THE USE OF ACTIVATED SLUDGE MODEL NO. 3 TO

MODEL AN ACTIVATED SLUDGE UNIT AT AN

INDUSTRIAL WASTEWATER TREATMENT

FACILITY

By

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CHAPTER I

INTRODUCTION

Introduction

Biological treatment of waste is a very important aspect of public health. There are varying types of treatment processes that are found today in wastewater treatment. Activated sludge is a very effective and common way to remove pollutants from wastewater. Activated sludge is a secondary wastewater treatment process used to remove biochemical oxygen demand (BOD) from wastewater. More recently the activated sludge process has been modified to remove nutrients from wastewater as well.

In a wastewater stream, such as a municipal wastewater stream, there are high amounts of organic material and ammonium. The organic material is the "food" for microorganisms. Microorganisms utilize the organic material and oxygen for energy and reproduction. Ammonium can be utilized by certain bacteria in such a way that will create an oxygen demand. Therefore, when this waste stream is emitted into the environment, it will exert an oxygen demand on the receiving water. Lower oxygen will dramatically affect the ecology of surface water. Therefore, this waste source must be degraded prior to entering the environment.

An activated sludge treatment process creates a controlled environment where this waste can be degraded. A waste stream will enter a reactor or reactors where the waste will be utilized by bacteria. The energy will be used for either cell maintenance or reproduction. This culture of bacteria will then be settled out in a secondary clarifier and pumped out of the system. When the waste stream leaves the secondary treatment process it is significantly lower in oxygen demanding materials.

There are two different waste streams that must be treated prior to discharge into the environment. The more common waste stream is municipal waste. Municipal waste is typically high in primary settle able solids, degradable organic material and nutrients. Municipal waste streams tend to be homogenous from facility to facility.

Typically an industrial waste stream is high in complex organic materials and toxics. Although, industrial waste streams vary a great deal. Additionally, industrial waste streams tend to have a lower flow when compared to municipal waste streams. The treatment of municipal and industrial biological treatment process is similar. Therefore both waste streams can be modeled mathematically in similar fashion. For this paper, an investigation will be into treatment of an industrial waste stream. The investigation will be conducted with an existing industrial waste stream. Data was collected from the industrial wastewater treatment facility.

Objective

The objective of this research is to (I) introduce the Activated Sludge Models (ASM), (II) examine the validity of Activated Sludge Model No. 3 (ASM 3), (III) apply ASM 3 to a specific industrial activated sludge unit to determine if the model accurately predicts the effluent ammonium concentration, (IV) determine the ammonium concentration sensitivity when stoichiometric parameters are varied, and (V) investigate changes in model inputs to reduce the effluent concentration of ammonium.

CHAPTER II

REVIEW OF LITERATURE

Activated Sludge Model

Biodegradation involves different types of bacteria populations and many input constituents. Necessary constituents must be present and bacteria must be cultured in a specific way in order to encourage degradation of organic material. The activated sludge process mirrors what occurs in nature, but in a controlled environment. What can occur in weeks in the natural environment can be controlled through wastewater treatment plant operations to occur in hours. Therefore, the activated sludge process is a complex operation.

With the advent of modern biology and chemistry coupled with the creation of the Clean Water Act, there has been a need to model accurately the activated sludge process. Engineers have made assumptions to simplify this process to create a manageable model. The Activated Sludge Models (ASM) describe specific types of bacterial behavior, with respect to uptake of organic material and nutrients. The Activated Sludge Models have been shown to accurately describe these processes in an effective way. (Dold et al. 1980)

Activated Sludge Model No. 1 was developed to model BOD and nitrogen removal. Activated Sludge Model No. 1 did not effectively describe all nutrient removal. Therefore Activated Sludge Model No. 2 was developed to incorporate, more accurately, biological nutrient removal of nitrogen and phosphorus. Although, Activated Sludge Model No. 2 was far more complex which created model operational difficulties. Activated Sludge Model No. 3 was developed to incorporate the simplicity of Activated Sludge Model No. 1 along with the accurate description of nutrient removal that is provided in Activated Sludge Model No. 2.

