-1				$\nu_{P6,TSS}$
P7	Anox. endog. respiration	f_{XI}				-1				$\nu_{P7,TSS}$
P8	Aerobic lysis of X_{PP}						-1			$\nu_{P8,TSS}$
P9	Anox. lysis of X_{PP}						-1			$\nu_{P9,TSS}$
P10	Aer. resp. of X_{PHA}							-1		$\nu_{P10,TSS}$
P11	Anox. resp. of X_{PHA}							-1		$\nu_{P11,TSS}$
	Composition matrix									
	Conservatives									
1	ThOD gThOD	1	1	1	1	1		1	1	
2	Nitrogen gN	$i_{N,XI}$	$i_{N,XS}$	$i_{N,BM}$		$i_{N,BM}$			$i_{N,BM}$	
3	Phosphorus gP	$i_{P,XI}$	$i_{P,XS}$	$i_{P,BM}$		$i_{P,BM}$	1		$i_{P,BM}$	
4	Ionic charge Mole +						$-1/31$			
	Observables									
5	TSS g TSS	$i_{TSS,XI}$	$i_{TSS,XS}$	$i_{TSS,BM}$	$i_{TSS,STO}$	$i_{TSS,BM}$	3.23	$i_{TSS,STO}$	$i_{TSS,BM}$	-1

3.2 Metabolic BPR Model

The IWA ASM relies mainly on the observed yields of the biomass (i.e. exchange of compounds) and uses a grey box approach towards the cell internal conversions by modeling the Poly-phosphate and COD storage compounds. With knowledge advancement, certain aspects of the internal cell metabolism have been understood in a better way that has encouraged the research groups of the Technical University of Delft to consider the internal cell metabolism processes of the PAOs and develop the metabolic bio-P module. The metabolic bio-P module is based on the formation and degradation of all relevant cell internal storage compounds (PHA, glycogen, and PP). All module yields are stoichiometrically related and follow the metabolic conversions mediated by ATP and $NADH_2$. ATP is adenosine triphosphate and it is the primary energy carrier in all living organisms on the Earth. When biological cells metabolize, the energy released is transferred to the ATP, which then moves to other parts of the cell to donate the energy to other functions. NADH is the nicotinamide adenine dinucleotide which is also an energy source and a source to balance the cell internal reduction potential as each molecule of NAD can acquire two electrons. The heart of the metabolic model consists of three metabolic yields, being the ATP formation per $NADH_2$, the biomass reduction per ATP and the ATP requirement for maintenance. The figure below compares the different modeling concepts in IWA ASM and Delft metabolic bio-P module.

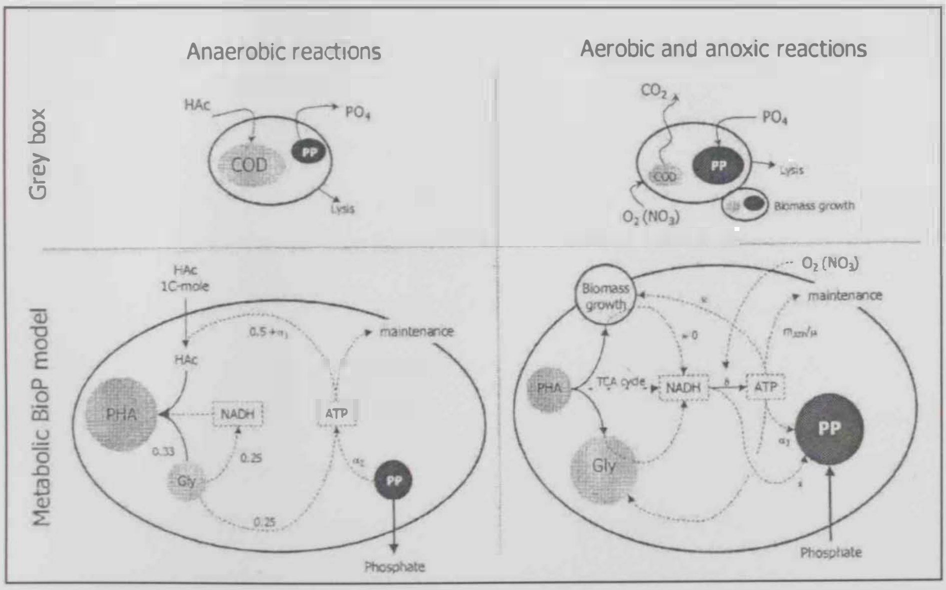


Figure 3-1 Different Modeling Concepts of BPR (Source: Meijer, 2004)

The first metabolic model was developed by Smolders et al. (1994a/b and 1995a/b) where a kinetic structure was proposed in which the consumption rate of the PHA storage compounds is a net result of biomass growth, poly-phosphate and glycogen formation. The model was describing the anaerobic and aerobic phases only of the EBPR. In 1996, a metabolic model for EBPR under anoxic conditions was proposed. A complete version of the metabolic model including the anaerobic, anoxic and aerobic phases was issued in 1997. This model was referred to as the Technical University of Delft Phosphorus Model (TUDP). In 1999, the TUDP model was integrated with the heterotrophic, hydrolytic and autotrophic reactions of the ASM2d and referred to as the TUD model. The reader is advised to refer to Meijer (2004) for detailed description of the model.

CHAPTER IV

MATHEMATICAL MODEL FORMULATION

In this chapter, a mathematical model describing a WWTP with BNR capability (WWTP/BNR) is developed using the IWA ASM3 with the EAWAG bio-P module. The developed model considers a primary clarifier together with an A^2O system as shown in the figure below.

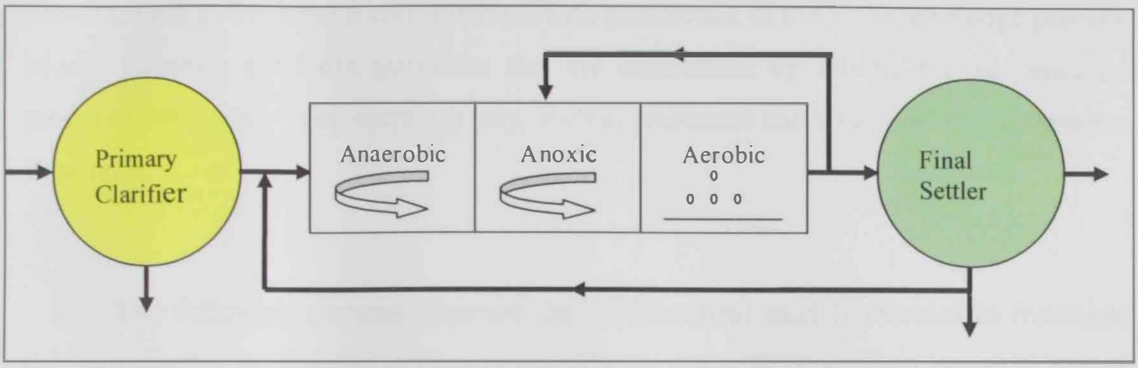


Figure 4-1 WWTP Scheme Considered in the Developed Mathematical Model

The primary sedimentation tank is added to the A^2O system as it is usually considered an important part of any WWTP. Grady et al. (1999), state that the use of the primary clarifier in the WWTP's is an economic issue, not a process issue. It is worth mentioning that the primary clarifier can actually be considered more economical when installed with the aerobic-only activated sludge systems rather than the BNR systems. In the aerobic-only activated sludge systems, primary clarifier can contribute in removing part of the particulate substrates (Xs) which reduces the biological load and therefore reduces the CAPEX and OPEX investments of the biological reactor. However, this might not be the case in the BNR systems since they might experience lack of substrate because of the substrate storage in the anaerobic phase. The anaerobic substrate storage phase might impose a real limitation of the subsequent denitrification, nitrification and COD removal processes.

Two recirculation streams are considered in the model, first is the conventional sludge recirculation to the anaerobic compartment which aims to utilize the active biomass collected in the final settler to achieve the COD and nutrients removal, and second is the internal recirculation from the aerobic compartment to the anoxic compartment which aims to achieve the denitrification process.

The mathematical model developed in this chapter is solved in an optimal design approach considering system constraints and objective cost functions. The developed mathematical model consists of two groups of components; model parameters and model variables. Model parameters are those quantities that remain constant during the design process, such as the kinetic and stoichiometric parameters of the activated sludge process. Model variables are those quantities that are determined by solving the mathematical model of the system in an optimum way, such as treatment unit's dimensions and streams flow rates.

The following sections illustrate the mathematical models selected to formulate the optimization problem of this study considering the WWTP scheme shown in Figure 4-1. The developed model consists of three main mathematical sub-models for (i) primary clarifier, (ii) biological treatment and (iii) final clarifier.

The considered models cannot be claimed to be the best verified and reality-representative models since every model has its own assumptions and restrictions. This is especially true for empirical models which are based on collected data only, and usually used to predict and not to explain a system. The developed model in this thesis can be used as a design tool for new plants or as a performance assessment tool for existing plants only after conducting model parameters calibration by verifying its results against actual data collected from waste water treatment plants having a similar scheme and operating under similar conditions.

4.1 Primary Clarifier

Primary clarifiers are usually installed at the upstream side of the biological reactor in order to remove particulate matter from the raw sewage and produce a clarified effluent to relieve the load on the subsequent biological treatment units. Primary clarifiers have to be designed to produce sludge with solids concentrations that can be easily handled and treated. Metcalf & Eddy (1991) consider the primary clarifier to be designed efficiently if it can achieve 50-70% suspended solids removal and 25-40% BOD_5 removal. Suidan et al. (1983) have shown that operating a treatment plant without primary sedimentation units might result in a total treatment cost increase by approximately 30%. Overflow rate and influent suspended solids concentration have been considered as the most important parameters that affect the performance of the primary clarifiers. Christoulas et al (1998) have emphasized that influent temperature is an important factor that affects particles settling velocity and velocity gradients.

Theoretical mathematical models have failed to predict the behaviour of the sedimentation tanks under actual operating conditions because of the difficulties in simulating the effect of the density currents and the complex phenomenon of the flocculation (Christoulas et al, 1998). Therefore, Empirical models were found to be more suitable for the design of primary clarifiers. Such models are developed by collecting data on process design variables from operational plants, and then identifying the correlation between these variables through the regression analysis. Arwani (2003) has presented a historical review of mathematical empirical models developed for primary clarifiers.

In this study, the empirical model of Christoulas et al. (1998) is selected for the primary settling process because it is recent and has shown good capability in fitting the observed data. In this model, influent suspended solids (TSS_{in}) are related to the effluent suspended solids (TSS_{eff_p}) by the following relation:

$$\frac{TSS_{eff\_P}}{TSS_{in}} = 1 - \left[a \exp\left(\frac{-b}{TSS_{in}} - cq \right) \right] \qquad \textbf{(4-1)}$$

where a, b (mg /L), and c (d/m) are positive parameters. The value of a and b are found to be related to temperature while c is a constant value. q (m/d) is the overflow rate which is defined as follows:

$$q = \frac{Q_{eff\_p}}{A_p} \tag{4-2}$$

where A_p is the surface area of the primary clarifier (m^2) and Q_{eff_p} is the effluent from the primary clarifier (m^3/d).

The sludge concentration of sedimentation tank has been modelled by either assuming that its concentration is limited by the hydraulic capacity of the withdrawal mechanisms, or by using the deferential thickening technique based on the limiting flux theory. The limiting flux theory depends mainly on modelling the settling velocity of the particles. In this study, the underflow solids concentration is calculated according to the solids flux theory given by Cho et al. (1996).

$$TSS_{Sludge\_p} = \left[K(n-1)\right]^{1/n} \left(\frac{n}{n-1}\right) \left(\frac{A_p}{Q_{sludge\_p}}\right)^{1/n} \tag{4-3}$$

where k (m/d) and n are settling constants of the primary sludge. k ranges between 65 to 460 m/day while n ranges between 1 to 5. A_p and Q_{sludge_p} are in m^2 and m^3/d respectively.

The concentrations of the other particulate compounds (X) in both clarified effluent (Q_{eff_P}) and sludge streams (Q_{sludge_P}), are calculated based on the assumption that the portion of each solid component in the suspended solids of any of the above-mentioned streams is same as the portion of that component in the primary influent suspended solids. In other words the solids distribution as a percentage of the suspended solids will remain the same in all three streams: influent, effluent and sludge waste stream:

$$X_{j\_eff} = X_{j\_in} \frac{TSS_{eff}}{TSS_{in}} \tag{4-4}$$

$$X_{j\_sludge} = X_{j\_in} \frac{TSS_{sludge}}{TSS_{in}} \tag{4-5}$$

where *j* represents the particulate components (i.e. STO, H, A, PAO, etc.). Moreover, it is assumed that all soluble components are not affected by the primary sedimentation.

The mass balance relationships, for flow (*Q*) and particulate components (*X*), considered around the primary clarifier, are as follows:

$$Q_{in} = Q_{eff} + Q_{sludge} \tag{4-6}$$

$$Q_{in} X_{in} = Q_{eff} X_{eff} + Q_{sludge} X_{sludge} \tag{4-7}$$

4.2 BNR Activated Sludge System

The mathematical model of the A^2O BNR activated sludge system is developed and considered in the optimization model formulated for the WWTP scheme shown in Figure 4-1. The A^2O system consists basically of an anaerobic compartment to achieve phosphorus release and then removal in the subsequent chapters, anoxic compartment to achieve total nitrogen removal and aerobic compartment to achieve COD removal. The ASM3 with the EAWAG Bio-P module has been used for the formulation of the A^2O system of equations, which are then included in the overall optimization problem. ASM3 model is rarely utilized in its full version and in most cases a reduced version is developed and adopted (Jeppsson, 1996). The following simplifications are considered during the formulation of the A^2O system of equations based on the ASM3/EAWAG Bio-P matrix (refer to Table 5-4):

1. The oxygen concentration in the aerobic compartment is controlled at all time to be greater than or equal to 2 mg/l. Therefore, the term $[S_{O2}/ (K_{O2}+S_{O2})]$ is assumed equal to 1. This term is introduced in all aerobic processes of ASM3 model to switch off the process when the oxygen concentration drops to zero.
2. The anoxic compartment is assumed to be purely anoxic, and oxygen concentration inside it is assumed to equal zero. Therefore, the term $[K_{O2}/ (K_{O2}+S_{O2})]$ is assumed equal to 1. This term is introduced in all anoxic processes

of ASM3 to reduce the process rate when the oxygen concentration in the anoxic compartment is greater than zero.

3. The nitrogen component (S_{N2}) is neglected and the denitrification process is traced through the nitrate & nitrite nitrogen (S_{NOX}).
4. Alkalinity dynamics are neglected and hence the term [S_{ALK}/ (K_{ALK}/S_{ALK})] is assumed equal to 1 (Chachuat et al., 2001). This term is introduced to switch off the process when the alkalinity of the wastewater drops to zero.

Implementing the above mentioned simplifications will result in a reduced ASM3/ EAWAG Bio-P model consisting of 13 state variables, as illustrated in Table 4-1.

Table 4-1 State Variables in Reduced ASM3/EAWAG Bio-P model

State Variable	Description
TSS	Total Suspended Solids
X_I	Inert Particulate
X_S	Slowly Biodegradable Substrate
X_H	Heterotrophic Organisms
X_{STO}	Cell Storage Product of heterotrophic Organisms
X_{PAO}	Phosphorus Accumulating Organisms
X_{PP}	Poly-Phosphate
X_{PHA}	Cell Storage Product of PAO
X_A	Autotrophic / Nitrifying Organisms
S_S	Soluble Substrate
S_{NOX}	Nitrate plus Nitrite Nitrogen
S_{NH4}	Ammonium plus Ammonia Nitrogen
S_{PO4}	Inorganic Soluble Phosphorus

Table 4-2 shows the formulation of the reduced processes' rates considered in the ASM3/EAWAG Bio-P model. All processes should result in a positive rate values (i.e. greater than or equal to zero). The complete formulation of the processes` rate equations can be found in Henze et al. (2000) and Rieger et al. (2001).

Table 4-2 **Reduced processes of ASM3/EAWAG Bio-P model**

	Process	***Process rate equation (concentration per unit time)***
R1	Hydrolysis	$k_H \frac{Xs / X_H}{K_X + Xs / X_H} X_H$
Heterotrophic organisms, aerobic and denitrifying activity		
R2	Aerobic Storage of Ss	$k_{STO} \frac{Ss}{K_S + Ss} X_H$
R3	Anoxic Storage of Ss	$k_{STO} \eta_{NOX} \frac{S_{NOX}}{K_{NOX} + S_{NOX}} \frac{Ss}{K_S + Ss} X_H$
R4	Aerobic Growth	$\mu_H \frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}} \frac{X_{STO} / X_H}{K_{STO} + X_{STO} / X_H} X_H$
R5	Anoxic Growth (Denitrification)	$\mu_H \eta_{NOX} \frac{S_{NOX}}{K_{NOX} + S_{NOX}} \frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}} \frac{X_{STO} / X_H}{K_{STO} + X_{STO} / X_H} X_H$
R6	Aerobic Endogenous Respiration	$b_{H,O_2} X_H$
R7	Anoxic Endogenous Respiration	$b_{H,NOX} \frac{S_{NOX}}{K_{NOX} + S_{NOX}} X_H$
R8	Aerobic Respiration of X_{STO}	$b_{STO,O_2} X_{STO}$
R9	Anoxic Respiration of X_{STO}	$b_{STO,NOX} \frac{S_{NOX}}{K_{NOX} + S_{NOX}} X_{STO}$
Autotrophic organisms, nitrifying activity		
R10	Aerobic growth of X_A, nitrification	$\mu_A \frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}} X_A$
R11	Aerobic Endogenous Respiration	$b_{A,O_2} X_A$
R12	Anoxic Endogenous Respiration	$b_{A,NOX} \frac{S_{NOX}}{K_{NOX} + S_{NOX}} X_A$
Phosphorus Accumulating Organisms		
P1	Storage of X_{PHA}	$q_{PHA} \frac{S_S}{K_{SS,PAO} + S_S} \frac{X_{PP} / X_{PAO}}{K_{PP,PAO} + X_{PP} / X_{PAO}} X_{PAO}$
P2	Aerobic Storage of X_{PP}	$q_{PP} \frac{S_{PO_4}}{K_{PO_4,PP} + S_{PO_4}} \frac{X_{PHA} / X_{PAO}}{K_{PHA} + X_{PHA} / X_{PAO}} \frac{K_{\max,PAO} - (X_{PP} / X_{PAO})}{K_{iPP,PAO} + K_{\max,PAO} - (X_{PP} / X_{PAO})} X_{PAO}$
P3	Anoxic Storage of X_{PP}	$q_{PP} \eta_{NO,PAO} \frac{S_{NO}}{K_{NO,PAO} + S_{NO}} \frac{S_{PO_4}}{K_{PO_4,PP} + S_{PO_4}} \frac{\frac{X_{PHA}}{X_{PAO}}}{K_{PHA} + \frac{X_{PHA}}{X_{PAO}}} \frac{K_{\max,PAO} - (\frac{X_{PP}}{X_{PAO}})}{K_{iPP,PAO} + K_{\max,PAO} - (\frac{X_{PP}}{X_{PAO}})} X_{PAO}$
P4	Aerobic Growth of X_{PAO}	$\mu_{PAO} \frac{S_{NH}}{K_{NH,PAO} + S_{NH}} \frac{S_{PO_4}}{K_{PO_4,PAO} + S_{PO_4}} \frac{X_{PHA} / X_{PAO}}{K_{PHA} + X_{PHA} / X_{PAO}} X_{PAO}$

	Process	**Process rate equation (concentration per unit time)**
P5	Anoxic Growth of X_{PAO}	$\mu_{PAO}\,\eta_{NO,PAO}\frac{S_{NO}}{K_{NO,PAO}+S_{NO}}\frac{S_{NH}}{K_{NH,PAO}+S_{NH}}\frac{S_{PO_4}}{K_{PO_4,PAO}+S_{PO_4}}\frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}}X_{PAO}$
P6	Aerobic endogenous respiration	$b_{PAO}X_{PAO}$
P7	Anoxic endogenous respiration	$b_{PAO}\,\eta_{NO,end,PAO}\frac{S_{NO}}{K_{NO,PAO}+S_{NO}}X_{PAO}$
P8	Aerobic lysis of X_{PP}	$b_{PP}X_{PP}$
P9	Anoxic lysis of X_{PP}	$b_{PP}\,\eta_{NO,lys,PP}\frac{S_{NO}}{K_{NO,PAO}}X_{PP}$
P10	Aerobic respiration of X_{PHA}	$b_{PHA}X_{PHA}$
P11	Anoxic respiration of X_{PHA}	$b_{PHA}\,\eta_{NO,resp,PHA}\frac{S_{NO}}{K_{NO,PAO}}X_{PHA}$

Table 4-3 shows typical values for the kinetic parameters of the ASM3/EAWAG Bio-P model appeared in table 8-2, at 20°C as suggested by Henze et al. (2000) and Rieger et al. (2001).

Table 4-3 **Typical values of kinetic parameters for ASM3/EAWAG Bio-P model**

Symbol	**Characterization**	**Value (20°C)**	**Units**
Typical kinetic parameters of ASM3 , Henze et al. 2000			
K_H	Hydrolysis rate constant	3	$gCOD_{X_S}(gCOD_{X_H})^{-1}d^{-1}$
K_X	Hydrolysis saturation constant	1	$gCOD_{X_S}(gCOD_{X_H})^{-1}$
Heterotrophic organisms X_H, aerobic and denitrifying activity			
k_{STO}	Storage rate constant	5	$gCOD_{X_S}(gCOD_{X_H})^{-1}d^{-1}$
η_{NOX}	Anoxic Reduction Factor	0.6	
K_{NOX}	Saturation constant for S_{NOX}	0.5	$gNO_3-N\ m^{-3}$
K_S	Saturation constant for substrate Ss	2	$gCOD_{S_S}\ m^{-3}$
K_{STO}	Saturation constant for X_{STO}	1	$gCOD_{X_{STO}}(gCOD_{X_H})^{-1}$
μ_H	Heterotrophic max. growth rate of X_H	2	d^{-1}
K_{NH4}	Saturation constant for S_{NH4}	0.01	$gN\ m^{-3}$

Symbol	**Characterization**	**Value (20°C)**	**Units**
$b_{H,O2}$	Aerobic endogen. Respiration rate of X_H	0.2	d^{-1}
$b_{H,NOX}$	Anoxic endogen. Respiration rate of X_H	0.1	d^{-1}
$b_{STO,O2}$	Aerobic respiration rate for X_{STO}	0.2	d^{-1}
$b_{STO,NOX}$	Anoxic respiration rate for X_{STO}	0.1	d^{-1}
Autotrophic organisms X_A, nitrifying Activity			
μ_A	Autotrophic max. growth rate of X_A	1	d^{-1}
$K_{A,NH4}$	Ammonium substrate saturation for X_A	1	$gN\ m^{-3}$
$b_{A,O2}$	Aerobic endogen. respiration rate of X_A	0.15	d^{-1}
$b_{A,NOX}$	Anoxic endogen. respiration rate of X_A	0.05	d^{-1}
Typical kinetic parameters of EAWAG Bio-P module, Rieger et al. 2001			
q_{PHA}	Rate constant for storage of X_{PHA}	6	d^{-1}
q_{PP}	Rate constant for storage of X_{PP}	1.5	d^{-1}
μ_{PAO}	Max. growth rate of X_{PAO}	1	d^{-1}
$\eta_{NO,PAO}$	Anoxic reduction factor growth of X_{PAO}	0.6	
b_{PAO}	Max. endogen. Respiration rate of X_{PAO}	0.2	d^{-1}
$\eta_{NO,end,PAO}$	Anoxic reduction factor for endogen. Respiration	0.33	
b_{PP}	Lysis X_{PP}	0.2	d^{-1}
$\eta_{NO,lys,PP}$	Anoxic reduction factor for lysis	0.33	
b_{PHA}	Respiration rate for X_{PHA}	0.2	d^{-1}
$\eta_{NO,resp,PHA}$	Anoxic reduction factor for respiration	0.33	
$K_{SS,PAO}$	Saturation constant for Ss	10	$gCOD\ m^{-3}$
$K_{PP,PAO}$	Saturation constant X_{PP}/X_{PAO}	0.05	$gP\ gCOD^{-1}$
K_{PHA}	Saturation constant for X_{PHA}/X_{PAO}	0.1	$gCOD\ gCOD^{-1}$
$K_{max,PAO}$	Max, ratio of X_{PP}/X_{PAO}	0.2	$gP\ gCOD^{-1}$
$K_{iPP,PAO}$	Saturation constant for $[K_{max,PAO}-(X_{PP}/X_{PAO})]$	0.05	$gP\ gCOD^{-1}$
$K_{NO,PAO}$	Saturation constant for S_{NO}	0.5	$gN\ m^{-3}$
$K_{PO4,PP}$	Saturation constant for S_{PO4} (X_{PP} Storage)	0.2	$gP\ m^{-3}$
$K_{PO4,PAO}$	Saturation constant for S_{PO4} (X_{PAO} growth)	0.01	$gP\ m^{-3}$
$K_{NH,PAO}$	Saturation constant for S_{NH}	0.05	$gN\ m^{-3}$

The ASM3/EAWAG Bio-P model is introduced in the form of stoichiometric and composition matrix (Tables 3-5 and 3-6). Henze et al. (2000) recommends the following equation to estimate the temperature effect on the kinetic parameters:

$$k_{(T)} = k_{(20^o C)} \; e^{\theta_T (T-20)} \tag{4-8}$$

Where θ_T (in °C) can be obtained from:

$$\theta_T = \frac{\ln \left({}^{K_{(T_1)}} \big/ {}_{K_{(T_2)}} \right)}{T_1 - T_2} \tag{4-9}$$

Table 4-4 shows typical values for the stoichiometric and composition parameters as suggested by Henze et al. (2000) and Rieger et al. (2001).

Table 4-4 Typical Stoichiometric and composition parameters of ASM3 / EAWAG Bio-P model

Symbol	Characterization	Value	Units
Typical Stoichiometric and composition parameters of ASM3 , Henze et al. 2000			
f_{SI}	Production of S_I in hydrolysis	0	$gCOD_{S_I}(gCOD_{X_S})^{-1}$
$\gamma_{STO,O2}$	Aerobic yield of stored product per S_s	0.85	$gCOD_{X_{STO}}(gCOD_{S_S})^{-1}$
$\gamma_{STO,NOX}$	Anoxic yield of stored product per S_s	0.8	$gCOD_{X_{STO}}(gCOD_{S_S})^{-1}$
$\gamma_{H,O2}$	Aerobic yield of heterotrophic biomass	0.63	$gCOD_{X_H}(gCOD_{X_{STO}})^{-1}$
$\gamma_{H,NOX}$	Anoxic yield of heterotrophic biomass	0.54	$gCOD_{X_H}(gCOD_{X_{STO}})^{-1}$
γ_A	Yield of autotrophic biomass per NO_3^--N	0.24	$gCOD_{X_A}(gN_{S_{NOX}})^{-1}$
f_{XI}	Production of X_I in endogen. respiration	0.2	$gCOD_{X_I}(gCOD_{X_{BM}})^{-1}$
$i_{N,SI}$	N content of S_I	0.01	$gN\ (gCOD_{S_I})^{-1}$
$i_{N,SS}$	N content of S_s	0.03	$gN\ (gCOD_{S_S})^{-1}$
$i_{N,XI}$	N content of X_I	0.02	$gN\ (gCOD_{X_I})^{-1}$
$i_{N,XS}$	N content of X_S	0.04	$gN\ (gCOD_{X_S})^{-1}$

Symbol	**Characterization**	**Value**	**Units**
$i_{N,BM}$	N content of biomass, X_H,X_A	0.07	$gN\ (gCOD_{X_{BM}})^{-1}$
$i_{TSS,XI}$	TSS to COD ratio for X_I	0.75	$gTSS(gCOD_{X_I})^{-1}$
$i_{TSS,XS}$	TSS to COD ratio for X_s	0.75	$gTSS(gCOD_{X_S})^{-1}$
$i_{TSS,BM}$	TSS to COD ratio for biomass ,X_H,X_A	0.9	$gTSS(gCOD_{X_{BM}})^{-1}$
Typical Stoichiometric and composition parameters of EAWAG Bio-P module, Rieger et al. 2001			
γPAO,O2	Yield Biomass / X_{PHA}	0.6	$gCOD\,(gCOD)^{-1}$
γPAO,NO	Yield Biomass / X_{PHA}	0.5	$gCOD\,(gCOD)^{-1}$
γPHA	Requirement of X_{PHA} per X_{PP} storage (p-storage)	0.2	$gCOD\ \ gP^{-1}$
γ_{PO4}	Requirement of XPP per XPHA storage (p-release)	0.35	$gP\ \ gCOD^{-1}$
$i_{P,SS}$	Phosphorus content of S_S	0	$gP\ \ gCOD^{-1}$
$i_{P,SI}$	Phosphorus content of S_I	0	$gP\ \ gCOD^{-1}$
$i_{P,XI}$	Phosphorus content of X_I	0.01	$gP\ \ gCOD^{-1}$
$i_{P,XS}$	Phosphorus content of X_S	0.005	$gP\ \ gCOD^{-1}$
$i_{P,BM}$	Phosphorus content of biomass (X_H,X_A,X_{PAO})	0.014	$gP\ \ gCOD^{-1}$
$i_{TSS,XI}$	TSS to COD ratio for X_I	0.75	$gTSS(gX_I)^{-1}$
$i_{TSS,XS}$	TSS to COD ratio for X_S	0.75	$gTSS(gX_S)^{-1}$
$i_{TSS,XSTO}$	TSS to COD ratio for X_{STO} resp. X_{PHA}	0.6	$gTSS(gX_{STO})^{-1}$
$i_{TSS,BM}$	TSS to COD ratio for biomass	0.9	$gTSS(g\,BM)^{-1}$
$i_{TSS,XPP}$	TSS to COD ratio for X_{PP}	3.23	$gTSS(g\,X_{PP})^{-1}$

4.2.1 Mass Balance Equations

Steady state mass balance equations for all system state variables are developed across the anaerobic, anoxic and aerobic reactors using the following general formula:

$$Mass\ In - Mass\ Out + [V_{reactor} \cdot Reaction\ Rate] = (dc/dt) * V_{reactor} \qquad (4\text{-}10)$$

For steady state analysis (dc/dt) = zero. The figure below shows the streams numbering system adopted during the model development:

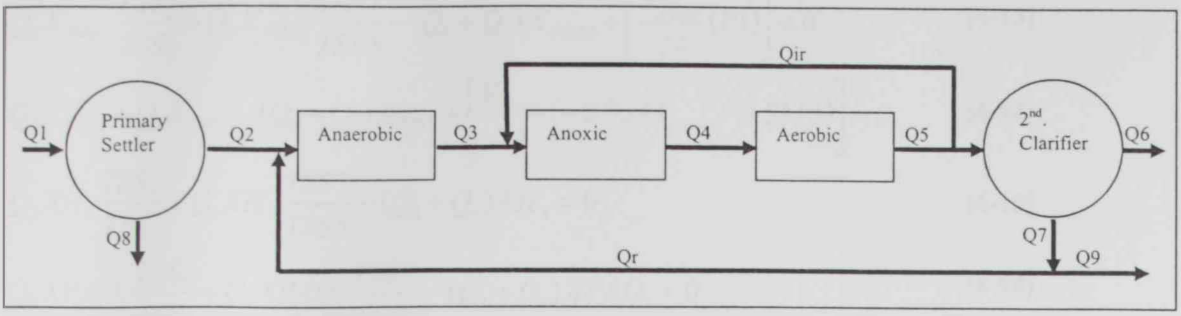


Figure 4-2 Process Flow Diagram of the Modeled A^2O System

As stated earlier, hydrolysis in ASM3 model is assumed to be active independently from the electron acceptor. Therefore, during the model formulation, hydrolysis is assumed to occur in all three reactors (i.e. anaerobic, anoxic and aerobic). The other process in the ASM3/EAWAG Bio-P model that is assumed to occur in the anaerobic compartment is the storage of the readily degradable substrates (S_s) in the form of cell-internal storage products (X_{PHA}) which primarily includes poly-hydroxy-alkanoates and glycogen. The Following is the system of equations developed for the anaerobic compartment:

$$Q_2 XS_1 \frac{TSS_2}{TSS_1} + Q_r XS_5 \frac{TSS7}{TSS5} - (Q_2 + Q_r) XS_3 + \left[\frac{V_{anaer}}{24} (-R1_{anaer}) \right] = 0 \quad (4\text{-}11)$$

$$Q_2 X_{pp1} \frac{TSS_2}{TSS_1} + Q_r X_{PP5} \frac{TSS7}{TSS5} - (Q_2 + Q_r) X_{PP3} + \left[\frac{V_{anaer}}{24} (-0.35P1) \right] = 0 \quad (4\text{-}12)$$

$$Q_2 X_{PHA1} \frac{TSS_2}{TSS_1} + Q_r X_{PHA5} \frac{TSS7}{TSS5} - (Q_2 + Q_r) X_{PHA3} + \left[\frac{V_{anaer}}{24} (P1) \right] = 0 \quad (4\text{-}13)$$

$$Q_2 X_{TSS2} + Q_r X_{TSS7} - (Q_2 + Q_r) X_{TSS3} + \left[\frac{V_{anaer}}{24} (-0.75R1_{anaer} - 0.53P1) \right] = 0 \quad (4\text{-}14)$$

$$Q_2 XH_1 \frac{TSS_2}{TSS_1} + Q_r XH_5 \frac{TSS7}{TSS5} - (Q_2 + Q_r) XH_3 = 0 \quad (4\text{-}15)$$

$$Q_2 XPAO_1 \frac{TSS_2}{TSS_1} + Q_r XPAO_5 \frac{TSS7}{TSS5} - (Q_2 + Q_r) XPAO_3 = 0 \quad (4\text{-}16)$$

$$Q_2 S_{S1} + Q_r S_{S5} - (Q_2 + Q_r) S_{S3} + \left[\frac{V_{anaer}}{24} (R_{1anaer} - P1) \right] = 0 \quad (4\text{-}17)$$

$$Q_2 SNH_1 + Q_r SNH_5 - (Q_2 + Q_r) SNH_3 + \left[\frac{V_{anaer}}{24} (0.01R_{1anaer} + 0.03P_1) \right] = 0 \quad (4\text{-}18)$$

$$Q_2 SPO_1 + Q_r SPO_5 - (Q_2 + Q_r) SPO_3 + \left[\frac{V_{anaer}}{24} (0.005R_{1anaer} + 0.35P_1) \right] = 0 \quad (4\text{-}19)$$

It can be noted that the system of equations for the anaerobic compartment does not include all ASM3/EAWAG-BioP model components as some of them, such as X_H, are not affected by any of the two processes assumed to occur in the anaerobic compartment which are hydrolysis ($R1_{anaer}$) and storage of X_{PHA} (P1).

In the same manner, the systems of equations for both anoxic and aerobic compartments are developed as follows:

For Anoxic compartment

$$Q_2 XI_1 \frac{TSS_2}{TSS_1} + Q_r XI_5 \frac{TSS7}{TSS5} + Q_{ir} XI_5 - (Q_{ir} + Q_2 + Q_r) XI_4 + \left[\frac{V_{anox}}{24} (0.2R7 + 0.2R12 + 0.2P7) \right] = 0 \tag{4-20}$$

$$(Q_2 + Q_r) XS_3 + Q_{ir} XS_5 - (Q_{ir} + Q_2 + Q_r) XS_4 + \left[\frac{V_{anox}}{24} (-R1_{anox}) \right] = 0 \tag{4-21}$$

$$Q_2 XH_1 \frac{TSS_2}{TSS_1} + Q_r XH_5 \frac{TSS7}{TSS5} + Q_{ir} XH_5 - (Q_{ir} + Q_2 + Q_r) XH_4 + \left[\frac{V_{anox}}{24} (R5 - R7) \right] = 0 \tag{4-22}$$

$$Q_2 XSTO_1 \frac{TSS_2}{TSS_1} + Q_r XSTO_5 \frac{TSS7}{TSS5} + Q_{ir} XSTO_5 - (Q_{ir} + Q_2 + Q_r) XSTO_4 + \left[\frac{V_{anox}}{24} (0.8R_3 - 1.85R_5 - R_9) \right] = 0 \tag{4-23}$$

$$Q_2 XPAO_1 \frac{TSS_2}{TSS_1} + Q_r XPAO_5 \frac{TSS7}{TSS5} + Q_{ir} XPAO_5 - (Q_{ir} + Q_2 + Q_r) XPAO_4 + \left[\frac{V_{anox}}{24} (P5 - P7) \right] = 0 \tag{4-24}$$

$$(Q_2 + Q_r) X_{PP3} + Q_{ir} X_{PP5} - (Q_{ir} + Q_2 + Q_r) X_{pp4} + \left[\frac{V_{anoxic}}{24} (P3 - P9) \right] = 0 \tag{4-25}$$

$$(Q_2 + Q_r) X_{PHA3} + Q_{ir} X_{PHA5} - (Q_{ir} + Q_2 + Q_r) X_{PHA4} + \left[\frac{V_{anoxic}}{24} (-0.2P3 - 2P5 - P11) \right] = 0 \tag{4-26}$$

$$Q_2 XA_1 \frac{TSS_2}{TSS_1} + Q_r XA_5 \frac{TSS7}{TSS5} + Q_{ir} XA_5 - (Q_{ir} + Q_2 + Q_r) XA_4 + \left[\frac{V_{anox}}{24} (-R12) \right] = 0 \tag{4-27}$$

$$(Q_2 + Q_r) X_{TSS3} + Q_{ir} X_{TSS5} - (Q_{ir} + Q_2 + Q_r) X_{TSS4} + \left[\frac{V_{anoxic}}{24} \begin{pmatrix} -0.75R_{1anox} + 0.48R_3 - 0.21R_5 - 0.75R_7 \\ -0.6R_9 - 0.75R_{12} + 3.11P_3 - 0.3P_5 \\ -0.75P_7 - 3.23P_9 - 0.6P_{11} \end{pmatrix} \right] = 0 \tag{4-28}$$

$$(Q_2 + Q_r) SS_3 + Q_{ir} SS_5 - (Q_{ir} + Q_2 + Q_r) SS_4 + \left[\frac{V_{anox}}{24} (R_{1anox} - R3) \right] = 0 \tag{4-29}$$

$$(Q_2 + Q_r) SNH_3 + Q_{ir} SNH_5 - (Q_{ir} + Q_2 + Q_r) SNH_4 + \left[\frac{V_{anox}}{24} \begin{pmatrix} 0.01R_{1anox} + 0.03R_3 - 0.07R_5 + 0.066R_7 \\ +0.066R_{12} - 0.07P_5 + 0.06P_7 \end{pmatrix} \right] = 0 \tag{4-30}$$

$$Q_2 SNO_1 + Q_r SNO_5 + Q_{ir} SNO_5 - (Q_{ir} + Q_2 + Q_r) SNO_4 + \left[\frac{V_{anox}}{24} \begin{pmatrix} -0.07R_3 - 0.3R_5 - 0.28R_7 - 0.35R_9 \\ -0.28R_{12} - 0.07P_3 - 0.34P_5 - 0.28P_7 \\ -0.34P_{11} \end{pmatrix} \right] = 0 \tag{4-31}$$

$$(Q_2 + Q_r) SPO_3 + Q_{ir} SPO_5 - (Q_{ir} + Q_2 + Q_r) SPO_4 + \left[\frac{V_{anoxic}}{24} \begin{pmatrix} 0.005R_{1anox} - 0.014R_5 + 0.012R_7 \\ +0.012R_{12} - P_3 - 0.014P_5 + 0.012P_7 + P_9 \end{pmatrix} \right] = 0 \tag{4-32}$$

For Aerobic compartment

$$(Q_{ir}+Q_2+Q_r)XI_4-\left[Q_6XI_5\frac{TSS_6}{TSS_5}+Q_{ir}XI_5+(Q_9+Q_r)XI_5\frac{TSS_7}{TSS_5}\right]+\left[\frac{V_{aer}}{24}(0.2R6+0.2R11+0.2P6)\right]=0 \tag{4-33}$$

$$(Q_{ir}+Q_2+Q_r)XS_4-\left[Q_6XS_5\frac{TSS_6}{TSS_5}+Q_{ir}XS_5+(Q_9+Q_r)XS_5\frac{TSS_7}{TSS_5}\right]+\left[\frac{V_{aer}}{24}(-R1_{aer})\right]=0 \tag{4-34}$$

$$(Q_{ir}+Q_2+Q_r)XH_4-\left[Q_6XH_5\frac{TSS_6}{TSS_5}+Q_{ir}XH_5+(Q_9+Q_r)XH_5\frac{TSS_7}{TSS_5}\right]+\left[\frac{V_{aer}}{24}(R4-R6)\right]=0 \tag{4-35}$$

$$(Q_{ir}+Q_2+Q_r)XSTO_4-\left[Q_6XSTO_5\frac{TSS_6}{TSS_5}+Q_{ir}XSTO_5+(Q_9+Q_r)XSTO_5\frac{TSS_7}{TSS_5}\right]+\left[\frac{V_{aer}}{24}(0.85R2-1.6R4-R8)\right]=0 \tag{4-36}$$

$$(Q_{ir}+Q_2+Q_r)XPAO_4-\left[Q_6XPAO_5\frac{TSS_6}{TSS_5}+Q_{ir}XPAO_5+(Q_9+Q_r)XPAO_5\frac{TSS_7}{TSS_5}\right]+\left[\frac{V_{aer}}{24}(P4-P6)\right]=0 \tag{4-37}$$

$$(Q_{ir}+Q_2+Q_r)X_{PP4}-\left[Q_6XPP_5\frac{TSS_6}{TSS_5}+Q_{ir}XPP_5+(Q_9+Q_r)XPP_5\frac{TSS_7}{TSS_5}\right]+\left[\frac{V_{aer}}{24}(P2-P8)\right]=0 \tag{4-38}$$

$$(Q_{ir}+Q_2+Q_r)X_{PHA4}-\left[Q_6X_{PHA5}\frac{TSS_6}{TSS_5}+Q_{ir}X_{PHA5}+(Q_9+Q_r)X_{PHA5}\frac{TSS_7}{TSS_5}\right]+\left[\frac{V_{aer}}{24}(-0.2P2-1.67P4-P10)\right]=0 \tag{4-39}$$

$$(Q_{ir}+Q_2+Q_r)XA_4-\left[Q_6XA_5\frac{TSS_6}{TSS_5}+Q_{ir}XA_5+(Q_9+Q_r)XA_5\frac{TSS_7}{TSS_5}\right]+\left[\frac{V_{aer}}{24}(R10-R11)\right]=0 \tag{4-40}$$

$$(Q_{ir}+Q_2+Q_r)X_{TSS4}-\left[Q_6X_{TSS_6}+Q_{ir}X_{TSS_5}+(Q_9+Q_r)X_{TSS_7}\right]+\left[\frac{V_{aer}}{24}\begin{pmatrix}-0.75R_{1aer}+0.51R_2-0.06R_4-0.75R_6\\-0.6R_8+0.9R_{10}-0.75R_{11}+3.11P_2\\-0.102P_4-0.75P_6-3.23P_8-0.6P_{10}\end{pmatrix}\right]=0 \tag{4-41}$$

$$(Q_{ir}+Q_2+Q_r)SS_4-\left[(Q_6+Q_9+Q_r+Q_{ir})SS_5\right]+\left[\frac{V_{aer}}{24}(R_{1aer}-R2)\right]=0 \tag{4-42}$$

$$(Q_{ir}+Q_2+Q_r)SNH_4-\left[(Q_6+Q_9+Q_r+Q_{ir})SNH_5\right]+\left[\frac{V_{aer}}{24}\begin{pmatrix}0.01R_{1aer}+0.03R_2-0.07R_4+0.066R_6\\-4.24R_{10}+0.066R_{11}-0.07P_4+0.066P_6\end{pmatrix}\right]=0 \tag{4-43}$$

$$(Q_{ir}+Q_2+Q_r)SNO_4-\left[(Q_6+Q_9+Q_r+Q_{ir})SNO_5\right]+\left[\frac{V_{aer}}{24}(4.17R_{10})\right]=0 \tag{4-44}$$

$$(Q_{ir}+Q_2+Q_r)SPO_4-\left[(Q_6+Q_9+Q_r+Q_{ir})SPO_5\right]+\left[\frac{V_{aer}}{24}\begin{pmatrix}0.005R_{1aer}-0.014R_4+0.012R_6-0.014R_{10}\\+0.012R_{11}-P_2-0.014P_4+0.012P_6+P_8\end{pmatrix}\right]=0 \tag{4-45}$$

In all equations, flow (Q) is in m^3/hr, concentration is in mg/l and volume is in m^3. Noting that all processes rates are expressed on "per day" basis in Table 4-3, the units balance across the developed system of equations is as follows:

$$\text{Mass}_{\text{In}} - \text{Mass}_{\text{Out}} + [V_{\text{reactor}} * \text{Reaction Rate}] = 0$$

$$\left[\frac{\text{m}^3}{\text{hr}} \times \frac{mg}{l}\right] - \left[\frac{\text{m}^3}{\text{hr}} \times \frac{mg}{l}\right] + \left[m^3 \times \frac{mg}{l\,.\,day} \times \frac{day}{24hr}\right] = 0 \qquad \textbf{(4-46)}$$

4.2.2 Oxygen Requirements Constraints

The oxygen is consumed in the aerobic compartment for two main reasons; the first is for the removal of the organic matter and second is for nitrification. The oxygen required for the organic matter removal and nitrification can be estimated from the following two equations (Grady et al. 1999):

$$R_{OH} = Q_2(S_{S2} + X_{S2} - S_{S5})\left[1 - \frac{(1 + f_{XI} b_H SRT_{aer})Y_H}{1 + b_H \theta_C}\right] \qquad \textbf{(4-47)}$$

$$R_{OA} = Q_2(S_{NH_4 2} + S_{NO_4 2} - S_{NH_4 5})\left[4.57 - \frac{(1 + f_{XI} b_A SRT_{aer})Y_A}{1 + b_A \theta_C}\right] \qquad \textbf{(4-48)}$$

where SRT_{aer} is the solids retention time in the aerobic compartment which represents the average time a particulate (X) constituent stays in the aerobic reactor. Mathematically, SRT is defined as the mass of particulates contained in the reactor divided by the mass discharged from the reactor.

$$SRT_{aer} = \frac{V_{aer} \times MLSS}{Q_{eff} TSS_{eff} + Q_{wast\ sludge} TSS_{wast.sludge}} \qquad \textbf{(4-49)}$$

The Air flow rate (AFR) which has to be supplied by the system air diffusers is calculated using the following expression (Grady et al., 1999):

$$AFR = \frac{6\ (RO_H + RO_A)}{n_e} \tag{4-50}$$

where AFR is in m^3/min, (RO_H+RO_A) is the total oxygen requirement in kg/h, and n_e is the field oxygen transfer efficiency expressed as percent of oxygen in the diffused air actually transferred into the liquid. The value of n_e depends on the diffuser nature and its installation depth and it typically varies between 6 to 15% (Grady et al. 1999).

Air diffusers in activated sludge systems usually provide the turbulence necessary to maintain solids in suspension. This has resulted in constraints on process design and operation. The upper feasible bio-reactor volume (m^3) can be related to the AFR using the following expression:

$$V_{aer} \le \frac{1000\, AFR}{AIR_L} \tag{4-51}$$

where AIR_L is the minimum air input rate that can be achieved by the installed air diffuser. A typical AIR_L value of 20 m^3/ (min.1000 m^3) is usually acceptable. The lower feasible bio-reactor volume can be given by the following expression:

$$V_{aer} \ge \frac{1000\, AFR}{AIR_U} \tag{4-52}$$

where AIR_U is the maximum possible air input rate that can be achieved by the installed air diffuser. A typical AIR_U value of 90 m^3/ (min.1000 m^3) is usually acceptable.

Another criteria imposed on the volume of the aerobic reactor is related to the maximum volumetric oxygen (not air) transfer rate that can be achieved economically on a sustainable basis , which is usually estimated around 0.1 kg O_2 / (m^3.hr) (Grady et al., 1999):

$$V_{aer} \geq \frac{(RO_H + RO_A)}{0.1} \tag{4-53}$$

The above mentioned criteria on oxygen and mixing requirements of the bio-reactor are considered in the optimization problem of this study. The aeration system consumes approximately 50 to 60% of the net power demand for a typical activated sludge wastewater treatment plant (USEPA Report, 1999). Therefore the designer is responsible for having the proper diffuser type and the optimal aerobic reactor volume in order to meet both mixing and oxygen requirements of the process at the lowest possible costs.

4.3 Secondary Sedimentation

The secondary clarifier plays a crucial role in activated sludge wastewater treatment process by receiving the mixed liquor from the aerobic compartment and clarifying it sufficiently to produce an effluent with an acceptable quality. Sludge produced from the secondary clarifier should be thickened in a proper way to maintain the desired solids level in the reactor through the sludge re-circulation stream and to achieve an effective treatment for the wasted sludge. This means that secondary settlers shall perform two functions in parallel: (i) clarification and (ii) thickening. Industry experience has shown that secondary clarifier is often the main bottleneck of the entire activated sludge process.

Several models have been developed for the secondary clarifier including simple empirical models as well as sophisticated computational fluid dynamics models. The reader is referred to Arwani (2003) for a historical review on the models developed for clarification and thickening in the secondary clarifier.

In the optimization problem formulated in this thesis; clarification in the secondary clarifier is modelled using Voutchkov (1992) empirical model:

$$TSS_6 = \frac{6.21 . \ln(MLSS.SVI)}{0.67 . \ln(H) - \ln(SR)} - 26.43 \tag{4-54}$$

where TSS_6 (in mg/l) is the total suspended solids in the plant effluent, MLSS (in g/l) is the mixed liquor suspended solids which is equal to TSS_5, SVI (in ml/g) is the sludge volume index, H (m) is the side water depth in the settling tank and SR (in m/hr) is the overflow rate in the secondary clarifier which is equal to Q6 / A_f. (i.e., A_f is the surface area of the final clarifier).

An SVI value greater than 200 ml/g indicates poor settling (Metcalf & Eddy, 1991). Regarding the side water depth, the current practice favours a minimum side-water depth of 3.5 to 4 meter. For the overflow rate, the typical range is 16-32 m^3/m^2 .d (Metcalf & Eddy, 1991).

The thickening process is modelled according to the solids flux theory as given by Cho et al. (1996):

$$TSS_7 = \left[K_w(n_w - 1)\right]^{1/n_w} \left(\frac{n_w}{n_w - 1}\right)\left(\frac{A_f}{Q_7}\right)^{1/n_w} \tag{4-55}$$

where k_w (m/d) and n_w are constants representing the thickening properties of the waste activated sludge, A_f is the surface area of the final clarifier in m^2 and Q_7 is the clarifier blow down in m^3/hr.

The concentrations of the other particulate compounds (X) in both clarified effluent *(Q_6)* and sludge streams *(Q_r)* are calculated based on the assumption that the portion of each solid component in the suspended solids of any of the above-mentioned streams is the same as the portion of that component in the secondary influent suspended solids. In other words, the solids distribution as a percentage of the suspended solids will remain the same in all three streams: influent, effluent and sludge waste stream:

$$X_{j\_eff} = X_{j\_in} \frac{TSS_{eff}}{TSS_{in}} \tag{4-56}$$

$$X_{j\_sludge} = X_{j\_in} \frac{TSS_{sludge}}{TSS_{in}} \tag{4-57}$$

where j represents the particulate components (i.e. STO, H, A, PAO, etc.). It is assumed that all soluble components are not affected by the secondary sedimentation.

The mass balance relationships (for flow Q and particulate components X), considered around the secondary clarifier, are as follows:

$$Q_5 - Q_{ir} = Q_6 + Q_7 \tag{4-58}$$

$$(Q_5 - Q_{ir})(X_5) = Q_6 X_6 + Q_7 X_7 \tag{4-59}$$

4.4 Cost Estimate

The cost estimate assignment during the conceptual study phase of an engineering project is of crucial importance to developers or government authorities prior to any decision on commencing any project work. This assignment includes the estimate of investment or capital costs; the operation and maintenance costs and performing a life cycle cost analysis that reflects the project economies during its lifetime period.

The term “Capital Costs” as commonly defined in construction projects includes the direct and indirect capital costs. Direct capital costs include the installed process equipment and associated piping and instrumentation; site civil works; buildings; roads and laboratories. Indirect capital costs include interest during construction; insurance contingency; project management and architectural and engineering fees. On the other hand, “Operating Costs” can be split into fixed and variable operating costs. Fixed operating costs consider the costs of regular maintenance and repair works which are usually related to the wastewater treatment plant capacity. Variable operating costs are directly related to the operation mode (i.e., full or partial capacity) of the wastewater treatment plant which include the chemical and power costs.