Activated Sludge Model No. 1

The Activated Sludge Model No. 2 (or ASM 2) was expanded from the Activated Sludge Model No. 1 (or ASM 1). Therefore, it is important to first understand ASM 1 to gain the necessary foundation for the ASM 2. (Dold et al. 1980)

The Activated Sludge Model No. 1 was first developed in the early 1980s to be a comprehensive wastewater modeling tool. A group of environmental scientists was formed under the direction of the International Association of Water Quality (or IAWQ) to formulate the ASM 1. The model incorporated BOD removal, nitrification, and de-nitrification of the wastewater. The ASM1 is a matrix format model that utilizes existing and accepted wastewater treatment formulas. These wastewater formulas are derived from a macro analysis of microbiology. The bacterial culture that is grown in the wastewater treatment facility is broken into two different cultures: the heterotrophic biomass and the autotrophic biomass (nitrifying bacteria). These two cultures are then modeled in time as they degrade substrate and remove nitrogen from the waste stream. ASM 1 uses 13 wastewater characteristics to define the model's inputs. These characteristics are to be obtained experimentally from data gathered from the wastewater treatment reactor that is to be modeled. (Metcalf et al. 2003) (Dold et al. 1986) (Dold et al. 1980)

The characteristics are:

X_i = Inert particulate organic matter (mg/L)

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This is the amount of non re-actable organic material present in the influent. This is highly dependent on the wastewater source. This is typically the larger organic particulate material that will settle in the secondary clarifier.

X_s = Slowly biodegradable substrate (mg/L as COD)

This is the amount of organic material that is smaller than the particulate organic matter but not dissolved into solution that is present in the influent. This is another variable that is highly dependent on the wastewater source. This material will eventually be degraded in the reactor if present for enough time. If the material is not degraded it will settle out in the secondary clarifier.

$X_{B,H}$ = Heterotrophic biomass (mg/L as COD)

Heterotrophic biomass is the concentration of bacteria in the reactor that uses organic carbon as the carbon source to create new biomass. These are the bacteria that utilize substrate in an aerobic reactor. This concentration can be controlled through normal operation of the wastewater treatment plant (WWTP).

$X_{B,A}$ = Autotrophic biomass (mg/L as COD)

Autotrophic biomass is the concentration of bacteria in the reactor that uses carbon dioxide (or other carbon compounds) as the carbon source for reproduction. These are the nitrifying bacteria. This concentration can be controlled through normal operation of the WWTP.

X_D = Debris from biomass death and lysis (mg/L as COD)

This is the concentration of dead biomass in the reactor/ reactors. This can be controlled through normal WWTP operations.

S_i = Inert soluble organic matter (mg/L as COD)

This is the concentration of organic material present in the influent that will not biodegrade in the reactor. This is another variable that depends highly on the wastewater source.

S_s = Readily biodegradable substrate (mg/L as COD)

This is the easily biodegradable organic material found in the influent. This is essentially the carbon source utilized by the heterotrophic biomass. The amount present in the influent will depend highly on the wastewater source.

S_o = Dissolved oxygen (mg/L as O_2)

The dissolved oxygen concentration is the amount present in the reactor/ reactors. The value can typically be controlled through normal WWTP operations.

S_{NO} = Nitrate-nitrogen (mg/L as N)

This is the influent nitrate concentration. This value will depend on the wastewater source.

S_{NH} = Ammonia-nitrogen (mg/L as N)

Ammonia-nitrogen is the influent ammonia concentration.

S_{NS} = Soluble biodegradable organic nitrogen (mg/L as N)

Soluble organic nitrogen is the concentration of dissolved degradable nitrogen present in the influent. The amount depends on the wastewater source.

X_{NS} = Particulate degradable organic nitrogen (mg/L as N)

This is the amount of non-dissolved biodegradable organic nitrogen. This amount depends on the wastewater source.

S_{ALK} = Alkalinity (molar units)

Alkalinity is the amount of carbonates, bicarbonates and hydroxide present in the wastewater. The amount of alkalinity will depend on the wastewater source.

Additionally, to simplify the model, a number of variables in the descriptive equations can be held constant. (Metcalf et al. 2003) In the ASM 1 model there are 19 fixed values. The values used for these inputs are typical and accepted values, as found in Metcalf and Eddy. (Metcalf et al. 2003)

Y_H = 0.60 (g biomass COD/ g COD utilized) Yield constant

f_D = 0.08 (g cell debris/ g biomass COD) Yield constant

$\dfrac{i_n}{xb}$ = 0.086 (g N/ g active biomass COD) Yield constant

$\dfrac{i_n}{xd}$ = 0.06 (g N/ g biomass debris COD) Yield constant

Y_A = 0.24 (g biomass COD/ g N oxidized) Yield constant

u_H = 6.0 (d^{-1})Maximum specific growth rate of heterotrophic bacteria

K_s = 20.0 (mg/L) Half-velocity constant for heterotrophic bacteria

$K_{O,H}$ = 0.10 (mg/L) DO half-velocity constant

K_{NO} = 0.20 (mg/L) Nitrate half-velocity constant

$b_{L,H}$ = 0.40 (g/ g-d) Decay/ lysis coefficient, heterotrophic

n_g = 0.80 (g/ g) Fraction of heterotrophic using nitrate under anoxic conditions