This subsection will emphasize on the cost estimate components of the A^2O process which is usually considered if wastewater nutrients are to be removed biologically. As stated earlier, phosphorus removal from wastewater can be achieved either by the chemical precipitation through chemical addition or by adopting the EBPR process, which takes advantage of the phosphorus uptake by the PAOs. Both chemical and biological methods can be used in the same plant if a higher level of phosphorus removal is required. Several researchers have shown that the BPR has a lower operating cost when compared with the chemical precipitation methods (Levlin et al., 2003).

Jiang F. et al. (2004 & 2005) studied two approaches for estimating the costs of phosphorus removal in wastewater treatment plants. The first is through having entirely new plants constructed on "Greenfield" sites and the second is through the adaptation of already existing wastewater treatment plants in order to achieve a higher level of phosphorus removal.

4.4.1 Capital Cost Estimate (CAPEX)

Estimation of capital costs of any wastewater treatment plant is usually done through three (3) main steps: (i) identifying the construction costs (i.e., direct capital cost); (ii) estimating the indirect costs as percentages of direct costs; and (iii) considering the inflation, especially when direct cost is estimated based on plants built several years back, in order to have a realistic updated capital cost estimate. The USEPA (1998) has identified standard factors used to estimate the capital costs of any treatment facility. Table 4-5 presents these factors:

Table 4-5 US EPA Standard Capital Cost Estimate Components for Waste Treatment Industry

CAPEX Factor	Component	CAPEX Estimate
Direct	Equipment	Technology Specific Cost
	Installation	25 – 55% of Equipment Cost
	Piping	31 – 66% of Equipment Cost
	Instrumentation & Control	6 – 30% of Equipment Cost
Indirect	Engineering	15% of Direct cost
	Contingency	15% of Direct Cost

Jiang F. et al. (2004) have estimated costs for different phosphorus removal systems and concluded that the total capital cost increase with the target P removal efficiency and the design capacity of the treatment facility. However, when the required removal efficiency exceeds 90%, CAPEX will increase considerably as a consequence of extra unit processes needed to be installed. The figure below illustrates the capital cost estimate in the U.S. for different sizes of A^2O systems as estimated by Jiang F. et al. (2004). The estimate is reported based on costs for 1978. The author has updated the cost to reflect the conditions in year 2006 by using the Engineering News Record (ENR) construction cost index which shows an ENR value of 2776 for year 1978 and ENR value of 7691 for March 2006.

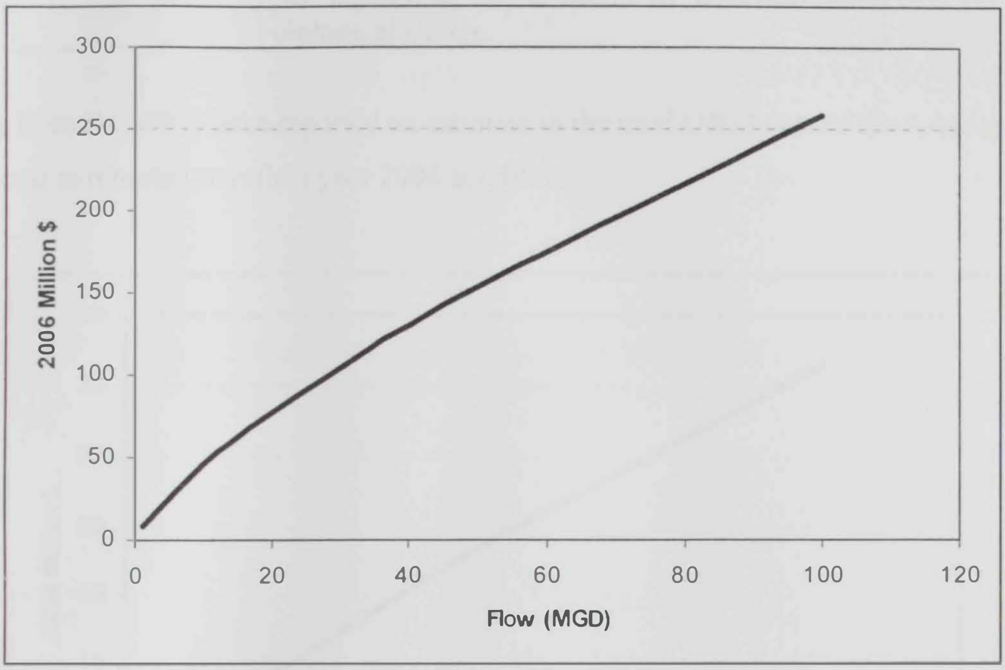


Figure 4-3 Overview on Capital Cost value of the A^2O system

4.4.2 Operation and Maintenance (O&M) Costs

The USEPA (1998) has identified the standard factors used to estimate the operation and maintenance costs of any treatment facility. The table below presents these factors. The prices mentioned in this table are indicative as they are applicable to the U.S. market only.

Table 4-6 US EPA Standard O&M Cost Estimate Components for Waste Treatment Industry

Factor	Estimate
Maintenance	4% of total CAPEX
Taxes & Insurance	2% of total CAPEX
Labour	28.21 \$ (2004) per hour
Electricity	0.0499 \$ (2004) per kWh
Chemicals	Not Required for the A^2O system
Wastes Disposal	Disposal costs are 0.27 \$ (2004) per Kg of solids for biological wastes and 1.24 \$ (2004) per Kg solids for a blend of chemical and biological sludge.

Jiang F. et al. (2004) have reported an estimate to the total O&M cost of the AAO system. The cost is reported to reflect year 2004 conditions.

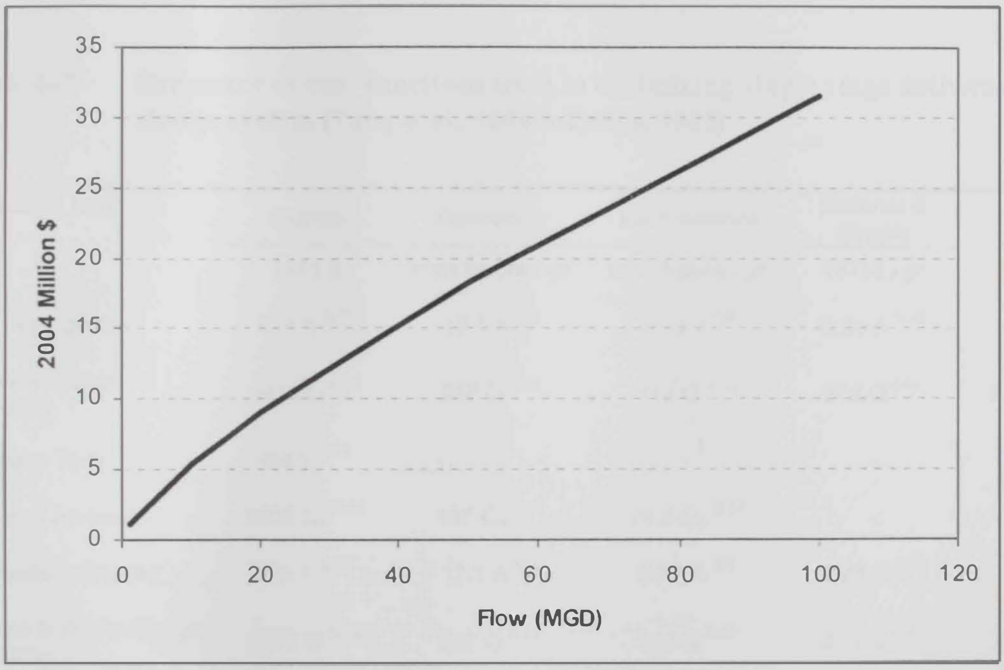


Figure 4-4 Overview on O&M cost value of the A^2O system

4.4.3 Cost Functions

Cost functions are those that describe the cost of a process unit as a function of design or operation parameters. Cost functions are considered important for any optimization problem in order to account for the capital and operational costs that usually play a significant role in defining the optimum design for any wastewater treatment facility.

Several studies were published on the development of cost estimate functions for different wastewater treatment processes. Tang et al. (1984) have conducted an early effort in this regard by developing cost functions that describe the most common unit processes considered in any wastewater treatment plant. Tyteca (1985) used the cost information provided by researchers previously to develop new cost functions classifieds in three categories: (i) investment cost, (ii) fixed operating cost and (iii) variable operating costs. Arwani (2003) has conducted a literature review on the history of cost functions development and came up with a summary of cost functions used in optimizing a single stage activated sludge process (i.e., aerobic only). Table 4-7 presents these functions:

Table 4-7 Summary of cost functions used in optimizing single stage activated sludge system (Tang et al., 1984 & Tyteca, 1985)

Process Unit	Capital	Operation	Maintenance	Material & Supply	Power
	1971 $	man hours / yr	man hours / yr	**1971$ / yr**	**kW hr / yr**
Primary Clarifier	$824\ A^{0.77}$	$17.1\ A^{0.6}$	$9.23\ A^{0.6}$	$8.26\ A^{0.76}$	-
Primary Sludge Pumping	$9870\ Q^{0.53}$	$257\ Q^{0.41}$	$112\ Q^{0.43}$	$214\ Q^{0.64}$	$23.85\ QH/\varepsilon_p$
Aeration Tank	$461\ V^{0.71}$	-	-	-	-
Diffused Aeration	$8533\ Q_a^{0.66}$	$187\ Q_a^{0.48}$	$74.4\ Q_a^{0.55}$	-	-
Secondary Clarifier	$824\ A^{0.77}$	$17.1\ A^{0.6}$	$9.23\ A^{0.6}$	$8.26\ A^{0.76}$	-
Return & Waste Sludge Pumping	$9870\ Q^{0.53}$	$257\ Q^{0.41}$	$112\ Q^{0.43}$	$214\ Q^{0.46}$	$23.85\ QH/\varepsilon_p$

A: Surface Area (m^2); Q: Flow (m^3/hr); V: Volume (m^3); Qa: Air Flow Rate (m^3 / min); H: Pumping Head (m); ε_p Pumping Efficiency.

As discussed earlier, the optimization problem of this thesis considers A^2O in its formulation. The main additional costing components of the A^2O system when compared with the single aerobic stage activated sludge system are as follows:

1. Capital cost of the anaerobic compartment.
2. Capital cost of the anoxic compartment.
3. Capital and operation cost of the internal recirculation flow.
4. Mixing energy cost for anaerobic and anoxic compartments.

In the optimization model formulation, the same cost function that estimates the capital cost of the aerobic compartment (refer to Table 4-7) is utilized in estimating the capital costs for both anaerobic and anoxic compartments. Moreover, the same cost functions that estimate the capital and operation cost for the return and waste sludge pumping (refer to Table 4-7) are utilized in estimating the capital and operation cost of the internal recirculation flow. Jiang F. et al. (2005) has presented the following cost function which estimates the mixing energy requirements for the anaerobic and anoxic compartments in order to keep the solids in suspension:

$$ME = UE * (V_{anaer} + V_{anox}) \tag{4-60}$$

where ME is the mixing energy in kW, UE is the unit energy consumption of mixing which is 0.014 kW/m^3 and V_{anaer} and V_{anox} are the volumes of the anaerobic and anoxic compartments. The cost of waste disposal is considered in the optimization model of this thesis by estimating the amount of the sludge generated form both primary and final settlers using the following equation:

$$M_{sludge} = X_u * Q_w \tag{4-61}$$

where X_u is the sludge concentration in the underflow stream and Q_w is flow of the waste stream. Sludge disposal can typically be responsible for 25 to 40% of the operating costs of an aerobic biological treatment system (Robin, 2005).

4.5 Optimization Problem

An optimization problem consists of an objective function, constraints, and bound on variables. Based on the mathematical models presented in the previous sections, the formulated optimization problem is explained as follows:

Objective Function

Minimize *Total Annual Cost* **(4-62)**

Constraints

Primary Clarifier

$$q\,A_p - 24Q_2 = 0$$

$$TSS_2 - \left[1-\left(a\exp^{\frac{-b}{TSS1}-cq}\right)\right]\times TSS_1 = 0$$

$$TSS_8 - \left[K\,(n-1)\right]^{\frac{1}{n}} \times \frac{n}{n-1}\times 1000\times\left[\frac{A_p}{24\,Q_8}\right]^{1/n} = 0$$

$$Q_2 + Q_8 - Q_1 = 0$$

$$Q_2TSS_2 + Q_8TSS_8 - Q_1TSS_1 = 0$$

Activated Sludge

Anaerobic (Equations from 4-11 to 4-19)

$$Q_2X_{i2} + Q_rX_{ir} - Q_3X_{i3} + V_{anaer}\,r_j = 0$$

Anoxic (Equations from 4-20 to 4-32)

$$Q_3X_{i3} + Q_{ir}X_{i\_ir} - Q_4X_{i4} + V_{anox}\,r_j = 0$$

Aerobic (Equations from 4-33 to 4-45)

$$Q_4X_{i4} - Q_5X_{i5} + V_{aer}\,r_j = 0$$

Where X_i represents applicable model state variables shown in Table 4-1 and r_j represents applicable model processes shown in Table 4-2

Design Constraints on V_{aer}

$$V_{aer} \le \frac{1000\,AFR}{AIR_L}$$

$$V_{aer} \geq \frac{1000\,AFR}{AIR_U}$$

$$V_{aer} \geq \frac{(RO_H + RO_A)}{0.1}$$

Secondary Clarifier

$$TSS_7 - \left[Kw\,(nw-1)\right]^{\frac{1}{nw}} \times \frac{nw}{nw-1} \times 1000 \times \left[\frac{A_p}{24\,(Q_9 + Qr)}\right]^{1/nw} = 0$$

$$X_{TSS6} - \frac{6.21 \times \ln(\frac{X_{TSS5}}{1000} \times SVI)}{0.67 \times \ln(H) - \ln(\frac{q_f}{24})} + 26.43 = 0$$

$$q_f - \frac{Q_6 \times 24}{A_f} = 0$$

$$Q_2 - Q_6 - Q_9 = 0$$

$$(Q_2 + Q_r)X_{TSS5} - Q_6 X_{TSS6} - (Q_9 + Q_r)X_{TSS7} = 0$$

Bounds

$$X_{lo} \leq X_i \leq X_{up}$$

where X_{lo} and X_{up} are the lower and upper bounds of the variables respectively. All effluent quality constraints (i.e. TSS, Soluble organics, phosphorus and nitrogen, etc.) were introduced to the model through the system bounds.

4.6 Optimization Using GAMS

The system of equations developed earlier can be described as highly non-linear since most of the constraints are functions of more than one variable. In addition to the ASM3/EAWAG Bio-P model state variables listed in Table 4-1, the table below lists the A^2O decision system variables of the optimization problem in this study.

Table 4-8 A^2O system variables in the optimization model

Symbol	Description	Units
A_p	Surface area of primary clarifier	m^2
q_P	Over flow rate of primary clarifier	m/d
A_F	Surface area of final clarifier	m^2
q_F	Over flow rate of final clarifier	m/d
V_{anaer}	Volume of anaerobic compartment	m^3
V_{anox}	Volume of anoxic compartment	m^3
V_{aer}	Volume of aerobic compartment	m^3
Q_r	Sludge re-circulation flow rate	m^3/hr
Q_{ir}	Internal Re-circulation flow rate	m^3/hr
Q_i	Process stream (i = 1 to 9)	m^3/hr
RO_H	Oxygen Requirement for removal of organic matter	kg/d
RO_A	Oxygen Requirement associated with nitrification	kg/d
AFR	Air flow rate	m^3/min

The developed mathematical model contains 49 variables (13 out of 49 are decision variables), 43 equality constraints (7 degrees of freedom) and 6 inequality constraints. This excludes other model variables, such as cost parameters, that are not part of the main A^2O system mathematical model and their values can only be calculated after solving the main system of equations.

The General Algebraic Modeling System (GAMS) is specifically designed for modeling linear, nonlinear and mixed integer optimization problems. The system is especially useful with large, complex problems. "GAMS" allows the user to concentrate on the modeling problem by making the setup simple. The system takes care of the time-consuming details of the specific machine and system software implementation. "GAMS" lets the user to concentrate on modeling by eliminating the need to think about purely technical machine-specific problems, such as address calculations, storage assignments, subroutine linkage, and input-output and flow control. "GAMS" increases the time available for conceptualizing and running the model, and analyzing the results. The

GAMS language is formally similar to commonly used programming languages. It is therefore familiar to anyone with programming experience. In GAMS, there is more than one solver available for different types of problems (i.e. linear, non-linear, etc.). For non-linear models, there are three standard algorithms available named as CONOPT, MINOS and SNOPT.

CONOPT algorithm is selected to solve the non-linear optimization problem of this study. CONOPT solver is usually used for large-scale nonlinear optimization problems (NLP). It is a feasible path solver based on the old proven GRG method. Three versions of the CONOPT solver have been issued till now. These are CONOPT, CONOPT2 and CONOPT3.

All components of CONOPT have been designed for large and sparse models. Models with over 10,000 constraints are routinely being solved. Specialized models with up to 1 million constraints have also been solved with CONOPT (Ref: www.gams.com).

The results of solving any optimization problem are usually affected by several factors such as the initial values, system bounds and scaling of variables. Having good initial values for the system variables, which satisfy or closely satisfy the constraints, reduces the work involved in finding the first feasible solution and therefore the computational effort in finding the final optimal solution. In the optimization problem of this study, EXCEL Solver is used in finding a "close to feasible" solutions for all system variables, which are then fed as initial values to the GAMS model.

System bounds usually fall into two categories: (i) Model bounds and (ii) Algorithm bounds. Model bounds represent reality constraints (i.e., some variables should always be positive) while algorithm bounds help the model algorithm by preventing it from moving away from the optimal solution.

In Non linear as well as linear programming algorithms, Search directions are determined by calculating the derivatives of the system constraints and objective function. Moreover, the function values are used to determine if the constraints are satisfied or not. The scaling of the variables and constraints (i.e., measurement units) determine the relative size of the derivatives and function values and therefore the search direction. In case system variables are not properly scaled, the algorithm might ignore smaller values by considering them zero, which will result in an inaccurate search direction.

4.7 Parameters Calibration

The parameters of the ASM3/EAWAG Bio-P model or any other models are not universal in the sense that every system could be modeled using same parameter values. These parameters have specific values, for the wastewater under consideration that can be found through standard methods given in the literature. The adjustment of the model parameters to reflect the actual system performance is generally referred to as model calibration.

Weijers et al. (1996) presented a literature review on calibration strategies and methods for assessing parameter identifiability of the ASM1 model. One approach is the steady state calibration where data obtained from the plant are averaged assuming that this average represent a steady state condition. However, the enhanced nutrients removal plants are more sensitive to disturbances caused by varying load and temperature than conventional plants because of the interaction between the process stages. Fitting the steady state of the model to an unsteady plant might result in having biased parameter estimates. Another disadvantage of steady state calibration is that the number of parameters that can be estimated is equal to or smaller than the number of outputs.

A better calibration approach is by fitting the historical dynamic data of the process with the dynamic model results. In this approach the number of parameters that can be determined is larger than the number of outputs. However, the low sampling frequency, which is usually once per week, might result in limited accuracy and therefore unsatisfactory calibration results. To have more accurate modeling, experiment duration and sampling frequency have to be chosen in relation to the time constants of the process and the spectrum of the influent variations. Hydraulic residence time (HRT) is one of the important time constants of the treatment process which has to be considered in determining the appropriate sampling frequency.

Gurkan et al. (2005) used SWOT analysis (Strength, Weakness, Opportunities and Threats) in studying four different systematic calibration protocols for full scale wastewater treatment systems (BIOMATH, HSG, STOWA and WERF). The systematic calibration protocols were proposed by different researchers in order to create a standard approach in performing the calibration study which makes the comparison between different calibrations of the ASMs possible. The need for these protocols came from the fact that the calibration studies performed in the past were based on different influent wastewater characterization methods, different kinetic parameter estimation methods, different selection of parameters to be calibrated and different priorities within the calibration steps.

Regarding the mathematical model of this study, several trials have been made by the author to find a wastewater treatment plant with similar scheme (Anaerobic-Anoxic-Aerobic) by contacting several government authorities and private consultants and contractors. Unfortunately, and within the limited search time available, no similar plant was found knowing that all major domestic wastewater treatment plants operating in UAE (such as AL Mafraq WWTP) are limited to anoxic and aerobic treatments only. Therefore, the model performance is assessed only against standard design parameters published in the literature such as Metcalf & Eddy (1991).

CHAPTER V

APPLICATION PROBLEM

In this section, the optimal design of a typical BNR system is introduced in order to examine the developed model results. As in any treatment plant design problem, input data available prior to the design commencement assignment should include the following:

1. Influent wastewater characteristics.
2. Effluent discharge (i.e., into the sea) criteria and/or irrigation water quality standards.
3. Constraints on space availability (if any).
4. Constraints on the financial investment (if any).

In case of using the ASM platform models as a design assisting tool, a comprehensive lab work has to be carried out to estimate the stoichiometric and kinetic parameters of these models.

5.1 Influent Characteristics

Influent to any WWTP should usually be characterized in terms of both quantity and quality. Determining the wastewater flow rates is considered a fundamental step in the design of any wastewater treatment facility. Metcalf & Eddy 1991 state that the average flow rate occurring over a 24-hr period based on total annual flow rate is used in evaluating the wastewater treatment plant capacity. As a daily average flow rate, the flow rate quantity considered in this illustrative problem is 36,000 m^3 /d (1,500 m^3/hr).

For the purpose of this illustrative problem, influent wastewater quality is assumed to have the medium strength wastewater characteristics as given by Metcalf & Eddy (1991) and shown in Table 5-1. For an actual design case, wastewater quality has to be characterized through standard test methods.

Table 5-1 **Medium Strength Untreated Influent Characteristics (Metcalf & Eddy, 1991)**

Contaminants	Concentration (mg/L)
Solids, Total (TS)	720
Dissolved, Total (TDS)	500
Fixed	300
Volatile	200
Suspended Solids (TSS)	230
Fixed	65
Volatile (VSS)	165
BOD, 5 day, 20 °C (BOD_5)	220
Total Organic Carbon (TOC)	160
Chemical Oxygen Demand (COD)	500
Nitrogen (total as N)	40
Organic	15
Free ammonia	25
Nitrites	0
Nitrates	0
Phosphorus (Total as P)	8
Organic	3
Inorganic	5

5.1.1 Translation of influent Composition into ASM components

The standard water composition shown in Table 5-1 cannot be used directly as input to the ASM model, since the influent composition should be first translated to the components considered in the ASM/EAWAG Bio-P model that are listed in Table 4-1. Grady et al. (1999) proposed a procedure to translate the influent composition into the ASM model components shown in Table 4-1 by using some simplifying assumptions discussed hereafter.

Grady et al. (1999) has divided the total influent COD into four components: (i) slowly biodegradable substrate (X_s), (ii) readily biodegradable substrate (S_S), (iii) inert particulate COD (X_I) and (iv) inert soluble COD (S_I). However, in the ASM3 model, the inert soluble COD (S_I) is considered negligible. It is a common practice in activated sludge modeling assignments to assume a negligible concentration (i.e., zero) for the biomass components (X_H, X_A and X_{PAO}) in the influent when compared with amount of biomass formed later within the activated sludge process. Henze et al. (2000) stated that more research would be required to study the impact of the already existing influent biomass on the activated sludge process. In this illustrative problem, all influent biomass components are assumed to equal zero.

Metcalf & Eddy (1991) estimate the total COD of a domestic wastewater to be approximately equal to 2.1 times the BOD_5 value.

$$COD_{total} \approx (2.27)\ (BOD_5) \tag{5-1}$$

Grady et al. (1999) proposed to estimate the biodegradable COD from the following expression:

$$COD_{biodeg} \approx (1.71)\ (BOD_5) \tag{5-2}$$

Inert COD is the difference between the total COD and biodegradable COD:

$$COD_{inert} = COD_{Total} - COD_{Biodeg} \tag{5-3}$$

Henze et al. (2000) suggest that 35 to 40 percent of the particulate organic matter in domestic wastewater is non-biodegradable. Volatile suspended solids (VSS) are considered representative of the particulate organic matter. Assuming that the composition of the inert particulate organic matter is like that of protein, which has a COD equivalent of 1.5 g COD / g protein, and that protein is totally volatile in a VSS test, then:

$$Inert\ Particulate\ (X_I) = 37.5\% * 1.5 * VSS = 0.56\ VSS \tag{5-4}$$

Regarding the partitioning of the biodegradable COD into slowly (X_s) and readily biodegradable (S_s) substrate, Grady et al. (1999) suggest that 43% of the biodegradable COD is readily biodegradable.

$$S_s = (0.43)\ (COD_{biodeg}) \tag{5-5}$$

$$X_s = COD_{biodeg} - S_s \qquad (5\text{-}6)$$

Regarding the nitrogen components, the ASM3 model divides nitrogen components into three types: (i) ammonium plus ammonia nitrogen (S_{NH4}), nitrate plus nitrite nitrogen (S_{NOX}) and denitrified nitrogen (S_{N2}). According to Henze et al. (2000), the S_{N2} concentration in the influent can be neglected. Moreover, most of the domestic wastewater contains no nitrate nitrogen (S_{NOX}) in the influent (Grady et al.,1999). Regarding the phosphorus content of the influent, in-organic soluble phosphorus (S_{PO4}) is assumed equal to the inorganic phosphorus value reported in Table 5-1. Particulate phosphorus is either hydrolyzed and released as soluble phosphorus or entrapped with the MLSS and removed with the waste solids. The poly-phosphate (X_{PP}) concentration in raw municipal wastewater is normally zero (Henze et al., 2000). It is reasonable to assume that all cell storage products concentrations in the influent equal to zero since they are mainly formed within the activated sludge process itself.

It is worth mentioning that the procedures mentioned above involve some degree of uncertainty. In a real design case, the author recommends to carry out the experimental lab test according to the procedures presented in Henze et al. (2000). Table 5-2 shows the composition of the medium strength wastewater (given in Table 5-1) after translation into ASM3 components.

Table 5-2 ASM3 Translated composition of a medium strength wastewater (Grady et al., 1999)

State Variable	Description	Concentration	Unit
TSS	Total Suspended Solids	230	g TSS m^{-3}
XI	Inert Particulate	92	g COD m^{-3}
XS	Slowly Biodegradable Substrate	214	g COD m^{-3}
XH	Heterotrophic Organisms	0	g COD m^{-3}
XSTO	Cell Storage Product of heterotrophic Organisms	0	g COD m^{-3}
XPAO	Phosphorus Accumulating Organisms	0	g COD m^{-3}
XPP	Poly-Phosphate	0	g P m^{-3}
XPHA	Cell Storage Product of PAO	0	g COD m^{-3}
XA	Autotrophic / Nitrifying Organisms	0	g COD m^{-3}
S_S	Soluble Substrate	162	g COD m^{-3}
SNOX	Nitrate plus Nitrite Nitrogen	0	g N m^{-3}
SNH_4	Ammonium plus Ammonia Nitrogen	25	g N m^{-3}
S_I	Inert Soluble (Not considered in the ASM3 model)	0	g COD m^{-3}
SPO_4	Inorganic Soluble Phosphorus	5	g P m^{-3}

5.2 Effluent Characteristics

The WWTP effluent is most commonly used for non-potable purposes (i.e. not for drinking) such as agriculture, landscape and public parks irrigation. Other non-potable applications include cooling water for power plants and oil refineries, industrial process water for facilities such as paper mills and carpet dyers, toilet flushing, dust control, construction activities and concrete mixing. Alternatively, WWTPs effluent might be discharged directly into the open sea, and in this case, attention has to be given to the nutrients removal (phosphorus and nitrogen) in order to prevent the eutrophication of the water body to avoid high concentrations of aquatic weeds and algae.

It is important to emphasize that the wastewater treatment plant designer should know what the plant effluent is intended for, as this is going to reflect directly on the effluent quality guidelines have to be followed and therefore on the level of treatment steps to be considered in the plant.

Thomas et al. (1994) stated that the seawater quality standards need to be set at or below the levels at which they are shown to damage coral reefs and in particular the nutrients which they need to be below the level at which they stimulate massive growth of weedy algae which overgrow and kill corals. The levels of nutrients that damage reefs are around hundred times lower than those that harm human beings, so use of human health water quality standards are actually deadly to coral reefs. Researchers have established critical levels of nitrogen and phosphorus which must not be exceeded if reefs are to remain healthy without being overgrown by weedy algae. These concentrations are 0.014 mg/l as N for nitrogen (0.040 mg/l as NO_3) and 0.003 mg/l as P for phosphorus (0.007 mg/l as PO_4).

It is usual to see different treated effluent quality guidelines from one country to another depending on their local requirements. Moreover, it is worth mentioning that not all countries can afford having very stringent treated effluent guidelines as this would require higher investments in the treatment facilities.

Many countries set a limit between 1 to 2 mg/l as the limit for the total phosphorus concentrations in discharges of wastewater treatment plants. In A^2O processes, effluent phosphorus concentration of less than 2 mg/l can be expected without effluent filtration (Metcalf & Eddy, 1991).

The American Water Works Association (AWWA) guideline for irrigation water requires a maximum phosphate limit of 2 mg/l. According to the Australian Guidelines for effluent quality issued in January 2004, with advanced treatment processes (i.e., BNR) the aim should be to reduce the total nitrogen to less than 10 mg/l and the total phosphorus to less than 5 mg/l. The polish legislation concerning treated wastewater quality standard requires total nitrogen of 15 mg/l for medium WWTPs and 10 mg/l for large WWTPs (Malgorzata et al., 2006).

The treated effluent, discharged into the sea, from any Wastewater Treatment Plant operating in Abu Dhabi Emirate (U.A.E.) shall meet the regulations specified by Abu Dhabi Environmental Agency. The limits suggested by Abu Dhabi Environmental Agency shows that they are sort of relaxed when compared with other more strict regulations. Table 5-3 summarizes the main effluent characteristics specified in this regulation.

Table 5-3 **Characteristics of treated wastewater at point of discharge into the sea as required by Abu Dhabi Environmental Agency**

Parameter	Symbol	Unit	Suggested Limit
Physical Properties			
Total Suspended Solids	TSS	mg/l	50
Total Dissolved Solids	TDS	mg/l	1500
pH		pH units	6 - 9
Floating Particles		mg/m^2	None
Temperature (higher than Background)	T	°C	5
Turbidity		NTU	75
Inorganic Chemical Properties			
Total Ammonia (as N)	NH_4^+	mg/l	2
Nitrate	NO_3-N	mg/l	40
Chlorine Residual	Cl^-	mg/l	1
Dissolved Oxygen	DO	mg/l	>3
Biochemical Oxygen Demand (BOD)	BOD_{5-20}	mg/l	50
Total Kieldahl Nitrogen as N	TKN	mg/l	10
Total Phosphorus (as P)	$PO4^{-3}$	mg/l	2
Chemical Oxygen Demand (COD)	COD	mg/l	100

Effluent characteristics for Al Mafraq Wastewater Treatment Plant, a major wastewater treatment plant operating in Abu Dhabi Emirate are summarized in Table 5-4. Phase 1 of Al Mafraq Wastewater treatment plant was commissioned in 1982 with average treatment capacity of 23 MIGD. Phase 2 was commissioned in 1997 adding an additional average treatment capacity of 34.5 MIGD. Phase 1 reactors are aerobic only while phase 2 reactors included anoxic channels with mixers to achieve nitrogen removal. All treated effluent from Al Mafraq plant is reused for irrigation purposes. The effluent concentration of nitrate (29.2 mg/l as NO_3-N) indicates poor denitrification which is only carried out for 60% of the influent stream.

Table 5-4 Average Effluent Analysis of AL Mafraq WWTP (April 1999)

Parameter	Units	Influent	After Primary	After Secondary	After Tertiary
Electrical Conductivity	μS / cm	2,900	3,300	3,100	3,000
pH	units	7	7.1	7.1	6.9
Biochemical Oxygen Demand (BOD)	mg/l	228	169	2.8	0.9
Chemical Oxygen Demand	mg/l	515	257	42	17
Total Alkalinity as $CaCO_3$	mg/l	223	222	56	37
Total Sulphides as S	mg/l	33	28.2	0.5	Nil
Suspended Solids	mg/l	179	169	7.2	2.4
Ammoniacal Nitrogen as N	mg/l	30	29	0.6	0.5
Nitrate Nitrogen as N	mg/l	x	x	6.6	6.6

You et al. (2002) studied the nitrification/denitrification performance of the A^2O system using pilot plant and batch experiments and reported total nitrogen removal efficiency from 48.4 to 78%. Yong et al. (2006) experimentally studied the performance of the A^2O BNR system and reported removal efficiencies of 92.3% for COD, 95.5% for phosphorus, 96% for ammonia and 79.5% for total nitrogen. They found that nitrate is the major constituent of the effluent total nitrogen (TN) concentration, indicating good nitrification for ammonium removal in the A^2O system.

Metcalf & Eddy (1991) state that in a well operating activated sludge plant treating domestic wastewater, effluent BOD_5 should usually vary between 2 to 10 mg/L suspended organics between 5 to 15 mg/L, and non-biodegradable organics between 2 to 5 mg/L. According to the same reference, the activated sludge process can achieve as low as 10 mg/l of TSS in the effluent.

The author would like to stress that the economic feasibility of the BNR level, that can be achieved using a BNR system, differs from one place to another based on the local market situation. For example, at certain situations, it would be more economical to consider chemical treatment methods (i.e., ferric chloride addition) to achieve higher levels of nutrients removal.

Currently in UAE, almost all treated sewage effluent is reused for irrigation purposes and this could be the reason why there is no clear attention to the nutrients issue. However, the rapid developments expected in both Abu Dhabi and Dubai emirates and specifically in the new artificial islands expected to be developed with in the next 10 years, would require the environmental agency to revise its discharge regulations. Such regulations should target more stringent limits especially those associated with nutrients. This is mainly because the majority of the wastewater effluent generated on these islands is discharged into the sea. Even if the generated effluent is re-used for irrigation purposes, it can easily infiltrate into the groundwater because of its shallow depth. Recent reports (by residents and eye witnesses) from the artificial palm island developed by Dubai government state that turbid water and algal blooms could clearly be noticed in the water surrounding the island. This is of course not a desirable situation for such islands developed to be places for leisure and tourism. Notification of this eutrophication phenomenon is very recent (to the date of writing this report) therefore; no independent technical report has addressed this issue yet and the problem highlight above is based on author's analysis only. Relatively stringent effluent characteristics are considered in this illustrative problem. Table 5-5 lists the bounds imposed on the treated effluent quality in the GAMS model.

Table 5-5 Constraints Imposed on the Effluent Quality Parameters in GAMS model (All with lower limit of 1E-6)

Quality Parameter	**Upper Limit (mg/l)**
Total Suspended Solids (TSS)	15
Soluble Substrate (S_s)	0.5
Ammonium plus Ammonia Nitrogen (S_{NH4})	1
Nitrate plus Nitrite Nitrogen (S_{NOX})	7
Inorganic Soluble Phosphorus (S_{PO4})	1

For the GAMS model developed in this thesis, constraints are imposed on the upper limit of the quality parameters. These constraints imposed on the upper limit were selected after reviewing several design data of A^2O systems. Other effluent quality parameters are left unbounded (i.e. bounded between 1E-6 and 1E6). It is important to realize that over-specified effluent constraints might result in having un-economic design.

5.3 Objective Function

The objective function of the optimization model formulated in this study is to achieve the minimum total annual cost of the A^2O system. As mentioned previously in section 4, the cost functions used in this study are derived from functions developed by Tang et al. (1984), Tyteca (1985) and Jiang et al. (2005). Both CAPEX and OPEX are considered in these cost functions. The total plant cost calculated from the optimization model is presented in 2006 US Dollars per year. Therefore, the capital cost is amortized annually based on a certain design life and a discount rate. The ENR construction cost index is used to update the capital and material and supply cost functions from their base year (1971), in which they have been developed, to year 2006. Table 5-6 presents the cost functions' parameters considered in the optimization problem.

Table 5-6 Cost Functions' Parameters Considered in the Optimization Problem

Parameter	Unit	Value
1971 Cost Index (BCI)	-	1581
2006 Cost Index (CI)	-	7689
Plant Design life	Years	30
Interest Rate	%	8
Amortization Factor (AF)		0.0888
Operating & Maintenance Wages (OMW)	\$ (2006) per man-hr	8
Power Cost (PC)	\$ (2006) per kWh	0.05
Pumping Head of returned sludge	meter	10
Pumping Head for Internal re-circulation	meter	5
Pumping Efficiency	%	80
Unit Energy Consumption of mixing (ME)	kW / m^3	0.014
Disposal cost per kg of Biological Solids (DC)	\$ (2006)	0.3

Considering the cost parameters in Table 5-6 and the cost functions stated in section 4, the total annual system cost can be calculated from the following expression:

Total Annual cost (2006$/yr) = Annual Capital Cost + O&M cost + Material for maintenance cost + Power cost for pumps + Power cost for mixing + Disposal cost.

$$= [(CI/BCI)*AF*CAPEX]+[OMW*O\&M]+[(CI/BCI)*MC]+[PC*Pconsum]+[ME*(V_{anaer}+V_{anoxic})*PC*24*365]+[DC*M_{Sludge}]$$

where:

CAPEX: Capital investment (1971$)

OMW: Operating and Maintenance Wages (2006$/man-hr)

O&M: Operation and Maintenance (man-hr/yr)

MC: material cost (1971$/yr)

PC: Power Cost (2006$/kWh)

Pconsum: Power consumption (KWh/yr)

ME: Mixing Energy (kW/m^3)

DC: Disposal Cost (2006$/kg of solids)

M_{Sludge}: Kilograms of sludge per year

5.4 Bounds on System Variables

As stated earlier, having reasonable bounds on the system variables that reflect the practical design requirements and the treatment process economies is very necessary to end with a practical feasible solution and avoid oversized design.

Metcalf & Eddy (1991) recommend setting the overflow rate of the primary clarifier low enough to ensure satisfactory performance at peak rates of flow. Typical design values of the primary clarifiers show that the overflow rate could range from 30 to 120 m^3/m^2.day and tanks diameters from 12 to 46 meter.

Regarding the A^{2}O BNR System, the following typical design information, stated in Metcalf & Eddy (1991), are considered in the optimization problem: (i) solids retention time (SRT) from 4 to 27 days, (ii) mixed liquor suspended solids from 3,000 to 5000 mg/l, (iii) return activated sludge (Q_r) from 20 to 50% of the influent and (iv) internal recirculation rate (Q_{ir}) from 100 to 300% of the influent.

On the secondary clarifier, typical design information given by Metcalf & Eddy (1991) suggests an overflow rate between 16-32 m^3/m^2.d. Table 5-7 presents a summary of bounds applied in the GAMS model. Other system variables are bounded between 1E-6 and 1E6.

Table 5-7 Bounds Imposed on the GAMS model variables

Parameter	**Unit**	**Lower Bound**	**Upper Bound**
Over flow rate of primary clarifier (q_p)	m/d	30	120
Over flow rate of secondary clarifier	m/d	16	32
Solids Retention Time (SRT)	d	4	27
Sludge recycle ratio (r)	% of influent	20	50
Internal recirculation ratio (ir)	% of influent	100	300
Mixed Liquor Suspended Solids (MLSS)	mg/l	3000	5000

The reader is referred to Appendix A for a copy of the GAMS input file.

5.5 Model Initial Point

The high nonlinearity of the mathematical model developed in this study requires a proper initial point (feasible or close to feasible) that can direct its convergence process into the right direction. The feasible initial point refers to specified values of all model variables that validate all listed constraints. For that reason, another mathematical tool is required. In this illustrative problem, Microsoft EXCEL Solver is used to get the required initial point for the developed GAMS model. In order to simplify the iteration process for EXCEL solver, the mathematical model is broken down into three parts solved in sequence. The solution found in every step is considered in the subsequent step. Following is a description of each part:

1) Primary Clarifier: The mathematical model of the primary clarifier consists of four equations and four variables. TSS2 is directly related to the pre-defined TSS1 and other pre-defined parameters; therefore, there is no need to include its model in the iteration. In order to facilitate the convergence process, q_p value of 120 m/day is assumed

2) Secondary Clarifier: The mathematical model of the secondary clarifier consists of five equations and seven variables. Effluent TSS (TSS_6) is assumed equal to 10 mg/l. The

value of Q_2, which is required for the flow balance equation across the tank, is already calculated from the primary clarifier set of equations.

3) A^2O System: The mathematical model of the A^2O system consists of 34 equations and 38 variables. Values of variables derived in the first two systems of equations are considered in this mathematical model.

Following the above approach, the initial point needed for the GAMS model is prescribed in Table 5-8. Definition of the variables in the table can be found in Table 4-1 and Table 4-8. All concentrations are expressed in mg/l.

Table 5-8 Initial Values for the system variables as derived using EXCEL Solver

Variable	Value	Variable	Value
Ap	299.80	S_{NH4}	9.64
q_p	120.00	S_{NO4}	0.03
Af	1925.06	X_{STO4}	910.14
qf	18.50	X_{A4}	57.52
Q2	1498.99	S_{PO4}	17.76
Q6	1483.66	X_{PHA4}	660.62
Q8	1.01	X_{PAO4}	1345.45
Q9	15.33	X_{PP4}	133.24
Qr	715.88	X_{I4}	2236.91
Qir	2,171	T_{SS4}	5208.38
V_{anaer}	1011.85	X_{S5}	378.91
V_{anox}	2999.68	X_{STO5}	917.87
V_{aer}	1911.03	X_{H5}	1342.81
TSS2	176.07	X_{A5}	58.25
S_{S3}	30.57	X_{PHA5}	622.02
X_{S3}	462.08	X_{PAO5}	1359.83
X_{H3}	1312.18	X_{PP5}	149.71
X_{PP3}	113.34	X_{I5}	2238.58
X_{PAO3}	2302.17	S_{NH5}	3.61
S_{NH3}	18.12	S_{NO5}	2.48
X_{PHA3}	706.19	S_{S5}	1.40
S_{PO3}	37.60	S_{PO5}	1.00
TSS3	5189.55	TSS5	5256.91
S_{S4}	35.80	TSS7	15903.11
X_{S4}	394.94	TSS8	79949.14
X_{H4}	1328.05		

5.6 Application Problem Results

An initial run for the GAMS model is carried out considering all above-mentioned issues related to the system constraints and initial point. The value of the objective function, representing the total system annual cost, is US$ 2,344,100 (2006) per year. Capital and the sludge disposal costs are the main contributors to the total system cost and this highlights the importance of selecting the most economically feasible sludge treatment and disposal method. Figure 5-1 illustrates the contribution percentage of every cost component considered in this study.

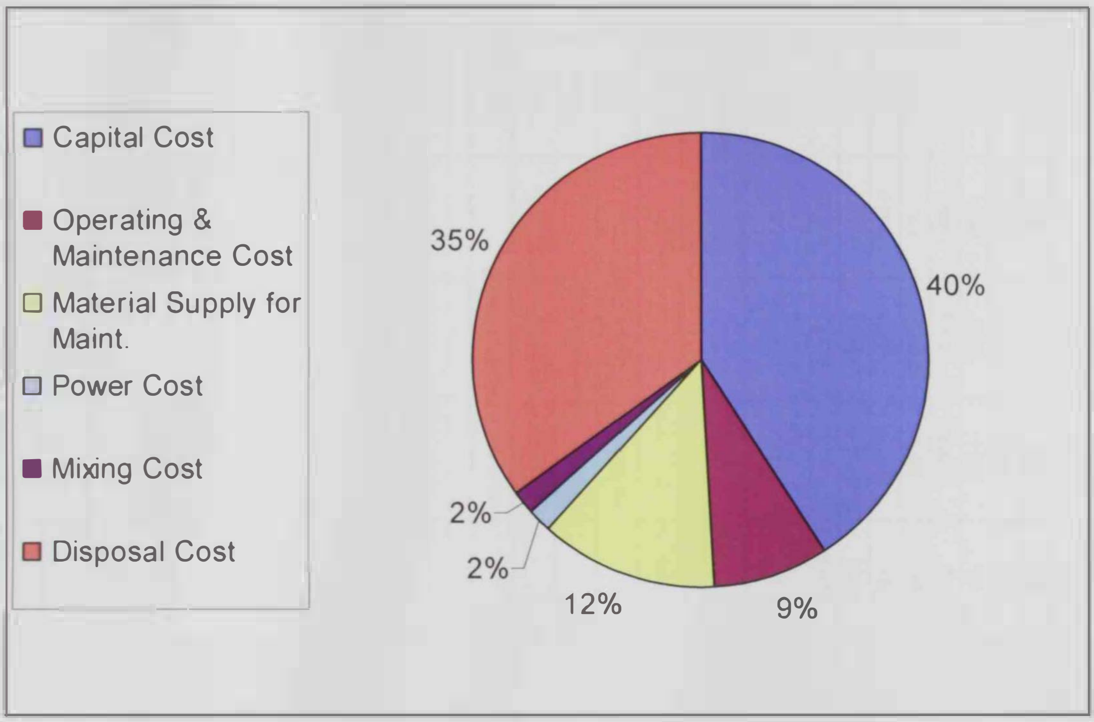
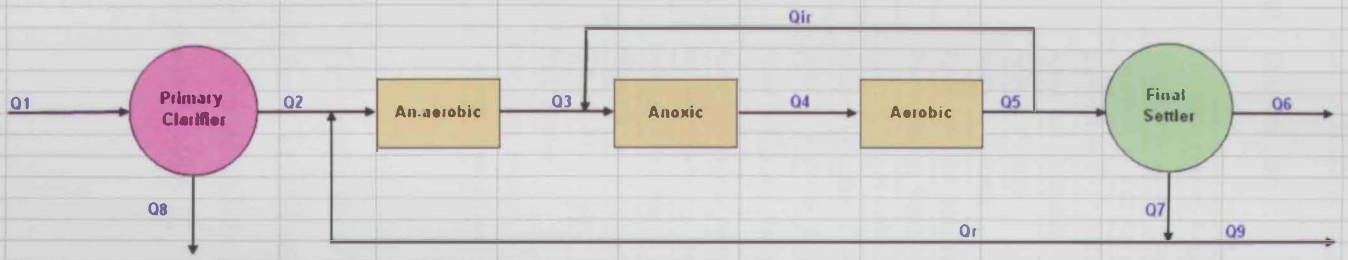


Figure 5-1 **Contribution of Different Cost Components into the total annual cost**

The model results are depicted below in a process flow diagram format.



V aer	Volume of Aerobic Comp. m^3	4,305.2
V anox	Volume of Anoxic Comp. m^3	5,508.6
V anaer	Volume of An-aerobic Comp. m^3	1,005.6
Total Tank Volume (m^3)		**10.819**

Ap	Surface Area of Primary Clarifier (m^2)	299.8
q_p	Over flowrate of Primary Clarifier (m/day)	120.0
Af	Surface Area of Final Clarifier (m^2)	1,628.0
q_f	Over flowrate of Final Clarifier (m/day)	21.9

r	Recirculation ratio	0.236
ir	Internal recirculation ratio	3.00
System Cost	2006 US$ / yr	$2,344,100

Stream Parameter	Description	Unit	Stream No. / ID										
			1	2	3	4	5	6	7	8	9	r	ir
Q	Flowrate	m^3 / hr	1,500.0	1,499.0	1,852.8	6,349.7	6,349.7	1,488.2	364.6	1.0	10.8	353.8	4,497.0
TSS	Total Suspended Solids	ppm	230.0	176.0	4,195.3	4,206.3	4,205.3	15.0	21,329.1	80,000.0	21,329.1	21,329.1	4,205.3
XI	Inert Particulate	ppm	92.4	70.7	2,041.3	2,046.3	2,048.6	7.3	10,390.5	32,139.1	10,390.5	10,390.5	2,048.6
XS	Slowly Biodeg. Substrate	ppm	214.4	164.1	286.5	189.1	176.3	0.6	894.0	74,584.3	894.0	894.0	176.3
XH	Heterotrophic Organisms	ppm	0.0	0.0	1,808.5	1,854.6	1,869.1	6.7	9,480.3	0.0	9,480.3	9,480.3	1,869.1
XSTO	Cell Storage Product of het. Organisms	ppm	0.0	0.0	572.4	611.0	591.1	2.1	2,997.8	0.0	2,997.8	2,997.8	591.1
XPAO	Phosphorus Accumulating Organisms	ppm	0.0	0.0	117.8	118.1	121.7	0.4	617.5	0.0	617.5	617.5	121.7
XPP	Poly-Phosphate	ppm	0.0	0.0	80.5	86.4	88.2	0.3	447.5	0.0	447.5	447.5	88.2
XPHA	Cell Storage Product of PAOrganisms	ppm	0.0	0.0	24.9	14.6	11.5	0.0	58.1	0.0	58.1	58.1	11.5
XA	Autotrophic / Nitrifying Organisms	ppm	0.0	0.0	112.5	115.0	116.2	0.4	589.3	0.0	589.3	589.3	116.2
SS	Soluble Substrate	ppm	161.8	161.8	133.8	15.5	0.246	0.2	0.2	161.8	0.2	0.2	0.2
SNOX	Nitrate plus Nitrite Nitrogen	ppm	0.0	0.0	1.3	0.2	7.0	7.0	7.0	0.0	7.0	7.0	7.0
SNH_4	Ammonium plus Ammonia Nitrogen	ppm	25.0	25.0	21.0	8.0	1.0	1.0	1.0	25.0	1.0	1.0	1.0
SPO_4	Inorganic Soluble Phosphorus	ppm	5.0	5.0	9.2	2.9	1.0	1.0	1.0	5.0	1.0	1.0	1.0

The results show that the internal recirculation ratio (ir) is on its upper bound of 3. In order to investigate the system performance at internal recirculation ratios higher than 3, the model was re-run with unbounded internal recirculation ratio (ir). Results are summarized in Table 5-9.

Table 5-9 System performance at unbounded upper limit of internal recirculation ratio

Symbol	*Description*	*Units*	*Upper Bound on Internal Recirc. = 3 (Metcalf & Eddy 1991)*	*Unbound Internal Recirc. ratio*
q	Overflow rate of Primary Clarifier	m/d	120.0	120.0
Ap	Surface Area of Primary Clarifier	m^2	299.8	299.8
qf	Overflow rate of Second. Clarifier	m/d	21.9	22.1
Af	Surface Area of Second. Clarifier	m^2	1628.0	1,617.9
V anaer	Anaerobic Volume	m^3	1,005.6	1,060.9
V anox	Anoxic Volume	m^3	5,508.6	3,345.9
V aer	Aerobic Volume	m^3	4,305.2	4,531
V tot	Total Reactor Volume	m^3	10,819	8,938
r	Recirculation Ratio	-	0.235	0.200
ir	Internal Recirculation Ratio	-	3.0	3.163
SRT tot	Solids Retention Time	d	7.50	5.90
TSS6	Total Suspended Solids	mg/L as TSS	15.0	15.0
SS6	Readily Biodeg. Substrate	mg/L as COD	0.24	0.25
SNH6	Ammonium plus Ammonia Nitrogen	mg/L as N	1.0	1.0
SNO6	Nitrate plus Nitrite Nitrogen	mg/L as N	7.0	7.0
SPO6	Inorganic Soluble Phosphorus	mg/L as P	1.0	1.0
MLSS	Mixed liquor suspended solids	mg/L	4205.2	4019.3
Q6	Effluent Flow Rate	m^3 /hr	1488.2	1489.0
Q9+Q8	Waste streams	m^3 / hr	11.7	10.9
Sludge	Disposed Sludge	Kg / d	7474.7	7502.7
Cost	System Annual Cost	2006 $ /year	2,344,100	2,316,600

The results show that the objective function value is improved by around 1.2%. In order to know exactly where the cost savings has occurred, comparison between the costs of the system when ir is unbounded against the cost of the system when ir is bounded by 3 is shown in Table 5-10.