n_h = 0.40 (g/ g) Fraction of anoxic/ aerobic hydrolysis rate fraction

K_a = 0.16 (L/ mg COD-d) Ammonification rate constant

K_h = 2.21 (g/ g-d) Particulate hydrolysis half-velocity constant

K_X = 0.15 (g/ g-d) Hydrolysis half-velocity constant

u_A = 0.76 (g/ g-d) Autotrophic maximum specific growth rate

K_{NH} = 1.0 (mg/L) Autotrophic half-velocity constant

$K_{O,A}$ = 0.75 (mg/L) DO half-velocity constant for autotrophs

$b_{L,A}$ = 0.07 (g/ g-d) Decay constant for autotrophs

ASM 1 was originally designed to be a "paper" model, in the format of a matrix as shown in Figure 1. (Metcalf et al. 2003) However, with the advent of the personal computer, the model has been incorporated into programs such as Microsoft Excel®.

Example 1-1 is used to explain how Activated Sludge Model No. 1 operates. Example 1-1 is an exercise to show how the process component and the process rate function together within the model. (Metcalf et al. 2003)

Example 1-1: Reaction for debris from biomass death and lysis (XD). The user will first examine Column 5 (X_D) and Column 14.

Process Component	Matrix Format	Process Rate
X_D (Column 5)		$r, ML^{-3}T^{-1}$ (Column 14)
f_D	Row 4	$b_{LH} \cdot X_{B,H}$
f_D	Row 5	$b_{LA} \cdot X_{BA}$

Under this column there are only two terms in rows 4 and 5. These two terms are then multiplied by their respective process rates which can be found in Column 14.

Process Component x Process Rate
$f_D b_{LH} \cdot X_{B,H}$
$f_D b_{LA} \cdot X_{BA}$

Once multiplied the terms in rows 4 and 5 are added together. This is the overall reaction process for the biomass death and lysis.

$$R_{X_D} = f_D \cdot \left(b_{LH} \cdot X_{B,H} \right) + f_D \cdot \left(b_{LA} \cdot X_{BA} \right)$$

ASM 1

Process	X_I	X_S	$X_{B,H}$	$X_{B,A}$	X_D	S_I	S_S	S_o	S_{NO}	S_{NH}	S_{NS}	X_{NS}	S_{ALK}	Process rate $r,\,ML^{-3}T^{-1}$
Aerobic growth of heterotrophs			1				$-\dfrac{1}{Y_H}$	$-\left(\dfrac{1-Y_H}{Y_H}\right)$		$-\dfrac{i_{XB}}{}$			$-\dfrac{i_{XB}}{14}$	$\left[u_H\left(\dfrac{S_S}{K_S+S_S}\right)\left(\dfrac{S_o}{K_{O,H}+S_o}\right)\right]X_{B,H}$
Anoxic growth of heterotrophs			1				$-\dfrac{1}{Y_H}$		$-\left(\dfrac{1-Y_H}{2.86Y_H}\right)$	$-i_{XB}$			$\dfrac{1-Y_H}{14(2.86)Y_H}-\dfrac{i_{XB}}{14}$	$u_H\left(\dfrac{S_S}{K_S+S_S}\right)\left(\dfrac{K_{O,H}}{K_{O,H}+S_o}\right)\left(\dfrac{S_{NO}}{K_{NO}+S_{NO}}\right)n_g\,X_{B,H}$
Aerobic growth of autotrophs				1				$-\left(\dfrac{4.57-Y_A}{Y_A}\right)$	$\dfrac{1}{Y_A}$	$-i_{XB}-\dfrac{1}{Y_A}$			$-\dfrac{i_{XB}}{14}-\dfrac{1}{7Y_A}$	$u_A\left(\dfrac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\dfrac{S_o}{K_{O,H}+S_o}\right)X_{B,A}$
Death and lysis of heterotrophs		$(1-f_D)$	-1		f_D							$\dfrac{i_N}{X_H}-\dfrac{f_{D,N}}{X_D}$		$b_{LH}X_{B,H}$
Death and lysis of autotrophs		$(1-f_D)$		-1	f_D							$\dfrac{i_N}{X_A}-\dfrac{f_{D,N}}{X_D}$		$b_{LA}X_{BA}$
Ammonification of soluble organic nitrogen										1	-1		$\dfrac{1}{14}$	$k_a\cdot S_{NS}\cdot X_{B,H}$
Hydrolysis of particulate organics		-1					1							$k_h\left[\dfrac{\dfrac{X_S}{X_{B,H}}}{K_h+\left(\dfrac{X_S}{X_{B,H}}\right)}\right]\left[\left(\dfrac{S_o}{K_{O,H}+S_o}\right)+n_h\left(\dfrac{K_{O,H}}{K_{O,H}+S_o}\right)\left(\dfrac{S_{NO}}{K_{NO}+S_{NO}}\right)\right]X_{B,H}$
Hydrolysis of particulate organic nitrogen											1	-1		$r_7\left(\dfrac{X_{NS}}{X_S}\right)$
Observed conversion rates														