Table 5-10 Cost comparison between the design of bounded internal recirculation ratio against the design of unbounded internal recirculation ratio

Cost Item	Component	Cost (2006 US$ per year)		% Change
		Upper Bound on Internal Recirc. = 3 (Metcalf & Eddy 1991)	Unbounded Internal Recirculation Ratio	
Capital Cost	Aerobic Tank	75,714	78,513	3.7
	Anoxic Tank	90,194	63,307	-29.8
	Anaerobic Tank	26,964	28,008	3.9
	Primary Settling Tank	28,736	28,736	0.0
	Secondary Settling Tank	105,741	105,236	-0.5
	Diffusers	144,035	144,048	0.0
	Primary Sludge Pumping	4,294	4,294	0.0
	Return Sludge Pumping	95,429	87,573	-8.2
	Internal Sludge Pumping	367,882	378,355	2.8
	Waste Sludge Pumping	15,030	14,405	-4.2
	Total	**954,019**	**932,475**	-2.3
Operation Cost	Primary Settling Tank	6,451	6,451	0.0
	Primary Sludge Pumping	2,969	2,969	0.0
	Diffusers	34,144	34,147	0.0
	Secondary Settling Tank	17,804	17,738	-0.4
	Return Sludge Pumping	33,929	31,714	-6.5
	Internal Sludge Pumping	98,020	100,207	2.2
	Waste Sludge Pumping	7,941	7,681	-3.3
	Total	**201,259**	**200,908**	-0.2
Material Cost	Primary Settling Tank	3,198	3,198	0.0
	Primary Sludge Pumping	1,050	1,050	0.0
	Secondary Settling Tank	11,569	11,514	-0.5
	Return Sludge Pumping	44,417	40,042	-9.8
	Internal Sludge Pumping	226,576	234,386	3.4
	Waste Sludge Pumping	4,767	4,529	-5.0
	Total	**291,576**	**294,719**	1.1
Power Cost	Primary Sludge Pumping	8	8	0.0
	Return Sludge Pumping	5,255	4,469	-15.0
	Internal Sludge Pumping	33,517	35,339	5.4
	Waste Sludge Pumping	80	74	-7.7
	Total	**38,859**	**39,890**	2.7
Mixing Cost	Anoxic Tank	33,779	20,517	-39.3
	Anaerobic Tank	6,167	6,506	5.5
	Total	**39,945**	**27,023**	-32.4
Disposal Cost		**818,441**	**821,586**	0.4
	Total	**2,344,100**	**2,316,600**	-1.2

From Table 5-10, it is clear that the reason for this improvement in the total cost is the 5% increase in the ir which resulted in reducing the r to its lower bound value. This 5% increase in the internal recirculation ratio (ir) has reduced the volume of the anoxic compartment by around 40% and this is actually the main cost saving that reduced the total system cost. The results also show that the sludge circulation ratio was reduced by around 15% resulting in a slight increase (by around 5%) in both anaerobic and aerobic reactors in order to compensate for the reduced amount of the recycled organisms into the system. Reducing the r will result also in reducing the MLSS value in the reactor and therefore less volume of waste streams are to be discharged from the system. From the above discussion we can conclude that the sludge circulation ratio (r) in this problem is basically governed by the denitrification process because it has to convey a sufficient amount of denitrifiers in order to achieve the required nitrate level. However, increasing the internal recirculation ratio (ir) to achieve the required denitrification level is more economical as it will result in reducing the organisms' r and the anoxic reactor volume considerably. The system sensitivity to the ir will be further investigated in the next section.

Since relaxing the upper bound of the internal recirculation ratio has resulted in reducing the sludge circulation rate to its lower bound of 0.2, another model run is carried out to investigate the model results when the lower bound of the sludge circulation ratio is omitted. Results have shown 1.5% improvement in the objective function value but with a reduction in the recirculation ratio by more than 50%. This is actually considered a large deviation from the common design practice and therefore the minimum sludge circulation ratio of 0.2 will be maintained.

It is also noticed that the system resulted in a primary clarifier design with maximum allowed overflow rate (q_p=120 m/day). To investigate the system performance at higher primary overflow rate value, the model was re-run with upper bound on primary overflow rate set equal to 1E+6. Results has shown that the model converge for almost 5 times higher primary overflow rate with a reduction in the total system annual cost by around 3% , refer to Table 5-11.

Table 5-11 **Model performance at unbounded primary overflow rate**

Symbol	*Description*	*Units*	*Value*
q	Overflow rate of Primary Clarifier	m/d	560.7
Ap	Surface Area of Primary Clarifier	m^2	64.2
qf	Overflow rate of Second. Clarifier	m/d	22.1
Af	Surface Area of Second. Clarifier	m^2	1,617.3
V anaer	Anaerobic Volume	m^3	1,224.8
V anox	Anoxic Volume	m^3	3,494.0
V aer	Aerobic Volume	m^3	5,221
V tot	Total Reactor Volume	m^3	9,940
r	Recirculation Ratio	-	0.200
ir	Internal Recirculation Ratio	-	3.276
SRT tot	Solids Retention Time	d	5.67
TSS6	Total Suspended Solids	mg/L as TSS	15.0
SS6	Readily Biodeg. Substrate	mg/L as COD	0.278
SNH6	Ammonium plus Ammonia Nitrogen	mg/L as N	1.0
SNO6	Nitrate plus Nitrite Nitrogen	mg/L as N	7.0
SPO6	Inorganic Soluble Phosphorus	mg/L as P	1.000
MLSS	Mixed liquor suspended solids	mg/L	4027.540
Q6	Effluent Flow Rate	m^3 /hr	1488.047
Q9+Q8	Waste streams	m^3 / hr	11.953
Sludge	Disposed Sludge	Kg / day	6946.208
Cost	System Annual Cost	2006 $ /year	2,266,600

The results in the table above indicate that the primary clarifier is not effectively participating in the treatment process and a reduction in the total system annual cost might be achieved if the system is designed without a primary clarifier.

The waste streams discharged from the system are either from the primary or the secondary clarifiers. However the type of the disposed sludge is different in each case. The sludge rejected from the primary clarifier contains mainly slowly biodegradable substrate (X_s) and inert particulates (X_I) in ratios equal to 70 and 30% respectively. In contrast, the sludge rejected from the secondary clarifiers is rich in the organisms grown in the biological reactor. The table below summarizes the composition the sludge rejected from the secondary clarifier.

Table 5-12 Composition of sludge rejected from the secondary clarifier

Component	Description	Units	Percent
X_I	Inert Particulate	mg/l	36.5
X_S	Slowly Biodeg. Substrate	mg/l	3.1
X_H	Heterotrophic Organisms	mg/l	39.9
X_{STO}	Cell Storage Product of het. Organisms	mg/l	8.4
X_{PAO}	Phosphorus Accumulating Organisms	mg/l	2.6
X_{PP}	Poly-Phosphate	mg/l	6.8
X_{PHA}	Cell Storage Product of PAO organisms	mg/l	0.2
X_A	Autotrophic / Nitrifying Organisms	mg/l	2.5

The above table shows that the heterotrophic organisms (X_H) and inert particulates (X_I) form more than 75% of the sludge composition. This result agrees with what has been reported by Koch et al. (2001).

CHAPTER VI

MODEL PERFORMANCE AND SENSITIVITY

In this section, the sensitivity of the developed mathematical model for the A^2O BNR system is explored under different realistic design conditions. Sensitivity analyses are beneficial in determining the direction of future data collection activities. Data for which the model is relatively sensitive would require careful characterization, as opposed to data for which the model are relatively insensitive. Two approaches are followed in studying the model sensitivity, first by varying the model input parameters over a reasonable range and second by changing the constraints applied on the model variables (either relaxing or tightening). Typically, and for the purpose of this study, model sensitivity to changes in influent temperature, flow rate and quality are noted. Model sensitivity to effluent quality is noted as well. The model performance is also tested for prescribed changes in the most sensitive kinetic parameters.

6.1 Effect of Temperature

Research has shown that the temperature of the influent to WWTPs has a significant impact on both sedimentation and biological treatment processes. The effect of temperature on sedimentation processes is still considered a hot research point because of the difficulties in predicting the behavior of the sedimentation tanks by theoretical mathematical models. Christoulas et al. (1998) found that influent temperature is an important factor that affects particles settling velocity and velocity gradients.

On the other hand, the temperature dependence of the biological reaction rates is very important in assessing the overall efficiency of the biological phosphorus and nitrogen removal process. Literature review revealed an agreement between most researchers in which better biological nitrogen removal efficiency can be achieved at higher temperatures but below 30°C. For example, Choi et al. (1998) reported, based on a lab scale modified UCT process, that the denitrification rate at 5°C is roughly 10 times lower than at 10°C.

Researchers have differentiated between the temperature effect on nitrifiers' growth and temperature effect on nitrifiers' activity. According to Metcalf & Eddy (1991a), Temperature has a strong effect on the growth of nitrifiers, but quantifying the effect has been difficult. Part of the difficulty in quantifying temperature effects is the fact that the optimum temperature is not fixed since it varies as the total ammonia-N concentration changes (Quinlan, 1984). The trend with optimal temperature for nitrifiers growth appears to be that the growth rate increases as temperature increases up to approximately 35°C with an overall range for growth between 4°C and 45 to 50°C (Antoniou et al. 1990). This means that at temperature range between 35°C and 50°C, nitrifiers can still grow but with reduced rate. Regarding the temperature effect on nitrifiers' activity, the optimal temperature for nitrifiers' activity has been reported to be as low as 15°C (Charley et al.,1980), but more typically appears to increase with increasing temperature up to approximately 30°C, slowing down as the temperature increases beyond that (Fdz-Polanco et al.,1994). Especially at lower temperatures, nitrification appears to be more severely affected than denitrification by temperature changes (Azevedo et al., 1995).

As with nitrification, temperature affects both the activity and the growth rate of the organisms involved in denitrification (de-nitrifiers) (Metcalf & Eddy 1991a). Denitrification is reported to occur at temperature range between 0 and 50°C, with optimum reaction rates occurring at 30 – 50°C (Barnes and Bliss, 1983). It is clear that higher temperatures are of greater concern on nitrification process than the de-nitrification process. It is important to note that the exponential expression suggested by Henze et al. (2000) (Eq 4-8 and Eq 4-9) to model the temperature effect on the organisms growth rate is a general mathematical expression suggested for all organisms' types and does not consider the specific temperature effect on the nitrifiers and de-nitrifiers. This exponential expression for the temperature effect on the kinetic parameters can probably be successfully applied at a temperature range between 10 to 30°C.

Contradictory results are noticed on the temperature effect on the Enhanced Biological Phosphorus Removal (EBPR). Beatons et al. (1999) investigated the temperature effect on the EBPR in SBR process operated at temperatures between 5 and 20 °C and at a constant SRT of 10 days. The experiment results reported that P-release is highest at temperature between 15 and 20°C. This concludes better phosphorus removal efficiency at higher temperatures. Obaja D. et al. (2003) operated experimentally a sequencing batch reactor (SBR) with anaerobic, anoxic and aerobic stages and concluded that good nutrient removal is achieved at temperatures higher than 16°C. However, Marklund and Morling (1994) used a full scale sequencing batch reactor to show the Enhanced Biological Phosphorus Removal was not lost even at temperatures as low as 3 to 8°C. Jonsson et al. (1996) showed using a full scale UCT plant that the concentration of soluble phosphorus in the plant effluent was lower than 0.3 mg/l even at temperatures below 10°C. Such removal efficiency can be achieved as long as enough volatile fatty acids are present in the wastewater. Converti et al. (1995) used a modified Anaerobic Oxic A/O process to study the temperature effect on the EBPR process for a range of 5 to 35°C. The results showed that the P removal efficiency varied between 60 to 62.5% over the considered temperature range. They stated that the time necessary to achieve the desired P removal was strongly increased as temperature decreased.

In this study, the effect of temperature on the kinetic parameters of the biological process is expressed using the exponential expression (Eq. 4-8 and Eq. 4-9) recommended in Henze et al. (2000). A quick review on the typical values of the kinetic parameters given in Henze et al. (2000), shows that some parameters are not affected by the temperature change. Values of the temperature-affected kinetic parameters at different temperatures are derived using the above-mentioned exponential expression and summarized in Table 6-1. It is obvious that kinetic parameter values increase as temperature increases.

Table 6-1 Values of Kinetic Parameters in in ASM3/EAWAG Bio-P module at different Temperatures

Parameter	*Temperature (°C)*			*Temperature Coefficient (θ)*
	10	*20*	*30*	
k_H	2	3	4.5	0.04
k_{STO}	2.5	5	10	0.07
U_H	1	2	4	0.07
b_{HO2}	0.1	0.2	0.4	0.07
b_{HNOX}	0.05	0.1	0.2	0.07
b_{STOO2}	0.1	0.2	0.4	0.07
b_{STO_NOX}	0.05	0.1	0.2	0.07
U_A	0.35	1	2.86	0.1
b_{AO2}	0.05	0.15	0.45	0.11
b_{ANox}	0.02	0.05	0.13	0.09
q_{PHA}	4.02	6	8.95	0.04
q_{PP}	1.01	1.5	2.24	0.04
U_{PAO}	0.5	1	2.01	0.07
b_{PAO}	0.1	0.2	0.4	0.07
b_{PP}	0.1	0.2	0.4	0.07
b_{PHA}	0.1	0.2	0.4	0.07

In order to study the temperature sensitivity of the A^2O system mathematical model, several model runs are carried out at temperatures between 10 to 30°C and compared with the base case run illustrated in section 5, which was carried out at 20°C.

At temperatures greater than 20°C, the model was unable to converge into a feasible solution unless the upper bound on either the r or the ir is relaxed. Since it was already concluded in the illustrative problem that relaxing the internal recirculation ratio (ir) will result in a more economic solution because of the considerable saving in the anoxic volume ractor, temperature sensitivity analysis is carried out without imposing any upper bound on the ir. Model results are summarized in Table 6-2.

Table 6-2 A^2O System Design at Different Temperatures

Symbol	*Description*	*Units*	*Temperatures °C*		
			10	*20*	*30*
q	Overflow rate of Primary Clarifier	m/d	120.0	120.0	120.0
Ap	Surface Area of Primary Clarifier	m^2	299.8	299.8	299.8
qf	Overflow rate of Second. Clarifier	m/d	22.1	22.1	22.1
Af	Surface Area of Second. Clarifier	m^2	1618.3	1,617.9	1,619.6
V anaer	Anaerobic Volume	m^3	1,675.8	1,060.9	961.1
V anox	Anoxic Volume	m^3	6,272.1	3,345.9	3,384.1
V aer	Aerobic Volume	m^3	11,217	4,530.9	4,976.0
V tot	Total Reactor Volume	m^3	19,164	8,938	9,321
r	Recirculation Ratio	-	0.200	0.200	0.200
ir	Internal Recirculation Ratio	-	3.3	3.163	3.561
SRT tot	Solids Retention Time	d	13.32	5.90	7.57
TSS6	Total Suspended Solids	mg/L as TSS	15.0	15.0	15.0
SS6	Readily Biodeg. Substrate	mg/L as COD	0.197	0.250	0.109
SNH6	Ammonium plus Ammonia Nitrogen	mg/L as N	1.00	1.0	0.37
SNO6	Nitrate plus Nitrite Nitrogen	mg/L as N	7.0	7.0	7.0
SPO6	Inorganic Soluble Phosphorus	mg/L as P	1.0	1.000	1.0
MLSS	Mixed liquor suspended solids	mg/L	4016.69	4019.327	4009.56
Q6	Effluent Flow Rate	m^3 /hr	1489.61	1489.035	1491.14
Q9+Q8	Waste streams	m^3 / hr	10.40	10.965	8.86
Sludge	Disposed Sludge	Kg / d	7190.59	7502.718	6347.75
AFR	Air Flow Rate	m^3 / min	267.44	258.4	298.56
Cost	System Annual Cost	2006 S /year	2,447,400	2,316,600	2,260,300

The results reported in Table 6-2 shows that the total system cost decreases as temperature decreases. It is also noted that the internal recirculation ratio slightly increase above and below the base case scenario. Refer to Figure 6-1.

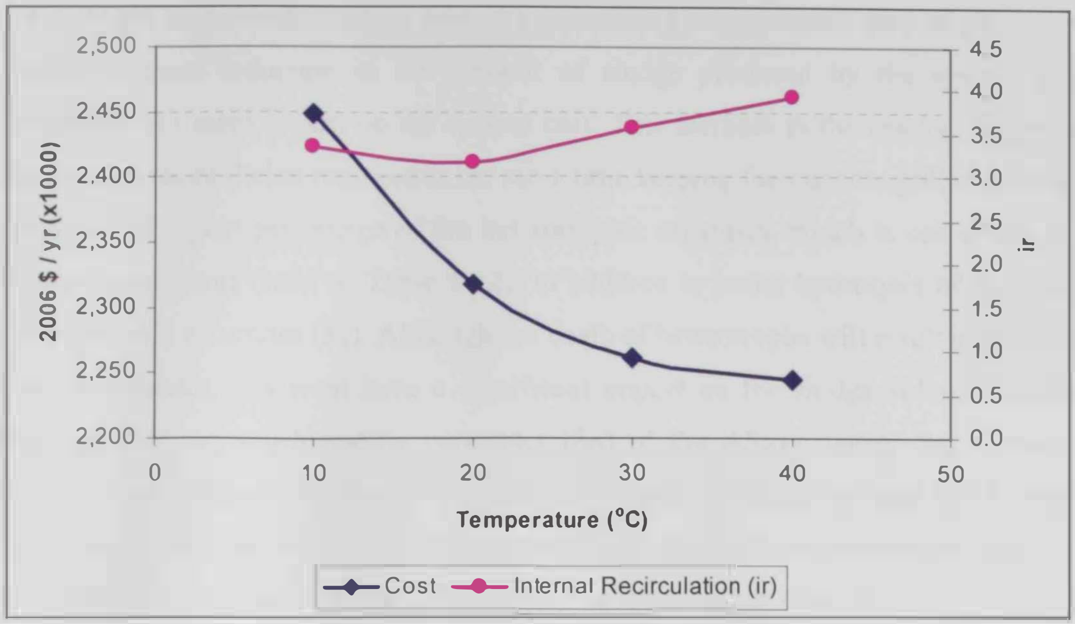


Figure 6-1 **Model Objective function value at different Temperatures**

At 10°C lower, the total system annual cost has increased by around 5.5%. The model behavior at lower temperature is expected and interpreted by the lower growth rates of the microorganisms at lower temperatures which have to be met by a new design with more than 114% larger reactor volume and 125% more retention time. The main increase in the reactor volume is in the aerobic compartment which is mainly governed by the nitrification process required to achieve an ammonium nitrogen level of less than or equal 1 mg/l. The ir has increased by around 5% to compensate for the lower denitrifiers growth rate.

At a temperatures higher than the base case scenario (i.e. 30 °C), the total system annual cost has decreased by around 2.5%. The results are clearly showing that the main savings in the system at higher temperatures came from the lower amounts of sludge to be disposed. At 30°C, the amount of generated sludge is lower by more than 15% compared to the amount generated at 20°C. As demonstrated in the illustrative problem, the disposal cost counts 35% of the total system annual cost and therefore it has a significant impact on the model objective function. This actually explains why the model has imposed a slight increase on the reactor volume (i.e. 4.3% at 30°C) and the internal recirculation ratio (i.e. 13% at 30°C). Although it might appear that increasing the reactor volume and the ir might increase the system cost, that was no the case where such slight increase results in more reduction in the amount of sludge produced by the system which eventually has more impact on the system cost. This increase in the reactor volume and the internal recirculation rate, and at the same time keeping the r unchanged, will result in the death of higher percentage of the heterotrophic organism, which is one of the main sludge components (refer to Table 5-12), in addition to better hydrolysis of the readily biodegradable substrates (X_s). Although the death of heterotrophs will result in producing inert particulates, this wont have a significant impact on the sludge volume reduction knowing that the stoichiometric parameter (f_{XI}) of the ASM3 matrix that relates the biomass endogenous respiration to the inert particulates generation is equal to 0.1 only. In other words, death of 1mg/l of biomass generates 0.1 mg/l of inert particulates. Moreover, the biomass contribution to the TSS ($i_{TSS,BM}$) is 20% higher than the inert particulates contribution to the TSS ($i_{TSS,XI}$).

In conclusion, the model results show that the objective function value is governed by the increase in the capital cost of the system (i.e. volume of reactor) at lower temperatures while it is governed by the sludge disposal cost at higher temperatures. We conclude also that the upper limit of 3 for the internal recirculation ratio (recommended by Metcalf & Eddy 1991) may not result into an economically feasible design especially at temperatures above 20°C, which is most likely the case in UAE and other GCC countries. At higher temperatures, it will be more economical to increase the ir to more than 3 while the r is maintained fixed. This will result in reducing the amount of sludge generated from the system as it will increase the biomass retention in the system and therefore their endogenous respiration rate. From the BNR/WWTPs operation point of view, increasing the internal recirculation ratio of the plant during the summer season can achieve a significant reduction in the amount of sludge generated and therefore reducing the OPEX.

6.2 Effect of Influent Flow Rate

In the base case problem, the influent flow rate was 1,500 m^3/hr. Considering the base case problem, model performance is examined for lower and higher flow rates. Results are summarized in Table 6-3.

Table 6-3 A^2O System Design at different influent flow rates (at 20°C)

Symbol	*Description*	*Units*	*Flow Rate (m^3/hr)*		
			500	*1500*	*2500*
q	Overflow rate of Primary Clarifier	m/d	120.0	120.0	120.0
Ap	Surface Area of Primary Clarifier	m^2	99.9	299.8	499.7
qf	Overflow rate of Second. Clarifier	m/d	22.1	22.1	22.1
Af	Surface Area of Second. Clarifier	m^2	539.3	1,617.9	2696.5
V anaer	Anaerobic Volume	m^3	353.3	1,060.9	1,769.0
V anox	Anoxic Volume	m^3	1,180.9	3,345.9	5,438.9
V aer	Aerobic Volume	m^3	1,509.4	4,530.9	7,554
V tot	Total Reactor Volume	m^3	3,044	8,938	14,762
r	Recirculation Ratio	-	0.200	0.200	0.200
ir	Internal Recirculation Ratio	-	3.14	3.16	3.2
SRT tot	Solids Retention Time	d	6.03	5.90	5.84
TSS6	Total Suspended Solids	mg/L as TSS	15.0	15.0	15.0
SS6	Readily Biodeg. Substrate	mg/L as COD	0.249	0.250	0.250
SNH6	Ammonium plus Ammonia Nitrogen	mg/L as N	1.0	1.0	1.0
SNO6	Nitrate plus Nitrite Nitrogen	mg/L as N	7.0	7.0	7.0
SPO6	Inorganic Soluble Phosphorus	mg/L as P	1.0	1.000	1.0
MLSS	Mixed liquor suspended solids	mg/L	4,019.3	4019.327	4,019.3
Q6	Effluent Flow Rate	m^3 /hr	496.3	1489.035	2,481.7
Q9+Q8	Waste streams	m^3 / hr	3.653	10.965	18.278
Sludge	Disposed Sludge	Kg / d	2,499.96	7502.718	12,506.6
AFR	Air Flow Rate	m^3 / min	86.12	258.4	430.6
Cost	System Annual Cost	2006 $ /year	1,039,100	2,316,600	3,423,800

The model results are expected as they show an increase in the total annual cost with increasing flow rate and vice versa. It is clear that the system design in terms of r, ir and the SRT is almost same for higher and lower flow rates. Other design parameters are either scaled up for higher flow rates or scaled down for lower flow rates. The design parameters are scaled up or down in a percentage equal to the percentage increase or decrease in the influent flow rate.

6.3 Effect of Wastewater Quality

As stated earlier, the base case design is carried out with a medium strength wastewater quality quoted from Metcalf & Eddy 1991. Model performance, at increased and decreased selected quality parameters is investigated in this subsection. The model is also tested with higher and lower strength wastewater quality both quoted from Metcalf & Eddy (1991) as well. Table 6-4 shows the model performance at different wastewater qualities compared to the base case run of this study.

Table 6-4 Model Performance at different Wastewater Qualities

Symbol	*Description*	*Units*	*Base Case*	*1*	*2*	*3*	*4*	*5*	*6*
Influent Characteristics									
Q	Flow Rate	m^3 / hr	1500	1500	1500	1500	1500	1500	1500
T	Temperature	^oC	20	20	20	20	20	20	20
BOD5	Biochemical Oxygen Demand (5days)	mg/l	220	220	220	**308**	220	**400**	**110**
COD	Chemical Oxygen Demand	mg/l	500	500	500	**708**	500	**1000**	**250**
VSS	Volatile Suspended Solids	mg/l	165	165	165	165	**229**	**275**	**80**
X_H	Heterotrophic Organisms	mg/l as COD	0	0	0	0	0	0	0
X_{STO}	Cell Storage Product of het. Organis.	mg/l as COD	0	0	0	0	0	0	0
X_{PAO}	Phosphorus Accumulating Organis.	mg/l as COD	0	0	0	0	0	0	0
X_{PP}	Poly-Phosphate	mg/l as P	0	0	0	0	0	0	0
X_{PHA}	Cell Storage Product of PAO	mg/l as COD	0	0	0	0	0	0	0
X_A	Autotrophic / Nitrifying Organisms	mg/l as COD	0	0	0	0	0	0	0
TSS	Total Suspended Solids	mg/l as TSS	230	230	230	230	**322**	**350**	**100**
SNH_4	Ammonium plus Ammonia Nitrogen	mg/l as N	25	**35**	25	25	25	**50**	**12**
SNOX	Nitrate plus Nitrite Nitrogen	mg/l as N	0	0	0	0	0	0	0
SPO_4	Inorganic Soluble Phosphorus	mg/l as P	5	5	**7**	5	5	**10**	**3**
A2O System Design									
q	Overflow rate of Primary Clarifier	m/d	120.0	120.00	120.00	120.00	120.0	120.00	120.00
Ap	Surface Area of Primary Clarifier	m^2	299.8	299.80	299.80	299.80	299.3	299.15	299.98
qf	Overflow rate of Second. Clarifier	m/d	22.1	22.09	22.09	22.10	22.1	22.08	22.1
Af	Surface Area of Second. Clarifier	m^2	1,617.9	1618.44	1617.54	1,620.2	1,612.8	1,612.0	1,623.5
V_{anaer}	Anaerobic Volume	m^3	1,060.9	1,120.7	1,107.6	1,110.2	1,384.4	1,582.4	577.9
V_{anox}	Anoxic Volume	m^3	3,345.9	6,219.4	3,494.8	3,379.7	4,194.1	8,343.7	916
V_{aer}	Aerobic Volume	m^3	4,530.9	5,084.3	4,701.7	7,854	5,827.4	8,204	2,984
V_{tot}	Total Reactor Volume	m^3	8,938	12,424	9,304	12,344	11,406	18,130	4,478

Symbol	*Description*	*Units*	*Base Case*	*1*	*2*	*3*	*4*	*5*	*6*
r	Recirculation Ratio	-	0.200	0.200	0.200	0.200	0.2	0.200	0.200
ir	Internal Recirculation Ratio	-	3.16	4.856	3.17	3.90	3.1	7.82	1.00
SRT_{tot}	Solids Retention Time	d	5.90	8.74	5.92	11.03	5.9	9.53	6.24
TSS6	Total Suspended Solids	mg/L as TSS	15.0	15.0	15.0	15.0	15.0	15.0	15.0
SS6	Readily Biodeg. Substrate	mg/L as COD	0.250	0.133	0.248	0.151	0.2	0.119	0.294
SNH6	Ammonium plus Ammonia Nitrogen	mg/L as N	1.0	0.85	1.00	0.43	1.0	0.68	0.66
SNO6	Nitrate plus Nitrite Nitrogen	mg/L as N	7.0	7.00	7.00	7.00	7.0	7.00	7.00
SPO6	Inorganic Soluble Phosphorus	mg/L as P	1.000	1.00	1.00	1.00	1.0	1.00	1.00
MLSS	Mixed liquor suspended solids	mg/L	4019.327	4016.09	4021.25	4005.77	4,034.3	4032.85	3992.04
Q6	Effluent Flow Rate	m^3 /hr	1489.035	1489.74	1488.62	1491.95	1,483.5	1482.87	1495.78
Q_9+Q_8	Waste streams	m^3 / hr	10.965	10.27	11.38	8.05	16.5	17.13	4.22
Sludge	Disposed Sludge	Kg / day	7502.718	7119.73	7729.98	5899.53	11,089.1	11520.47	2522.26
AFR	Air Flow Rate	m^3 / min	258.4	305.055	258.39	370.29	248.4	492.27	143.04
Cost	System Annual Cost	2006 $ /year	2,316,600	2,563,200	2,348,500	2,316,400	2,751,500	3,513,000	1,257,700

In case 1, increasing the Ammonium plus ammonia nitrogen (SNH_4) concentration by 40% (i.e. from 25 mg/ l to 35 mg/ l) has resulted in an increase in the total system annual cost by around 10%. Such increase has resulted in an increased reactor volume and mainly the aerobic compartment in order to provide the sufficient nitrification capacity. The higher nitrification capacity has resulted in increasing the ir by more than 50% and the anoxic compartment by 85% in order to accommodate the increase in the nitrate (NO_3) formation and maintain the required level of nitrate in the effluent.

In case 2, the inorganic phosphorus concentration is increased by 40% (from 5 to 7 mg/ l). This increase has increased the total system annual cost by 1.4% only. This indicates that the system cost is seven times more sensitive to the increase in the ammonium concentration compared to the increase in the phosphorus concentration of the influent. The main design change is noticed on the reactor volume which is increased by around 4% and reflected on all reactors. The increase in the anaerobic compartment is required in order to allow the PAOs to achieve better storage of X_{PHA} components which are going to be respired during the phosphorus uptake phase in both anoxic and aerobic compartments. The increase in the anoxic and the aerobic compartments is also necessary to compensate for the reduced amount of substrates transferred from the anaerobic compartment because of the higher substrate consumption in the anaerobic phase caused by the PAOs.

In case 3, Both COD and BOD are increased by around 40% considering the relation $COD \approx 2.3\ BOD_5$ while other quality parameters are kept unchanged from the base case values. This increase in the COD & BOD has resulted in a minimal reduction in the total annual system cost (less than 0.01%). However, a major change is noticed in the optimal volume of the aerobic reactor. The SRT is almost doubled at fixed r which resulted in 20% less sludge volume because of the longer endogenous respiration phase available for the organisms. The system has mainly increased the aerobic compartment volume since endogenous respiration rate is faster under aerobic conditions.

In case 4, both VSS and TSS are increased by 40% considering the relation $VSS \approx 0.71 * TSS$. The VSS is directly related to the concentration of the inert particulates through the relation: Inert Particulate (X_I) =0.56 VSS. The Inert particulates does not undergo any treatment during the process but produced through the aerobic and anoxic endogenous respiration processes of the heterotrophic and autotrophic organisms. Therefore, the amount of (X_I) increases during the biological treatment process and then settles in the final sedimentation tank. So, increasing the amount of the inert particulates will result in increasing the amount of sludge produced from the system and therefore a considerable increase in the system cost as the sludge disposal counts for 35% of the total system cost, Refer to Figure 5-1. Increasing the TSS by 40% has increased the produced amount of sludge by around 50% and the total system annual cost by around 20%. Because of the considerable waste disposal cost, the system will try to maintain the MLSS value by fixing the sludge circulation ratio (r) at its lower limit. Therefore, increasing the X_I concentration in the reactor will result in a decrease in the concentration of the X_H, X_A, and X_{PAO} organisms. This explains the increase in the total reactor volume which is accompanied by an increased amount of waste to dispose the extra inert particulates. Results are showing almost a linear relationship between the concentration of the VSS and the total system annual cost; Refer to Figure 6-2.

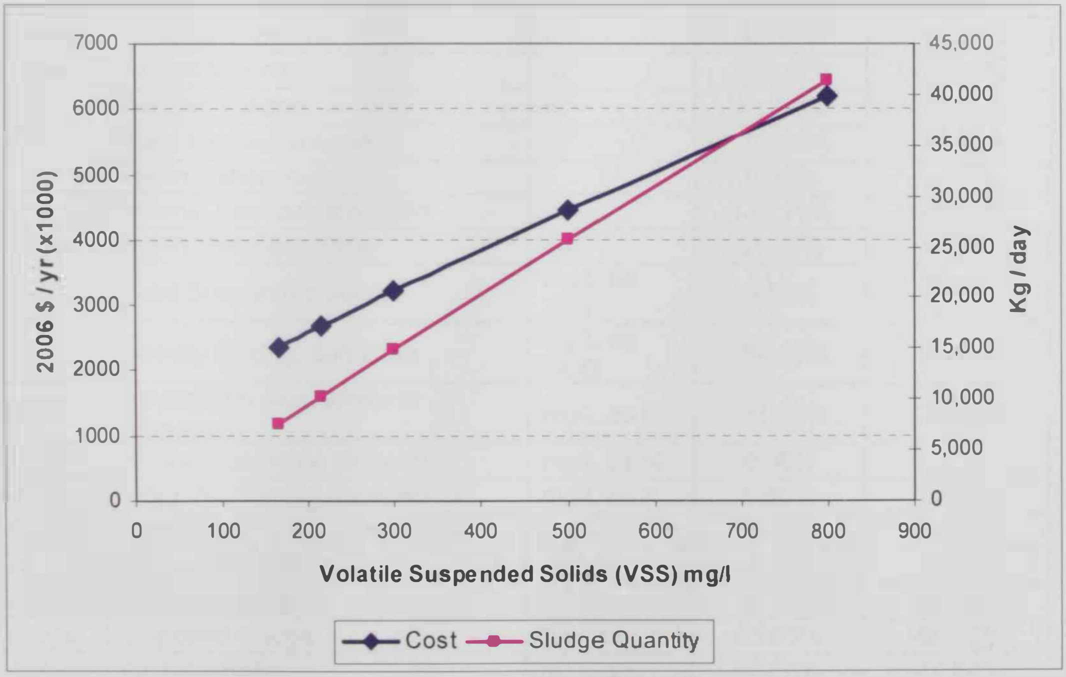


Figure 6-2 Impact of Volatile Suspended Solids on the total system Cost and sludge quantities produced

In cases 5 and 6, model performance is investigated for high and low strength wastewater characteristics. Wastewater composition for both cases is quoted from Metcalf & Eddy (1991). The results show total cost increase for the high strength wastewater case and decrease for the low strength wastewater case. Model results are considered expected and reasonable; refer to Table 6-5. Minor change is noticed in the design of the primary and secondary clarifiers, which indicates that any change in wastewater strength will mainly impact the design of the biological treatment process considering a fixed effluent TSS requirement. In both cases, the trade-off between the internal recirculation ratio and the nitrification rate in the aerobic reactor has resulted in having better nitrification results.

Table 6-5 Percentage increase / decrease in the system design parameters considering high and low strength wastewater characteristics.

Symbol	*Description*	*Units*	*Case 4 (High Strength)*	*Case 5 (Low Strength)*
q	Overflow rate of Primary Clarifier	m/day	0.00%	0.00%
Ap	Surface Area of Primary Clarifier	m^2	-0.22%	0.06%
qf	Overflow rate of Second. Clarifier	m/day	-0.05%	0.10%
Af	Surface Area of Second. Clarifier	m^2	-0.36%	0.35%
V anaer	Anaerobic Volume	m^3	49.15%	-45.53%
V anox	Anoxic Volume	m^3	149.37%	-72.64%
V aer	Aerobic Volume	m^3	81.08%	-34.13%
V tot	Total Reactor Volume	m^3	102.85%	-49.90%
r	Recirculation Ratio	-	0.00%	0.00%
ir	Internal Recirculation Ratio	-	147.11%	-68.38%
SRT tot	Solids Retention Time	day	61.66%	5.78%
TSS6	Total Suspended Solids	mg/L as TSS	0.00%	0.00%
SS6	Readily Biodeg. Substrate	mg/L as COD	-52.40%	17.60%
SNH6	Ammonium plus Ammonia Nitrogen	mg/L as N	-31.60%	-33.90%
SNO6	Nitrate plus Nitrite Nitrogen	mg/L as N	0.00%	0.00%
SPO6	Inorganic Soluble Phosphorus	mg/L as P	0.00%	0.00%
MLSS	Mixed liquor suspended solids	mg/L	0.34%	-0.68%
Q6	Effluent Flow Rate	m^3 /hr	-0.41%	0.45%
Q9+Q8	Waste streams	m^3 / hr	56.24%	-61.50%
Sludge	Disposed Sludge	Kg / day	53.55%	-66.38%
AFR	Air Flow Rate	m^3 / min	90.54%	-44.64%
Cost	System Annual Cost	2006 $ /year	51.64%	-45.71%

6.4 Effect of Effluent Characteristics

The bounds applied on the effluent characteristics in the base case design are derived from practical limits of BNR system; refer to Table 5-5. In this subsection, model performance is explored at more stringent effluent quality bounds. The simulation results are summarized in Table 6-6. It is worth mentioning that effluent quality requirement varies from one regulation to another based on different health, environmental and economical perspectives. Required effluent quality varies also based on the envisaged use for effluent, which is either disposed to the sea, used for irrigation purposes or sometimes for industrial purposes.

Table 6-6 Model performance at more stringent effluent quality parameters

Symbol	*Description*	*Units*	*Base Case*	Case 1	Case 2	Case 3
				Upper Bound on TSS = 7.5 mgll	*Upper Bound on Nitrate = 3.5 mgll*	*Upper Bound on Phosphorus = 0.5 mgll*
q	Overflow rate of Primary Clarifier	m/day	120.0	120	120	120
Ap	Surface Area of Primary Clarifier	m^2	299.8	299	299	299
qf	Overflow rate of Second. Clarifier	m/day	22.1	17.5	22.1	22.1
Af	Surface Area of Second. Clarifier	m^2	1617.9	2049	1618	1617
V anaer	Anaerobic Volume	m^3	1,060.9	946.8	1,060.2	1,077.5
V anox	Anoxic Volume	m^3	3,345.9	3,179.0	5,742.9	3,398.0
V aer	Aerobic Volume	m^3	4,530.9	4,386.5	4,508.3	4,575.7
V tot	Total Reactor Volume	m^3	8,938	8,512	11,311	9,051
r	Recirculation Ratio	-	0.200	0.200	0.200	0.200
ir	Internal Recirculation Ratio	-	3.160	3.208	7.706	3.162
SRT tot	Solids Retention Time	day	5.90	6.53	7.60	5.91
TSS6	Total Suspended Solids	mg/L as TSS	15.0	7.5	15.0	15.0
SS6	Readily Biodeg. Substrate	mg/L as COD	0.250	0.218	0.211	0.249
SNH6	Ammonium plus Ammonia Nitrogen	mg/L as N	1.00	0.86	1.00	1.00
SNO6	Nitrate plus Nitrite Nitrogen	mg/L as N	7.0	7.0	3.5	7.0
SPO6	Inorganic Soluble Phosphorus	mg/L as P	1.0	1.0	1.0	0.5
MLSS	Mixed liquor suspended solids	mg/L	4,019.3	4,568.3	4,018.3	4,019.8
Q6	Effluent Flow Rate	m^3 /hr	1,489.0	1,490.1	1,489.2	1,488.9
Q9+Q8	Waste streams	m^3 / hr	10.97	9.93	10.75	11.07
Sludge	Disposed Sludge	Kg / day	7,502.7	7,632.6	7,387.1	7,560.9
AFR	Air Flow Rate	m^3 / min	258.4	263.2	258.9	258.4
Cost	System Annual Cost	2006 $ /year	2,316,600	2,355,500	2,851,900	2,325,000

In case1, the upper bound of the TSS is set on 7.5 mg/l instead of 15 mg/l. The total system annual cost is increased by 2% for this 50% reduction in the TSS requirement. Quick review of the model results show that the model has tackled this new TSS requirement by reducing the overflow rate of the secondary clarifier by almost 20% resulting in more than 25% increase in the surface area of the secondary clarifier. The model results also show that the total volume of the reactor is reduced by around 5%; however, the other effluent characteristics are still met. This actually draws an important conclusion on the impact of the secondary clarifier design on the biological treatment. In the base case scenario, where the TSS upper bound is 15 mg/l, the model has sized the reactor 5% larger in order to reduce the MLSS value which in turn results in a smaller surface area for the secondary clarifier. This means that the cost functions of the secondary clarifier were governing the design of the biological reactor in the base case simulation.

In case 2, the upper bound of the nitrate and nitrite nitrogen (S_{NO3}) is reduced by 50% to be 3.5 mg/l instead of 7 mg/l. The design results shows that the main design changes were in the increased volume of the anoxic reactor (around 72%) and in the ir which was increased by 140% resulting in an increase in the total system cost by around 23%. It is clear from the results that the required nitrate level in the plant effluent is a highly economic issue with direct impact on the required plant investments.

In case 3, the upper bound of the inorganic phosphorus level (S_{PO4}) is made more stringent by reducing it to 0.5 instead of 1.0 mg/ l. No significant change is noticed in the system design except increasing the anaerobic reactor volume by around 1.5% resulting in an increase in the total system annual cost by 0.36%.

From the above discussion, it can be concluded that the total system cost of the plant is more sensitive to nitrate requirement in the effluent rather than phosphorus or TSS.

6.5 Effect of Kinetic Parameters

The developed ASM3/EAWAG Bio-P model has considered a total of 65 kinetic and stoichiometric parameters in its mathematical formulation where 36 parameters are kinetic and the remaining are stoichiometric. Values of these parameters are assumed as recommended by Henze et al (2000) and Rieger et al. (2001). The ASM3/EAWAG Bio-P model is introduced in the form of stoichiometric and composition matrix based on the suggested values for these stoichiometric parameters. Therefore the stoichiometric parameters are actually imbedded in the original matrix structure and they don't exist as independent parameters in this formulation. Based on the above discussion, the sensitivity analysis in this subsection is limited to the kinetic parameters only. Most of kinetic parameters are temperature dependent with exponential functions, therefore; the model sensitivity to the effective kinetic parameters is investigated at different temperatures. Table 6-7 shows the percentage change in the total annual system cost after increasing and decreasing the values of the kinetic parameters by 50% at 20 °C & 40 °C. The impact of the other kinetic parameters not shown in Table 6-7 is found to be marginal.

Table 6-7 Percentage Change in Objective Function Value due to variations in Kinetic Parameters

Parameter	Description	Unit	20 °C		40 °C	
			+50%	-50%	+50%	-50%
μ_H	Heterotrophic max. growth rate of X_H	d^{-1}	-0.514%	1.623%	-0.107%	0.089%
μ_A	Autotrophic max. growth rate of X_A	d^{-1}	0.514%	**5.197%**	0.098%	-0.544%
μ_{PAO}	Max. growth rate of X_{PAO}	d^{-1}	0.013%	0.730%	-0.049%	0.860%
K_H	Hydrolysis rate constant	$gCOD_{Xs} (gCOD_{XH})d^{-1}$	-0.285%	0.881%	0.156%	0.441%
b_{HO2}	Aerobic endogen. Respiration rate of X_H	d^{-1}	-0.315%	0.660%	0.352%	-0.530%
b_{AO2}	Aerobic endogen. respiration rate of X_A	d^{-1}	0.017%	0.263%	-0.169%	-0.009%
b_{PAO}	Max. endogen. respiration rate of X_{PAO}	d^{-1}	0.125%	-0.108%	0.793%	-0.120%
b_{PHA}	Respiration rate for X_{PHA}	d^{-1}	0.000%	-0.004%	-0.013%	0.018%

It is clear form the results shown in Table 6-7 that each kinetic parameter has a different effect on the model solution. It is noticed also that the same kinetic parameter has a different effect on the objective function value at different temperature. The most significant effect on the objective function value is reported by μ_A when reduced by 50% indicating that this parameter should be given the highest attention as it imposes the highest impact on the system cost. Most of the other parameters impacted the objective function value by less than 1%.

The analysis done in Table 6-7 gives a good indication about the level of uncertainty in the objective function value when considering the typical values of the kinetic parameters suggested by the model developers. It is clear now that majority of these kinetic parameters have an impact of less than 1% on the system design when their values are increased or deceased by 50%; this actually supports the use of such models as a preliminary design tools in the conceptual phase of the project knowing that as an industry practice followed by most engineering consultants, the budget estimate of any project in the conceptual phase is usually presented with ±40% allowance.

In order to have a closer look on where specifically the system design differs at different kinetic parameters values; three illustrative model runs are presented in the table below considering different organisms growth rates parameters since the model has highest sensitivity when those parameters are changed.

Table 6-8 Model performance at different Kinetic and stoichiometric Parameters at 20°C

Symbol	*Description*	*Units*	*Base Case*	Case 1	Case 2	Case 3
q	Overflow rate of Primary Clarifier	m/d	120.0	120.0	120.0	120.0
Ap	Surface Area of Primary Clarifier	m^2	299.8	299.8	299.8	299.8
qf	Overflow rate of Second. Clarifier	m/d	22.1	22.1	22.0	22.0
Af	Surface Area of Second. Clarifier	m^2	1617.9	1617.9	1623.4	1623.3
V_{anaer}	Anaerobic Volume	m^3	1,060.9	1,057.5	2,291.5	1,060.0
V_{anox}	Anoxic Volume	m^3	3,345.9	3,142.4	6,609.0	3,350.0
V_{aer}	Aerobic Volume	m^3	4,530.9	4,525.6	13,328.8	4,429
V tot	Total Reactor Volume	m^3	8,938	8,725	22,229	8,839
r	Recirculation Ratio	-	0.200	0.200	0.211	0.218
ir	Internal Recirculation Ratio	-	3.160	3.095	3.671	3.126
SRT tot	Solids Retention Time	day	5.90	5.74	19.04	5.96
TSS6	Total Suspended Solids	mg/L as TSS	15.0	15.0	15.0	15.0
SS6	Readily Biodeg. Substrate	mg/L as COD	0.250	0.235	0.141	0.252
SNH6	Ammonium plus Ammonia Nitrogen	mg/L as N	1.00	1.00	1.00	1.00
SNO6	Nitrate plus Nitrite Nitrogen	mg/L as N	7.0	7.0	7.0	7.0
SPO6	Inorganic Soluble Phosphorus	mg/L as P	1.0	1.0	0.01	1.00
MLSS	Mixed liquor suspended solids	mg/L	4,019.3	4,019.5	4,071.6	4,119.5
Q6	Effluent Flow Rate	m^3 /hr	1,489.0	1,489.0	1,491.3	1,488.6
Q9+Q8	Waste streams	m^3 / hr	10.97	10.99	8.75	11.44
Sludge	Disposed Sludge	Kg/d	7,502.7	7,517.6	6,165.3	7,511.1
AFR	Air Flow Rate	m^3 / min	258.4	258.2	307.2	258.4
Cost	System Annual Cost	2006 $ /year	2,316,600	2,304,700	2,437,000	2,320,200

Where:

In case 1: Heterotrophic max. growth rate of X_H (μ_H) increased from 2 to 3 d^{-1}

In case 2: Autotrophic max. growth rate of X_A (μ_A) reduced from 1 to 0.5 d^{-1}

In case 3: Max. growth rate of X_{PAO} (μ_{PAO}) increased from 1 to 2 d^{-1}

In case 1, the heterotrophic maximum growth (u_H) rate of the heterotrophs (X_H) is increased by 50%. The results show that the total system cost is insignificantly reduced by 0.5%; and this reduction can be mainly related to the reduced volume of the reactor because of the higher heterotrophs growth rates.

In case 2, the autotrophic maximum growth rate (μ_A) of the autotrophs (X_A) is reduced by 50% leading to an increase in the total system cost by around 5%. Reducing the growth rate of the autotrophs will directly affect the nitrification process resulting in an almost three time's larger aerobic reactor. It is clear that the system is more sensitive to the autotrophic rather than heterotrophic growth rate because autotrophs are already assigned with 50% lower growth rate. This large increase in the aerobic reactor volume which resulted in a large increase in the SRT and at the same time the slight increase in the sludge circulation ratio (r); will all increase the endogenous respiration phase and therefore reduce the amount of sludge generated from the system. The simulation results of case 2 show around 20% reduction in the amount of generated sludge. This reduction in the amount of sludge resulted in reducing the organisms' concentration in the recycled stream which in turn resulted in an increase in the volumes of both anaerobic and anoxic compartments.

In case 3, the maximum growth rate of the phosphate accumulating organisms (μ_{PAO}) is increased by 100% leading to an insignificant increase in the total system cost by around 0.16%. This slight increase in the system cost is expected because the higher growth rates for the PAOs which will result in storing higher amounts of substrates in the anaerobic reactor to accomplish the phosphorus release and therefore less substrate will be available for the other organisms to grow in the subsequent anoxic and aerobic reactors. Therefore the system has increased the r by around 10% in order to introduce more particulate substrate (X_s) into the anoxic and aerobic compartment and achieve the required phosphorus, ammonium and nitrate levels.

CHAPTER VII

CONCLUSIONS AND FUTURE RESEARCH

Biological Nutrients removal from both domestic and industrial wastewater has been recognized as one of the necessary processes that are required to prevent surface water pollution through eutrophication. Therefore, many wastewater treatment plants have been designed to be capable to achieve the acceptable level of nutrient concentration in their discharged effluent and specifically those where the treated effluent is discharged directly into the sea. The continuous development of knowledge concerning the nutrients removal mechanisms led to a better mathematical characterization for the process biology which in turn led into the involvement of the computer models as powerful tool for designing WWTP with BNR capability.

System optimal formulation, like the one developed in this research, can be very useful design tools where an optimal plant design for a given input data and effluent quality can be obtained based on pre-defined design constraints. Such models are very efficient to carry out design options evaluation and comparison. In this research, a mathematical model is developed for the Phoredox process which is one of the most popular processes applied in wastewater treatment plants to achieve BNR. The Phoredox process is a single sludge process where the wastewater influent passes through anaerobic, anoxic and aerobic phases in series manner. The mathematical optimization approach is used in solving the developed model aiming to find the most optimum design that can achieve the lowest capital (CAPEX) and operation (OPEX) costs. The software package “GAMS”, which is a powerful optimization tool, has been used in this study to perform the optimization runs. It is very important to realize that in any cost optimization problems, the applied cost functions play a key role in driving the response of the optimization model. This is because the mathematical structure of the model tries always to find the most economical and cost effective design. Therefore, incorporating a realistic cost functions that reflects the local market situation is important to get a reasonable and reliable results.

The following points summarize the main findings of this research obtained from the model results analysis:

1. The upper limit of three "3" assigned by Metcalf & Eddy (1991) for the ir as a typical design parameter for the A^2O system needs to be relaxed since it is found to be an obstacle against achieving an economic design; this is especially in plants where a stringent nitrate level is required in the effluent. In such plants, limiting the ir would require the system to increase the main r in order to introduce more denitrifiers into the system which consequently would require an increase in the volume of the anoxic reactor so that an appropriate retention time can be achieved. The CAPEX and OPEX investments required to increase the ir are certainly lower than those required to increase both main r and anoxic volume reactor.
2. The wastewater influent temperature in United Arab Emirates and other GCC countries usually varies between 20°C in winter and 35 to 40°C in summer. The model results has shown that more economical design for the A^2O BNR system might be achieved if the highest influent temperature is considered rather than the lowest temperature. The higher organisms' growth rates at temperatures higher than 20°C will result in a considerable increase in the amount of sludge generated from the system which in turn will increase the operation cost of the plant (OPEX) significantly. Increasing the SRT by 75% during the high temperature operation can reduce the total amount of the sludge generated from the system by around 35%. This will lead into a significant reduction in the operation cost of the plant knowing that sludge handling, treatment and disposal is one of the most expensive items that increases the life cycle cost of the plant considerably.
3. The BNR A^2O system is more sensitive to the variations in the ammonium plus ammonia nitrogen concentration (S_{NH4}) than the variations in the phosphorus concentration (S_{PO4}). Results of the simulation model have shown that 40% increase in the ammonium plus ammonia nitrogen concentration (S_{NH4}) in the influent has increased the total annual system cost by 10% while the same increase in the phosphorus concentration has increased the total annual system cost by 1.5% only.
4. Considering the fact that the organisms growth rate increases exponentially with the increased substrate concentration in the influent. In WWTPs where seasonal increase is experienced in the influent COD level; the best operation practice is to

increase the SRT of the plant to its maximum possible limit and fixing the r to its lowest possible limit in order to alleviate the expected increase in the sludge volume because of the higher organisms growth rates. This practice will participate in elongating the endogenous respiration phase of the organisms which form more than 70% of the sludge generated from the system.

5. The concentration of the VSS in the influent is of a significant impact on the system operation cost as it can be directly translated into an increase in the amounts of sludge generated from the system which in turn increases the operation cost of the plant.
6. The model results have shown that the TSS removal achieved in a primary clarifier is not significant enough to accomplish savings in the subsequent biological process design that pays back the capital investment of the primary clarifier itself. However, the primary clarifier might participate effectively in removing the solids that might have an inhibition effect on the biomass of the activated sludge system; such effect is not considered in the model of this study and any final decision on the feasibility of the primary clarifier should be judged against it.
7. The current quality regulations for the treated sewage effluent discharged into the sea in United Arab Emirates need to be revised so that more stringent requirements for nutrients level are considered. The need for these more stringent regulations came from the recently noticed eutrophication phenomenon that started to appear in the surface water surrounding the newly developed islands. The new required nutrients level has to be studied carefully as are directly related to the dilution effect and the water circulation rate in the area of discharge.
8. Most probably, any level of nitrate and phosphorus removal can be achieved using the A^2O BNR system, provided that the system is properly designed with appropriate design parameters. However, the economically feasible level of nutrients removal that can be achieved biologically is different from one situation to another depending on the local market economies. For example, at certain situations it could be more economical to achieve 60% of the required nutrients removal biologically while the remaining 40% are removed chemically.
9. Sensitivity analysis on the kinetic parameters of the ASM3-EAWAG Bio-P model has shown that the maximum growth rate of the autotrophs (μ_A) is by far the highest parameter that impacted the objective function value. The objective

function value is increased by around 5% when the parameter value reduced by 50% at 20°C.

10. A more Stringent nitrate effluent requirement will have a considerable impact on both CAPEX and OPEX investments. The results of the mathematical model developed in this study have shown that applying 50% more stringent nitrate requirement requires 2.5 times more internal recirculation ratio, 70% larger anoxic reactor volume and consequently more than 20% increase in the total annual cost.

7.1 Future Research

The following points summarize the main areas of this research that still deserve further investigation:

1. Consider more appropriate performance models for both primary and secondary clarifiers, and preferably models that are developed based on data collected from a plant operating in the same area where the overall optimization model is intended to be used.
2. Develop more specific cost functions that represent the actual situation of the local market in the area where the optimization model is intended to be used.
3. Conduct detailed uncertainty analysis in order to have an accurate assessment to the model results reliability. This is actually an intensive statistical work which requires identification to the statistical properties of all model random parameters. Based on the nature of the random parameters, the most appropriate probability distribution shall be selected.
4. Perform model calibration and field verification using the standard calibration protocols developed for wastewater treatment plants. Reader is referred to Gurkan Sin et al. (2005) for further elaboration on the different calibration protocols currently exist and the differences between them.
5. Optimizing the pumping heads for the different A^2O process streams by considering different process arrangement.

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Appendix A GAMS Model Input File

```
Scalar
Q1       influent to primary clarifier flowrate (m3 per hour) /1500/
T        stream 1 temperature in oC /20/
BOD5     stream 1 BOD5 at 20 oC (mg per L) /220/
COD      stream 1 total chemical oxygen demand (mg per L) /500/
VSS      stream 1 Volatile Suspended soilds /165/
XH1      hetotrophic biomass in influent (mg per L)/0/
XSTO1    storage particulates in influent (mg per L) /0/
XPAO1    poly-phosphate accumulating organisms in influent /0/
XPP1     poly phosphate in influent /0/
XPHA1    poly-hydroxy alkanoates in influent /0/
XA1      Autotrophic biomass in influent (mg per L) /0/
TSS1     stream 1 Total suspended Solids (mg per L as SS) /230.0/
SNH1     stream 1 Ammonium nitrogen (mg per L as N) /25/
SNO1     soluble nitrate and nitrite nitrogen in stream 1 (mg per L) /0/
SPO1     Inorganic soluble phosphorus in influent /5/
SO5      Oxygen concentration in the aerobic compartment /2/

* Parameters of primary clarifier model
c        constant in primary clarifier (day per m) /0.0035/
n        settling index in primary sludge(value between 1-5) /2.3/
k        ettling constant of the primary sludge (65-460 m per day) /400/

* Parameters of secondary clarifier model
nw       settling constant for the final clarifier /1.8/
kw       settling constant for the final clarifier (m per day) /385/
SVI      Sludge volume index (ml per g) /150/
H        Side water depth of final clarifier /3.7/

* 1.4.4 Design parameters for the bio-reactor
ne       Field oxygen transfer efficiency /10/
AIRU     max air input rate (m3 per min air per 1000 m3 volume) /90/
AIRL     min air input rate (m3 per min air per 1000 m3 volume) /20/
fXI      production of XI in endogen. respiration (g COD XI per g COD biomass)/0.2/
YH       aeroic yield of heterotrophic biomass (g COD XH per g COD XSTO)/0.63/
YA       yield of autotrophic biomass per NO3-N (g COD XA per g N SNO)/0.24/

* Cost parameters

BCI      Base cost index /1581/
CI       cost index for 2006 /7688.90/
CRF      capital recovery factor for 8% and 30yrs /0.0888/
OMW      Operating maintenance wages $perhr /8/
PC       Power Cost ($perKWhr) /0.05/
PHr      Pumping head of returned sludge /10/
PHir     Pumping head of internal re-circulation /5/
PE       pumping efficiency /0.8/
UE       unit energy consumption of mixing (kW per m3) /0.014/

* Kinetic Parameters for Bio-P module at T=20oC
qPHA_20 /6/
qPP_20 /1.5/
uPAO_20 /1/
```

```
nNOPAO /0.6/
bPAO_20 /0.2/
nNO_end_PAO /0.33/
bPP_20 /0.2/
nNO_lys_PP /0.33/
bPHA_20 /0.2/
nNOrespPHA /0.33/
KSSPAO /10/
KHCOPAO /0.1/
KPP_PAO /0.05/
KO_PAO /0.2/
KPHA /0.1/
KmaxPAO /0.2/
Ki_PP_PAO /0.05/
KNO_PAO /0.5/
KPO4_PP /0.2/
KPO4_PAO /0.01/
KNH_PAO /0.05/

*Kinetic parameters for ASM3 at 20 0C

kH        hydrolysis rate constant (g CODxs (g CODxh)^-1 d^-1)) /3/
kX        hydrolysis saturation constant (g CODxs (g CODxh)^-1) /1/

*Heterotrophic organisms Xh
kSTO      storage rate constant (g CODss (g CODxh)^-1 d^-1)) /5/
nnox /0.6/
kO2 /0.2/
kNox /0.5/
Ks        Saturation constant for substrate Ss (g CODss m^-3) /2/
KXSTO  saturation constant for XSTO (g CODxsto (g CODxh)^-1) /1/
Uh        Heterotrophic max growth rate of Xh (d^-1) /2/
KNH4    Saturation constant for ammonium SNH4 (g N m^-3) /0.01/
bHO2      Aerobic endogenous respiration rate of Xh (d^-1) /0.2/
bHNox /0.1/
bSTOO2 Aerobic respiration rate for XSTO (d^-1) /0.2/
bSTONox /0.1/

*Autotrophic organisms XA , nitrifying activity
UA Autotrophic max growth rate XA (d^-1)  /1/
KANH4 Ammonium substrate saturation for XA (g N m^-3) /1/
kAO2 /0.5/
bAO2 Aerobic endogenous respiration rate of XA (d^-1) /0.15/
bANOX /0.05/;

parameters
a         constant in christoulas model
b         constant in christoulas model (mg per L)
CODbio            biodegradable COD in steam 1
CODinert          inert COD in steam 1

XI1       particulate inert in stream 1
SI1       soluble inert in stream 1
SS1       readily biodegradable substrate in stream 1
XS1       slowly biodegradable susbstrate in stream 1
qPHA, qPP , uPAO , bPAO , bPP , bPHA;

a=1.71-0.03*T;
b=683.6-21.13*T;
```

```
CODbio=1.71*BOD5;
CODinert=COD-CODbio;
XI1=0.56*VSS;
SI1=CODinert-XI1;
SS1=0.43*CODbio;
XS1=CODbio-SS1;
qPHA=qPHA_20*(EXP(0.04*(T-20)));
qPP=qPP_20*(EXP(0.04*(T-20)));
uPAO=uPAO_20*(EXP(0.07*(T-20)));
bPAO=bPAO_20*(EXP(0.07*(T-20)));
bPP=bPP_20*(EXP(0.07*(T-20)));
bPHA=bPHA_20*(EXP(0.07*(T-20)));

Variables
* primary settling tank
q overflow rate (m per day)
Ap surface area of the primary clarifier(m2)
qf Over flow rate of final clarifier (m per day)
Af surface area of the final clarifier (m**2)
Vanaer , Vanox , Vaer
r,ir,SRTtot,TSS6,SS5,SNH5,SNO5,SPO5,TSS5,Q6,Q98,sludge
AFR Air flow rate (m3 air per min)
Objfun
Q2 flowrate stream 2 (m3 per hour)
Q9,Q8
XI5,XS5,XH5,XSTO5,XPAO5,XPP5,XPHA5,XA5
TSS2 suspended solids in stream 2 (ppm as ss)
TSS8 suspended solids in stream 8 (mg per L as ss)
* Final settler equations
TSS7 suspended solids in stream 7 (ppm as ss)
Qr recycled flow (m3 per hour)
* Other system variables
XS3,XH3,XPAO3,XPP3,XPHA3,TSS3,SS3,SNH3,SPO3,XI4,XS4,XH4,XSTO4,XPAO4,XPP4,XPHA4,X
A4,TSS4,SS4,SNH4,SNO4,SPO4,Qir,anaer,anox
*Reaction Rates
R1aer,R1anox,R1anaer,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12
P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P11
* Reactor design
ROH Oxygen Requiremnet for removal of organic matter (kg per day)
ROA Oxygen Requiremnet associated with nitrification (kg per day)
CCAerT,CCAnoxT,CCAnaerT,CCPST,CCFST,CCAFR,CCDAF,CCPSP,CCRSP,CCISP
OCPST,OCPSP,OCDAF,OCFST,OCRSP,OCISP
MCPST,MCPSP,MCFST,MCRSP,MCISP
PCPSP,PCRSP,PCISP,MEAnoxT,MEAnaerT,DCOST,CCWSP,OCWSP,MCWSP,PCWSP
SRTaer Solids retention time (hr);
Equations
* model of first clarifier
C1 flow balance on the primary clarifier
C2 surface area of the primary clarifier (m^2)
C3 XSS2 suspended solids model of primary clarifier
C4 suspended solids in stream 8 (mg per L as ss)
C5 XSS balance on the primary clarifier
C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,C17,C18,C19,C20,C21,C22,C23,C24,C25
C26,C27,C28,C29,C30,C31,C32,C33,C34,C35,C36,C37,C38,C39,C40,C41,C42,C43,C44
C45,C46,C47,C48,C49,C50,C51,C52,C53,C54,C55,C56,C57,C58,C59,C60,C61,C62,C63
C64,C65,C66,C67,C68,C69,C70,C71,C72,C73,C74,C75,C76,C77,C78,C79,C80,C81,C82
C83,C84,C85,C86,C87,C88,C89,C90,C91,C92,C93,C94,C95,C96,C97,C98,C99,C100,C101
C102,C103,C104,C105,C106,C107,C108,C109,C110,C111,C112,C113,c114,c115;

C1..
```

```
Q1 =e= Q2+Q8;
C2..
Ap=e=(Q2*24)/q;
C3..
TSS2=e=(1-(a*exp((-b/TSS1)-c*q)))*TSS1;
C4..
TSS8=e=((K*(n-1))**(1/n))*(n/(n-1))*((Ap/(Q8*24))**(1/n))*1e3;
C5..
Q1*TSS1 =e= Q2*TSS2 + Q8*TSS8;
C6..
TSS7=e=((Kw*(nw-1))**(1/nw))*(nw/(nw-1))*1000*((Af/((Q9+Qr)*24))**(1/nw));
C7..
TSS6=e=((6.21*log(1e-3*TSS5*SV1))/(0.67*log(H)-log(qf/24)))-26.43;
C8..
0=e=qf-((Q6*24)/Af);
C9..
0=e=Q2-Q6-Q9;
C10..
0=e=((Q2+Qr)*TSS5) - (Q6*TSS6) -((Q9+Qr)*TSS7);
C11..
R1aer=e=kH*(XS5/XH5)*(1/(kX+(XS5/XH5)))*XH5;
C12..
R1anox=e=kH*(XS4/XH4)*(1/(kX+(XS4/XH4)))*XH4;
C13..
R1anaer=e=kH*(XS3/XH3)*(1/(kX+(XS3/XH3)))*XH3;
C14..
R2=e=kSTO*(SS5/(Ks+SS5))*XH5;
C15..
R3=e= kSTO * nnox*(SNO4/(kNox+SNO4))*(SS4/(Ks+SS4))*XH4;
C16..
R4=e=Uh*(SNH5/(KNH4+SNH5))*(XSTO5/XH5)*(1/(KXSTO+(XSTO5/XH5)))*XH5;
C17..
R5=e=Uh*nnox*(SNO4/(kNox+SNO4))*(SNH4/(KNH4+SNH4))*(XSTO4/XH4)*(1/(KXSTO+(XSTO4/
XH4)))*XH4;
C18..
R6=e= bHO2*XH5;
C19..
R7=e=bHNox*(SNO4/(kNox+SNO4))*XH4;
C20..
R8=e=bSTOO2*XSTO5;
C21..
R9=e=bSTONox*(SNO4/(kNox+SNO4))*XSTO4;
C22..
R10=e=UA*(SNH5/(KANH4+SNH5))*XA5;
C23..
R11=e=bAO2*XA5;
C24..
R12=e=bANOX*(SNO4/(kNox+SNO4))*XA4;
C25..
P1=e=qPHA*(SS3/(KSSPAO+SS3))*(XPP3/XPAO3)*(1/(KPP_PAO +(XPP3/XPAO3)))*XPAO3;
C26..
P2=e=qPP*(SPO5/(KPO4_PP+SPO5))*(XPHA5/XPAO5)*(1/(KPHA+(XPHA5/XPAO5)))*(KmaxPAO-
(XPP5/XPAO5))*(1/(Ki_PP_PAO +KmaxPAO-(XPP5/XPAO5)))*XPAO5;
C27..
P3=e= qPP*nNOPAO*(SNO4/(KNO_PAO
+SNO4))*(SPO4/(KPO4_PP+SPO4))*(XPHA4/XPAO4)*(1/(KPHA+(XPHA4/XPAO4)))*(KmaxPAO-
(XPP4/XPAO4))*(1/(Ki_PP_PAO +KmaxPAO-(XPP4/XPAO4)))*XPAO4;
C28..
P4=e=uPAO*(SNH5/(KNH_PAO
+SNH5))*(SPO5/(KPO4_PAO+SPO5))*(XPHA5/XPAO5)*(1/(KPHA+(XPHA5/XPAO5)))*XPAO5;
```

```
C29..
P5=e=uPAO*nNOPAO*(SNO4/(KNO_PAO +SNO4))* (SNH4/(KNH_PAO
+SNH4))*(SPO4/(KPO4_PAO+SPO4))*(XPHA4/XPAO4)*(1/(KPHA+(XPHA4/XPAO4)))*XPAO4;
C30..
P6=e=bPAO*XPAO5;
C31..
P7=e= bPAO*nNO_end_PAO * (SNO4/(KNO_PAO +SNO4))*XPAO4;
C32..
P8=e=bPP*XPP5;
C33..
P9=e=bPP*nNO_lys_PP*(SNO4/KNO_PAO)*XPP4;
C34..
P10=e=bPHA*XPHA5;
C35..
P11=e=bPHA*nNOrespPHA*(SNO4/KNO_PAO)*XPHA4;
C36..
0=e=(Q2*SS1)+(Qr*SS5)-((Q2+Qr)*SS3)+((Vanaer/24)*(R1anaer-P1));
C37..
0=e=((Q2+Qr)*SS3)+(Qir*SS5)-((Qir+Q2+Qr)*SS4)+((Vanox/24)*(R1anox-R3));
C38..
0=e=((Qir+Q2+Qr)*SS4)-((Q2+Qr+Qir)*SS5)+((Vaer/24)*(R1aer-R2));
C39..
0=e=(Q2*XS1*(TSS2/TSS1))+(Qr*XS5*(TSS7/TSS5))-((Q2+Qr)*XS3)+((Vanaer/24)*(-1*R1anaer));
C40..
0=e=((Q2+Qr)*XS3)+(Qir*XS5)-((Qir+Q2+Qr)*XS4)+((Vanox/24)*(-1*R1anox));
C41..
0=e=((Qir+Q2+Qr)*XS4)-((Qir+Q2+Qr)*XS5)+((Vaer/24)*(-1*R1aer));
C42..
0=e=(Q2*SNO1)+(Qr*SNO5)+(Qir*SNO5)-((Qir+Q2+Qr)*SNO4)+((Vanox/24)*(-0.07*R3-0.3*R5-
0.28*R7-0.35*R9-0.28*R12-0.07*P3-0.34*P5-0.28*P7-0.34*P11));
C43..
0=e=((Qir+Q2+Qr)*SNO4)-((Q2+Qr+Qir)*SNO5)+((Vaer/24)*(4.17*R10));
C44..
0=e=(Q2*SNH1)+(Qr*SNH5)-((Q2+Qr)*SNH3)+((Vanaer/24)*(0.01*R1anaer+0.03*P1));
C45..
0=e=((Q2+Qr)*SNH3)+(Qir*SNH5)-((Qir+Q2+Qr)*SNH4)+((Vanox/24)*(0.01*R1anox+0.03*R3-
0.07*R5+0.066*R7+0.066*R12-0.07*P5+0.06*P7));
C46..
0=e=((Qir+Q2+Qr)*SNH4)-((Q2+Qr+Qir)*SNH5)+((Vaer/24)*(0.01*R1aer+0.03*R2-
0.07*R4+0.066*R6-4.24*R10+0.066*R11-0.07*P4+0.066*P6));
C47..
0=e=(Q2*XPAO1*(TSS2/TSS1))+(Qr*XPAO5*(TSS7/TSS5))-((Q2+Qr)*XPAO3);
C48..
0=e=((Q2+Qr)*XPAO3)+(Qir*XPAO5)-((Qir+Q2+Qr)*XPAO4)+((Vanox/24)*(P5-P7));
C49..
0=e=((Qir+Q2+Qr)*XPAO4)-((Qir+Q2+Qr)*XPAO5)+((Vaer/24)*(P4-P6));
C50..
0=e=(Q2*XPP1*(TSS2/TSS1))+(Qr*XPP5*(TSS7/TSS5))-((Q2+Qr)*XPP3)+((Vanaer/24)*(-0.35*P1));
C51..
0=e=((Q2+Qr)*XPP3)+(Qir*XPP5)-((Qir+Q2+Qr)*XPP4)+((Vanox/24)*(P3-P9));
C52..
0=e=((Qir+Q2+Qr)*XPP4)-((Qir+Q2+Qr)*XPP5)+((Vaer/24)*(P2-P8));
C53..
0=e=(Q2*XH1*(TSS2/TSS1))+(Qr*XH5*(TSS7/TSS5))-((Q2+Qr)*XH3);
C54..
0=e=((Q2+Qr)*XH3)+(Qir*XH5)-((Qir+Q2+Qr)*XH4)+((Vanox/24)*(R5-R7));
C55..
0=e=((Qir+Q2+Qr)*XH4)-((Qir+Q2+Qr)*XH5)+((Vaer/24)*(R4-R6));
C56..
```

```
0=e=(Q2*XA1*(TSS2/TSS1))+(Qr*XA5*(TSS7/TSS5))+(Qir*XA5)-
((Qir+Q2+Qr)*XA4)+((Vanox/24)*(-1*R12));
C57..
0=e=((Qir+Q2+Qr)*XA4)-((Qir+Q2+Qr)*XA5)+((Vaer/24)*(R10-R11));
C58..
0=e=(Q2*XSTO1*(TSS2/TSS1))+(Qr*XSTO5*(TSS7/TSS5))+(Qir*XSTO5)-
((Qir+Q2+Qr)*XSTO4)+((Vanox/24)*(0.8*R3-1.85*R5-R9));
C59..
0=e=((Qir+Q2+Qr)*XSTO4)-((Qir+Q2+Qr)*XSTO5)+((Vaer/24)*(0.85*R2-1.6*R4-R8));
C60..
0=e=(Q2*XPHA1*(TSS2/TSS1))+(Qr*XPHA5*(TSS7/TSS5))-((Q2+Qr)*XPHA3)+((Vanaer/24)*(P1));
C61..
0=e=((Q2+Qr)*XPHA3)+(Qir*XPHA5)-((Qir+Q2+Qr)*XPHA4)+((Vanox/24)*(-0.2*P3-2*P5-P11));
C62..
0=e=((Qir+Q2+Qr)*XPHA4)-((Qir+Q2+Qr)*XPHA5)+((Vaer/24)*(-0.2*P2-1.67*P4-P10));
C63..
0=e=(Q2*SPO1)+(Qr*SPO5)-((Q2+Qr)*SPO3)+((Vanaer/24)*(0.005*R1anaer+0.35*P1));
C64..
0=e=((Q2+Qr)*SPO3)+(Qir*SPO5)-((Qir+Q2+Qr)*SPO4)+((Vanox/24)*(0.005*R1anox-
0.014*R5+0.012*R7+0.012*R12-P3-0.014*P5+0.012*P7+P9));
C65..
0=e=((Qir+Q2+Qr)*SPO4)-((Q2+Qr+Qir)*SPO5)+((Vaer/24)*(0.005*R1aer-0.014*R4+0.012*R6-
0.014*R10+0.012*R11-P2-0.014*P4+0.012*P6+P8));
C66..
0=e=(Q2*XI1*(TSS2/TSS1))+(Qr*XI5*(TSS7/TSS5))+(Qir*XI5)-
((Qir+Q2+Qr)*XI4)+((Vanox/24)*(0.2*R7+0.2*R12+0.2*P7));
C67..
0=e=((Qir+Q2+Qr)*XI4)-((Qir+Q2+Qr)*XI5)+((Vaer/24)*(0.2*R6+0.2*R11+0.2*P6));
C68..
0=e=(Q2*TSS2)+(Qr*TSS7)-((Q2+Qr)*TSS3)+((Vanaer/24)*(-0.75*R1anaer-0.53*P1));
C69..
0=e=((Q2+Qr)*TSS3)+(Qir*TSS5)-((Qir+Q2+Qr)*TSS4)+((Vanox/24)*(-0.75*R1anox+0.48*R3-
0.21*R5-0.75*R7-0.6*R9-0.75*R12+3.11*P3-0.3*P5-0.75*P7-3.23*P9-0.6*P11));
C70..
0=e=((Qir+Q2+Qr)*TSS4)-((Qir+Q2+Qr)*TSS5)+((Vaer/24)*(-0.75*R1aer+0.51*R2-0.06*R4-0.75*R6-
0.6*R8+0.9*R10-0.75*R11+3.11*P2-0.102*P4-0.75*P6-3.23*P8-0.6*P10));
C71..
SRTaer=e=(Vaer*TSS5)/((Q6*TSS6)+(Q9*TSS7));
C72..
ROH=e=(Q2*24*1000)*(1e-6)*(SS1+(XS1*(TSS2/TSS1))-SS5)*(1-(((1+fXI*bHO2*(SRTaer/24))*YH) /
(1+bHO2*(SRTaer/24))));
C73..
ROA=e=(Q2*24*1000)*(1e-6)*(SNH1+SNO1-SNH5)*(4.57-(((1+fXI*bAO2*(SRTaer/24))*YA)/
(1+bAO2*(SRTaer/24))));
C74..
AFR=e=(6*((ROH+ROA)/24))/ne;
C75..
Vaer=g=(1000*AFR)/ AIRU;
C76..
Vaer=l=(1000*AFR)/AIRL;
C77..
Vaer=g=((ROH+ROA)/24)/0.1;
*Capital Cost
C78..
CCAerT=e=461*Vaer**0.71;
C79..
CCAnoxT=e=461*Vanox**0.71;
C80..
CCanaerT=e=461*Vanaer**0.71;
C81..
```

```
CCPST=e=824*Ap**0.77;
C82..
CCFST=e=824*Af**0.77;
C83..
CCDAF=e=8533*AFR**0.66;
C84..
CCPSP=e=9870*Q8**0.53;
C85..
CCWSP=e=9870*Q9**0.53;
C86..
CCRSP=e=9870*Qr**0.53;
C87..
CCISP=e=9870*Qir**0.53;
*Operating and Maintenance Cost
C88..
OCPST=e=(17.1*Ap**0.6)+(9.23*Ap**0.6);
C89..
OCPSP=e=(257*Q8**0.41)+(112*Q8**0.43);
C90..
OCWSP=e=(257*Q9**0.41)+(112*Q9**0.43);
C91..
OCDAF=e=(187*AFR**0.48)+(74.4*AFR**0.55);
C92..
OCFST=e=(17.1*Af**0.6)+(9.23*Af**0.6);
C93..
OCRSP=e=(257*Qr**0.41)+(112*Qr**0.43);
C94..
OCISP=e=(257*Qir**0.41)+(112*Qir**0.43);
*Material  Supply
C95..
MCPST=e=8.62*Ap**0.76;
C96..
MCPSP=e=214*Q8**0.64;
C97..
MCWSP=e=214*Q9**0.64;
C98..
MCFST=e=8.62*Af**0.76;
C99..
MCRSP=e=214*Qr**0.64;
C100..
MCISP=e=214*Qir**0.64;
*Power Cost
C101..
PCPSP=e=(23.85*Q8*PHir)/PE;
C102..
PCWSP=e=(23.85*Q9*PHir)/PE;
C103..
PCRSP=e=(23.85*Qr*PHr)/PE;
C104..
PCISP=e=(23.85*Qir*PHir)/PE;
* Mixing Energy
C105..
MEAnoxT=e=UE*Vanox;
C106..
MEAnaerT=e=UE*Vanaer;
* Disposal Cost
C107..
DCOST=e=0.3*(TSS7*Q9+TSS8*Q8)*(1/1000)*24*365;

C108.
```

```
Objfun=e=(((CI*CRF)/BCI)*(CCAerT+CCAnoxT+CCanaerT+CCPST+CCFST+CCDAF+CCPSP+CCRS
P+CCISP+CCWSP))
+(OMW*(OCPST+OCPSP+OCDAF+OCFST+OCRSP+OCISP+OCWSP))+((CI/BCI)*(MCPST+MCPSP
+MCFST+MCRSP+MCISP+MCWSP))
+(PC*(PCPSP+PCRSP+PCISP+PCWSP))+(PC*24*365*(MEAnoxT+MEAnaerT))+DCOST;
C109..
Qir=e=ir*Q2;
C110..
Qr=e=r*Q2;
C111..
Vanaer=e=anaer*(Vaer+Vanaer+Vanox);
C112..
Vanox=e=anox*(Vaer+Vanaer+Vanox);
C113..
SRTtot=e=(1/24)*((Vaer*TSS5+Vanox*TSS4+Vanaer*TSS3))/((Q6*TSS6)+(Q9*TSS7));
C114..
Sludge=e=(TSS7*Q9+TSS8*Q8)*(1/1000)*24;
C115..
Q98=e=Q9+Q8;
*initial values
Q2.l=1498.986;  Q8.l= 1.014;
Qr.l=352.136;   Q6.l=1487.943;
Q9.l=11.043;    TSS2.l=176.039;
TSS8.l=80000.000;       q.l=119.830;
Ap.l=300.224;   TSS6.l=15.000;
TSS7.l=21371.804;       qf.l=21.940 ;
Af.l=1627.671;  Vanaer.l=1137.788;
Vanox.l=5167.271;       Vaer.l=4406.028;
Qir.l=4496.958; SS3.l=109.611;
XS3.l=287.537;  XH3.l=1574.062;
XPP3.l=90.390;  XPAO3.l=338.114;
SNH3.l=21.825;  XPHA3.l=85.860;
SPO3.l=18.189;  TSS3.l=4172.806;
SS5.l=0.249;    XS5.l=179.262;
XH5.l=1628.094; XSTO5.l=512.797;
XA5.l=113.105;  XPHA5.l=47.321;
XPAO5.l=349.720;        XPP5.l=108.013;
XI5.l=2007.452; SNH5.l=1.000;
SNO5.l=7;       SPO5.l=0.042;
TSS5.l=4205.076;        SS4.l=12.285;
XS4.l=193.272;  XH4.l=1615.179;
SNH4.l=8.102;   SNO4.l=0.180;
XSTO4.l=529.356;        XA4.l=111.960;
SPO4.l=2.400;   XPHA4.l=55.624;
XPAO4.l=347.270;        XPP4.l=105.840;
XI4.l=2005.066; TSS4.l=4206.831;
R1aer.l=484.445; R1anox.l=517.849;
R1anaer.l=729.375;      R2.l=900.623;
R3.l=1103.248;  R4.l=772.217;
R5.l=126.508;   R6.l=325.619;
R7.l=42.762;    R8.l=102.559;
R9.l=14.015;    R10.l=56.553;
R11.l=16.966;   R12.l=1.482;
P1.l=1566.157;  P2.l=96.761;
P3.l=89.948;    P4.l=154.667;
P5.l=33.613;    P6.l=69.944;
P7.l=6.068;     P8.l=21.6032;
P9.l=2.515;     P10.l=9.464;
P11.l=1.322;
*Bounds
```

```
Q2.lo=1e-6;       Q2.up=1e6;
Q8.lo=1e-6;       Q8.up=1e6;
TSS2.lo=1e-6;     TSS2.up=1e6;
TSS8.lo=1e-6;     TSS8.up=80000;
q.lo=30;          q.up=120;
Ap.lo=1e-6;       Ap.up=1e6;
Qr.lo=1e-6;       Qr.up=1e6;
Q9.lo=1e-6;       Q9.up=1e6;
TSS7.lo=1e-6;     TSS7.up=1e6;
qf.lo=16;         qf.up=32;
Af.lo=1e-6;       Af.up=1e6;
Q2.lo=1e-6;       Q2.up=1e6;
Q8.lo=1e-6;       Q8.up=1e6;
Vaer.lo=1e-6;     Vaer.up=1e6;
Qir.lo=1e-6;      Qir.up=1e6;
Vanox.lo=1e-6;    Vanox.up=1e6;
Vanaer.lo=1e-6;   Vanaer.up=1e6;
XS3.lo=1e-6;      XS3.up=1e6;
XH3.lo=1e-6;      XH3.up=1e6;
XPAO3.lo=1e-6;    XPAO3.up=1e6;
XPP3.lo=1e-6;     XPP3.up=1e6;
XPHA3.lo=1e-6;    XPHA3.up=1e6;
TSS3.lo=1e-6;     TSS3.up=1e6;
SS3.lo=1e-6;      SS3.up=1e6;
SNH3.lo=1e-6;     SNH3.up=1e6;
SPO3.lo=1e-6;     SPO3.up=1e6;
XI4.lo=1e-6;      XI4.up=1e6;
XS4.lo=1e-6;      XS4.up=1e6;
XH4.lo=1e-6;      XH4.up=1e6;
XSTO4.lo=1e-6;    XSTO4.up=1e6;
XPAO4.lo=1e-6;    XPAO4.up=1e6;
XPP4.lo=1e-6;     XPP4.up=1e6;
XPHA4.lo=1e-6;    XPHA4.up=1e6;
XA4.lo=1e-6;      XA4.up=1e6;
TSS4.lo=1e-6;     TSS4.up=1e6;
SS4.lo=1e-6;      SS4.up=1e6;
SNH4.lo=1e-6;     SNH4.up=1e6;
SNO4.lo=1e-6;     SNO4.up=1e6;
SPO4.lo=1e-6;     SPO4.up=1e6;
XI5.lo=1e-6;      XI5.up=1e6;
XS5.lo=1e-6;      XS5.up=1e6;
XSTO5.lo=1e-6;    XSTO5.up=1e6;
XPAO5.lo=1e-6;    XPAO5.up=1e6;
XPHA5.lo=1e-6;    XPHA5.up=1e6;
XH5.lo=1e-6;      XH5.up=1e6;
XA5.lo=1e-6;      XA5.up=1e6;
SS5.lo=1e-6;      SS5.up=0.5;
SNH5.lo=1e-6;     SNH5.up=1;
SNO5.lo=1e-6;     SNO5.up=7;
SPO5.lo=1e-6;     SPO5.up=1;
TSS6.lo=1e-6;     TSS6.up=15;
XPP5.lo=1e-6;     XPP5.up=1e6;
TSS5.lo=3000;     TSS5.up=5000;
R1aer.lo=1e-6;    R1aer.up=1e6;
R1anox.lo=1e-6;   R1anox.up=1e6;
R1anaer.lo=1e-6;  R1anaer.up=1e6;
R2.lo=1e-6;       R2.up=1e6;
R3.lo=1e-6;       R3.up=1e6;
R4.lo=1e-6;       R4.up=1e6;
R5.lo=1e-6;       R5.up=1e6;
```

```
R6.lo=1e-6;      R6.up=1e6;
R7.lo=1e-6;      R7.up=1e6;
R8.lo=1e-6;      R8.up=1e6;
R9.lo=1e-6;      R9.up=1e6;
R10.lo=1e-6;     R10.up=1e6;
R11.lo=1e-6;     R11.up=1e6;
R12.lo=1e-6;     R12.up=1e6;
P1.lo=1e-6;      P1.up=1e6;
P2.lo=1e-6;      P2.up=1e6;
P3.lo=1e-6;      P3.up=1e6;
P4.lo=1e-6;      P4.up=1e6;
P5.lo=1e-6;      P5.up=1e6;
P6.lo=1e-6;      P6.up=1e6;
P7.lo=1e-6;      P7.up=1e6;
P8.lo=1e-6;      P8.up=1e6;
P9.lo=1e-6;      P9.up=1e6;
P10.lo=1e-6;     P10.up=1e6;
P11.lo=1e-6;     P11.up=1e6;
SRTaer.lo=24;    SRTaer.up=480;
ROH.lo=1e-6;     ROH.up=1e6;
ROA.lo=1e-6;     ROA.up=1e6;
AFR.lo=1e-6;     AFR.up=1e6;
ir.lo=1;  ir.up=1e6;
r.lo=0.2; r.up=0.5;
SRTtot.lo=4;     SRTtot.up=27;
Display
X11,SS1,XS1;
model BioP12 /all/ ;
option nlp = CONOPT2;
solve BioP12 using nlp minimizing Objfun ;
```

Appendix B GAMS Model Output File

```
MODEL STATISTICS

BLOCKS OF EQUATIONS   115   SINGLE EQUATIONS    115
BLOCKS OF VARIABLES   119   SINGLE VARIABLES    119
NON ZERO ELEMENTS     613   NON LINEAR N-Z      484
DERIVATIVE POOL        21   CONSTANT POOL       103
CODE LENGTH          6881


GENERATION TIME    =     0.020 SECONDS   1.9 Mb    WIN197-119


EXECUTION TIME     =     0.020 SECONDS   1.9 Mb    WIN197-119
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G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m


         S O L V E      S U M M A R Y

   MODEL   BioP12          OBJECTIVE  Objfun
   TYPE    NLP             DIRECTION  MINIMIZE
   SOLVER  CONOPT2         FROM LINE  796

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE         2344138.6389

 RESOURCE USAGE, LIMIT          0.129      1000.000
 ITERATION COUNT, LIMIT        46         10000
 EVALUATION ERRORS              0             0


  C O N O P T 2   Windows NT/95/98  version 2.071F-007-042
  Copyright (C)   ARKI Consulting and Development A/S
                  Bagsvaerdvej 246 A
                  DK-2880 Bagsvaerd, Denmark

 Using default control program.


 ** Warning **  The variance of the derivatives in the initial
                point is large (= 4.7 ). A better initial
                point, a better scaling, or better bounds on the
                variables will probably help the optimization.


 ** Optimal solution. There are no superbasic variables.


 CONOPT time Total                          0.121 seconds
   of which: Function evaluations           0.059 = 48.4%
             Derivative evaluations         0.000 =  0.0%
```

```
Work length =    0.32 Mbytes
   Estimate =    0.32 Mbytes
   Max used =    0.17 Mbytes

                  LOWER     LEVEL     UPPER    MARGINAL

---- EQU C1     -1500.000 -1500.000 -1500.000  -556.269
---- EQU C2          .         .         .      85.518
---- EQU C3       230.000   230.000   230.000   312.599
---- EQU C4          .         .         .      -0.080
---- EQU C5     -3.450E+5 -3.450E+5 -3.450E+5    -2.707
---- EQU C6          .         .         .      14.139
---- EQU C7       -26.430   -26.430   -26.430  6268.534
---- EQU C8          .         .         .   -1.225E+4
---- EQU C9          .         .         .     140.652
---- EQU C10         .         .         .       2.353
---- EQU C11         .         .         .      13.511
---- EQU C12         .         .         .       2.625
---- EQU C13         .         .         .       0.173


                  LOWER     LEVEL     UPPER    MARGINAL

---- EQU C14         .         .         .       0.832
---- EQU C15         .         .         .     -46.833
---- EQU C16         .         .         .    -122.823
---- EQU C17         .         .         .    -400.109
---- EQU C18         .         .         .     546.917
---- EQU C19         .         .         .     388.523
---- EQU C20         .         .         .     275.603
---- EQU C21         .         .         .     -35.281
---- EQU C22         .         .         .    3998.976
---- EQU C23         .         .         .   -3486.917
---- EQU C24         .         .         .   -4771.753
---- EQU C25         .         .         .     -42.451
---- EQU C26         .         .         .      61.485
---- EQU C27         .         .         .       1.565
---- EQU C28         .         .         .    -162.664
---- EQU C29         .         .         .    -395.351
---- EQU C30         .         .         .     874.092
---- EQU C31         .         .         .     695.012
---- EQU C32         .         .         .      25.736
---- EQU C33         .         .         .      32.775
---- EQU C34         .         .         .     436.107
---- EQU C35         .         .         .     182.849
---- EQU C36         .         .         .       1.045
---- EQU C37         .         .         .       1.052
---- EQU C38         .         .         .       1.115
---- EQU C39         .         .         .       0.678
---- EQU C40         .         .         .       0.678
---- EQU C41         .         .         .       0.677
---- EQU C42         .         .         .       4.858
---- EQU C43         .         .         .      81.569
---- EQU C44         .         .         .      80.860
---- EQU C45         .         .         .      80.860
---- EQU C46         .         .         .      80.862
---- EQU C47         .         .         .      -0.785
---- EQU C48         .         .         .      -0.674
---- EQU C49         .         .         .      -0.673
```

```
---- EQU C50        .      .      .      -0.397
---- EQU C51        .      .      .      -0.385
---- EQU C52        .      .      .      -0.385
---- EQU C53        .      .      .       1.147
---- EQU C54        .      .      .       1.147
---- EQU C55        .      .      .       1.151
---- EQU C56        .      .      .      23.629
---- EQU C57        .      .      .      23.638
---- EQU C58        .      .      .      -2.504
---- EQU C59        .      .      .      -2.493
---- EQU C60        .      .      .      -3.405
---- EQU C61        .      .      .      -3.405
---- EQU C62        .      .      .      -3.388
---- EQU C63        .      .      .       4.909
---- EQU C64        .      .      .       4.909
---- EQU C65        .      .      .       4.909
---- EQU C66        .      .      .        EPS
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General Algebraic Modeling System


             LOWER    LEVEL    UPPER   MARGINAL

---- EQU C67        .      .      .        EPS
---- EQU C68        .      .      .       1.595
---- EQU C69        .      .      .       1.595
---- EQU C70        .      .      .       1.595
---- EQU C71        .      .      .    1090.392
---- EQU C72        .      .      .      55.104
---- EQU C73        .      .      .      55.104
---- EQU C74        .      .      .     434.881
---- EQU C75        .         1435.067    +INF      .
---- EQU C76                   -INF  -8610.400      .      .
---- EQU C77        .      .      +INF   106.157
---- EQU C78        .      .      .       0.432
---- EQU C79        .      .      .       0.432
---- EQU C80        .      .      .       0.432
---- EQU C81        .      .      .       0.432
---- EQU C82        .      .      .       0.432
---- EQU C83        .      .      .       0.432
---- EQU C84        .      .      .       0.432
---- EQU C85        .      .      .       0.432
---- EQU C86        .      .      .       0.432
---- EQU C87        .      .      .       0.432
---- EQU C88        .      .      .       8.000
---- EQU C89        .      .      .       8.000
---- EQU C90        .      .      .       8.000
---- EQU C91        .      .      .       8.000
---- EQU C92        .      .      .       8.000
---- EQU C93        .      .      .       8.000
---- EQU C94        .      .      .       8.000
---- EQU C95        .      .      .       4.863
---- EQU C96        .      .      .       4.863
---- EQU C97        .      .      .       4.863
---- EQU C98        .      .      .       4.863
---- EQU C99        .      .      .       4.863
---- EQU C100       .      .      .       4.863
---- EQU C101       .      .      .       0.050
---- EQU C102       .      .      .       0.050
```

```
---- EQU C103      .      .      .      0.050
---- EQU C104      .      .      .      0.050
---- EQU C105      .      .      .    438.000
---- EQU C106      .      .      .    438.000
---- EQU C107      .      .      .      1.000
---- EQU C108      .      .      .      1.000
---- EQU C109      .      .      .   -431.781
---- EQU C110      .      .      .        EPS
---- EQU C111      .      .      .        EPS
---- EQU C112      .      .      .        EPS
---- EQU C113      .      .      .        EPS
---- EQU cl14      .      .      .        EPS
---- EQU cl15      .      .      .        EPS


                    LOWER          LEVEL          UPPER          MARGINAL

---- VAR q          30.000         120.000        120.000        -154.647
---- VAR Ap         1.0000E-6      299.797        1.0000E+6      .
---- VAR qf         16.000         21.940         32.000         .
---- VAR Af         1.0000E-6      1627.970       1.0000E+6      .
---- VAR Vanaer     1.0000E-6      1005.639       1.0000E+6      .
---- VAR Vanox      1.0000E-6      5508.552       1.0000E+6      .
---- VAR Vaer       1.0000E-6      4305.200       1.0000E+6      .
---- VAR r          0.200          0.235          0.500          .
---- VAR ir         1.000          3.000          3.000          -6.472E+5
---- VAR SRTtot     4.000          7.501          27.000         .
---- VAR TSS6       1.0000E-6      15.000         15.000         -1.023E+4
---- VAR SS5        1.0000E-6      0.246          0.500          .
---- VAR SNH5       1.0000E-6      1.000          1.000          -1.527E+4
---- VAR SNO5       1.0000E-6      7.000          7.000          -4.943E+5
---- VAR SPO5       1.0000E-6      1.000          1.000          -6634.071
---- VAR TSS5       3000.000       4205.263       5000.000       .
---- VAR Q6         -INF           1488.206       +INF           .
---- VAR Q98        -INF           11.794         +INF           .
---- VAR sludge     -INF           7474.727       +INF           .
---- VAR AFR        1.0000E-6      258.312        1.0000E+6      .
---- VAR Objfun     -INF           2.3441E+6      +INF           .
---- VAR Q2         1.0000E-6      1498.986       1.0000E+6      .
---- VAR Q9         1.0000E-6      10.780         1.0000E+6      .
---- VAR Q8         1.0000E-6      1.014          1.0000E+6      .
---- VAR XI5        1.0000E-6      2048.696       1.0000E+6      .
---- VAR XS5        1.0000E-6      175.460        1.0000E+6      .
---- VAR XH5        1.0000E-6      1871.844       1.0000E+6      .
---- VAR XSTO5      1.0000E-6      592.021        1.0000E+6      .
---- VAR XPAO5      1.0000E-6      118.948        1.0000E+6      .
---- VAR XPP5       1.0000E-6      87.038         1.0000E+6      .
---- VAR XPHA5      1.0000E-6      11.185         1.0000E+6      .
---- VAR XA5        1.0000E-6      116.181        1.0000E+6      .
---- VAR TSS2       1.0000E-6      176.072        1.0000E+6      .
---- VAR TSS8       1.0000E-6      79949.137      80000.000      .
---- VAR TSS7       1.0000E-6      21369.925      1.0000E+6      .
---- VAR Qr         1.0000E-6      352.523        1.0000E+6      .
---- VAR XS3        1.0000E-6      285.901        1.0000E+6      .
---- VAR XH3        1.0000E-6      1811.093       1.0000E+6      .
---- VAR XPAO3      1.0000E-6      115.088        1.0000E+6      .
---- VAR XPP3       1.0000E-6      79.467         1.0000E+6      .
---- VAR XPHA3      1.0000E-6      24.384         1.0000E+6      .
---- VAR TSS3       1.0000E-6      4191.567       1.0000E+6      .
---- VAR SS3        1.0000E-6      134.216        1.0000E+6      .
```

```
---- VAR SNH3         1.0000E-6      21.005         1.0000E+6     .
---- VAR SPO3         1.0000E-6      9.069          1.0000E+6     .
---- VAR XI4          1.0000E-6      2046.347       1.0000E+6     .
---- VAR XS4          1.0000E-6      189.058        1.0000E+6     .
---- VAR XH4          1.0000E-6      1857.256       1.0000E+6     .
---- VAR XSTO4        1.0000E-6      611.016        1.0000E+6     .
---- VAR XPAO4        1.0000E-6      118.084        1.0000E+6     .

---- VAR XPP4         1.0000E-6      85.283         1.0000E+6     .
---- VAR XPHA4        1.0000E-6      14.263         1.0000E+6     .
---- VAR XA4          1.0000E-6      115.032        1.0000E+6     .
---- VAR TSS4         1.0000E-6      4206.333       1.0000E+6     .
---- VAR SS4          1.0000E-6      15.608         1.0000E+6     .
---- VAR SNH4         1.0000E-6      8.049          1.0000E+6     .
---- VAR SNO4         1.0000E-6      0.155          1.0000E+6     .
---- VAR SPO4         1.0000E-6      2.943          1.0000E+6     .
---- VAR Qir          1.0000E-6      4496.958       1.0000E+6     .
---- VAR anaer        -INF           0.093          +INF      .
---- VAR anox         -INF           0.509          +INF      .
---- VAR R1aer        1.0000E-6      481.267        1.0000E+6     .
---- VAR R1anox       1.0000E-6      514.774        1.0000E+6     .
---- VAR R1anaer      1.0000E-6      740.766        1.0000E+6     .
---- VAR R2           1.0000E-6      1024.945       1.0000E+6     .
---- VAR R3           1.0000E-6      1170.566       1.0000E+6     .
---- VAR R4           1.0000E-6      890.633        1.0000E+6     .
---- VAR R5           1.0000E-6      130.598        1.0000E+6     .
---- VAR R6           1.0000E-6      374.369        1.0000E+6     .
---- VAR R7           1.0000E-6      44.019         1.0000E+6     .
---- VAR R8           1.0000E-6      118.404        1.0000E+6     .
---- VAR R9           1.0000E-6      14.482         1.0000E+6     .
---- VAR R10          1.0000E-6      58.090         1.0000E+6     .
---- VAR R11          1.0000E-6      17.427         1.0000E+6     .
---- VAR R12          1.0000E-6      1.363          1.0000E+6     .
---- VAR P1           1.0000E-6      599.252        1.0000E+6     .
---- VAR P2           1.0000E-6      79.536         1.0000E+6     .
---- VAR P3           1.0000E-6      14.269         1.0000E+6     .
---- VAR P4           1.0000E-6      54.357         1.0000E+6     .
---- VAR P5           1.0000E-6      9.099          1.0000E+6     .
---- VAR P6           1.0000E-6      23.790         1.0000E+6     .
---- VAR P7           1.0000E-6      1.847          1.0000E+6     .
---- VAR P8           1.0000E-6      17.408         1.0000E+6     .
---- VAR P9           1.0000E-6      1.748          1.0000E+6     .
---- VAR P10          1.0000E-6      2.237          1.0000E+6     .
---- VAR P11          1.0000E-6      0.292          1.0000E+6     .
---- VAR ROH          1.0000E-6      6542.617       1.0000E+6     .
---- VAR ROA          1.0000E-6      3789.863       1.0000E+6     .
---- VAR CCAerT       -INF           1.7532E+5      +INF      .
---- VAR CCAnoxT      -INF           2.0885E+5      +INF      .
---- VAR CCAnaerT     -INF           62435.974      +INF      .
---- VAR CCPST        -INF           66540.251      +INF      .
---- VAR CCFST        -INF           2.4485E+5      +INF      .
---- VAR CCDAF        -INF           3.3352E+5      +INF      .
---- VAR CCPSP        -INF           9943.170       +INF      .
---- VAR CCRSP        -INF           2.2097E+5      +INF      .
---- VAR CCISP        -INF           8.5185E+5      +INF      .
---- VAR OCPST        -INF           806.394        +INF      .
---- VAR OCPSP        -INF           371.146        +INF      .
---- VAR OCDAF        -INF           4268.025       +INF      .
---- VAR OCFST        -INF           2225.557       +INF      .
---- VAR OCRSP        -INF           4241.083       +INF      .
```

```
---- VAR OCISP        -INF         12252.502      +INF    .
---- VAR MCPST        -INF         657.501        +INF    .
---- VAR MCPSP        -INF         215.917        +INF    .
---- VAR MCFST        -INF         2378.803        +INF          .
---- VAR MCRSP        -INF         9132.999       +INF    .
---- VAR MCISP        -INF         46588.832      +INF    .
---- VAR PCPSP        -INF         151.154        +INF    .
---- VAR PCRSP        -INF         1.0510E+5      +INF    .
---- VAR PCISP        -INF         6.7033E+5      +INF    .
---- VAR MEAnoxT      -INF         77.120         +INF    .
---- VAR MEAnaerT     -INF         14.079         +INF    .
---- VAR DCOST        -INF         8.1848E+5      +INF    .
---- VAR CCWSP        -INF         34802.716      +INF    .
---- VAR OCWSP        -INF         992.611        +INF    .
---- VAR MCWSP        -INF         980.166        +INF    .
---- VAR PCWSP        -INF         1606.950       +INF    .
---- VAR SRTaer       24.000       71.645         480.000   .

**** REPORT SUMMARY :       0     NONOPT
                    0 INFEASIBLE
                    0  UNBOUNDED
                    0     ERRORS
EXECUTION TIME      =       0.010 SECONDS    0.7 Mb      WIN197-119
USER: GAMS Development Corporation, Washington, DC   G871201:0000XX-XXX
     Free Demo,  202-342-0180,  sales@gams.com,  www.gams.com   DC9999

**** FILE SUMMARY

INPUT       C:\DOCUMENTS AND SETTINGS\NAWRAS\MY DOCUMENTS\MY
THESIS\GAMS\BIOP12.G
        MS
OUTPUT     C:\WINDOWS\GAMSDIR\BIOP12.LST
```

توطئة

يتزايد الطلب يوما بعد يوم من أجل تحسين نوعية المياه المعالجة خصوصا إذا كانت تصرف إلى مياه البحر. إن المياه المعالجة التي يتم صرفها إلى مياه البحر يجب أن تكون محتوية على أقل مستوى ممكن من المواد الغذائية و ذلك من أجل تجنب حدوث ظاهرة نمو النباتات الطحلبية التي تؤدي إلى نفاذ الاكسجين و بالتالي الإضرار بالكائنات البحرية كالشعاب المرجانية.

بالإضافة إلى ما ذكر آنفا ، يتزايد الطلب على تجنب إستخدام المواد الكيميائية (نظرا لتكلفتها العالية) لمعالجة المياه المستخدمة و الإعتماد قدر الإمكان على طرق المعالجة البيولوجية من أجل تحقيق المستوى المطلوب من المواد الغذائية في المياه المعالجة المصروفه إلى البحر.

يتم في هذه الأطروحة إجراء دراسة شاملة لكيفية عمل تصميم إقتصادي بأسلوب تعاظمي و بإستخدام النماذج الزمنية للحمأة المنشطة (ASM) لعمليات معالجة المياه المستخدمة الغنية بالمواد الغذائية آخذين بنظر الإعتبار تكاليف رأس المال و التشغيل.

لقد بينت هذه الدراسة أن نسبة التدوير الداخلي للمياه المستخدمة (من المفاعل الهوائي إلى المفاعل النيتروجيني) داخل محطة المعالجة هو أحد العوامل المهمة التي تساهم بشكل كبير في تحقيق تصميم اقتصادي لمنظومة المعالجة.

تقترح الدراسة اتباع فلسفة جديدة في تصميم منظومات المعالجة القادرة على إزالة المواد الغذائية بحيث يؤخذ بنظر الإعتبار تكاليف رأس المال و التشغيل. لقد بينت نتائج الدراسة انه يمكن تحقيق تصميم اقتصادي بشكل أكبر اذا أخذ بنظر الإعتبار درجات الحرارة القصوى للمياه المستخدمة بدلا من المفهوم السائد الذي يعتبر درجات الحرارة الدنيا في التصميم.

جامعة الإمارات العربية المتحدة

عمادة الدراسات العليا

برنامج ماجستير موارد المياه

نمذجة بأسلوب تعاظمي بإستخدام تقنيات النمذجة الزمنية المتقدمة لمعالجة المياه المستخدمة الغنية بالعناصر الغذائية

نورس نبيل الغزالي

رسالة مقدمة إلى عمادة الدراسات العليا

استكمالا لمتطلبات الحصول على درجة الماجستير في علوم موارد المياه

يونيو 2006