Fig. 1- ASM 1

(Metcalf; Eddy 2003)

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Activated Sludge Model No. 2

       Activated Sludge Model No. 2 (or ASM 2) essentially builds on ASM 1. ASM 2 was developed in the late 1980s. ASM 2 takes into account biological excess phosphorus removal. Phosphorus is a very important building block for all organisms. It is essential for cell reproduction of algae. Municipal waste streams typically have between 4-16 mg/L of phosphorus. (Metcalf et al. 2003) This additional phosphorus can create algae blooms in the receiving waters. Algae blooms negatively impact the recreational use and ecology of surface water. In a conventional activated sludge treatment plant, very little phosphorus is utilized by organisms for reproduction. Under the correct conditions, certain heterotrophic bacteria will store large amounts of phosphorus inside their cells. These special bacteria are called polyP heterotrophs. The ASM 2 allows for the incorporation of the polyP heterotrophs into the model. (Barker et al. 1997)

       The incorporation of the additional parameters created a larger and more complicated model. Therefore some of the input variables were modified for ease of use. The ASM 2 has 19 parameter input variables. The ASM 2 model inputs are defined experimentally just as the ASM 1. Listed below is a comparison of some key terms in Activated Sludge Model No. 2 and their counterpart in Activated Sludge Model No. 1. (Metcalf et al. 2003) (Barker et al. 1997)

ASM 2   ASM 1 Equivalent

Z_H = Active non-polyP heterotrophic biomass $X_{B,H}$
              (g cell COD/ m^3)

Z_A = Active autotrophic biomass (g cell COD/ m^3) $X_{B,A}$

Z_P = Active polyP heterotrophic biomass   -
              (g cell COD/ m^3)

The active polyP heterotrophic biomass is the concentration of bacteria that store large amounts of phosphorus. The concentration can be controlled through normal biomass wasting.

Z_E = Endogenous mass (g cell COD/ m^3) X_D

S_{ENM} = Enmeshed slowly biodegradable substrate X_S
             (g cell COD/ m^3)

S_{BSC} = Readily biodegradable "complex" substrate S_S
             (g cell COD/ m^3)

S_{BSA} = Readily biodegradable short chain fatty acid (SCFA) substrate   -
             (g cell COD/ m^3)

The readily biodegradable short chain fatty acid (SCFA) is essentially the amount of poly-b-hydroxybutyrate (PHB) that can be utilized by the polyP organisms. This concentration is found in the influent and it is highly dependent on the waste source.

S_{PHB} = Stored SCFA   -
                      (g cell COD/ m^3)

Stored SCFA is the amount that is converted into PHB and stored by the polyP organism in the anaerobic phase of the treatment process. This can be controlled to a certain extent through biomass wasting.

S_{UP} = Particulate un-biodegradable matter X_i
                      (g cell COD/ m^3)

S_{US} = Un-biodegradable soluble substrate S_i
                      (g cell COD/ m^3)

P_{PP-LO} = Releasable stored polyP (g P/ m^3)   -

This is the amount of polyP that can be released in ensuing anaerobic conditions. This is usually small amounts; therefore PP-LO is in the subscript. This is an uncontrollable value.

P_{PP-HI} = Fixed stored polyP (g P/ m^3)   -

This is the amount of polyP that will not be released in ensuing anaerobic conditions. This is usually large amounts; therefore, PP-HI is in the subscript. This is an uncontrollable value.

P_{O4} = Soluble phosphate (g P/ m^3)   -

This is the amount of dissolved phosphate that is found in the influent and converted phosphate in the anaerobic treatment phase. Phosphate is utilized and stored by the polyP organisms in the anoxic/ aerobic phase of the treatment process.

N_{BP} = Particulate biodegradable organic nitrogen X_{NS}
                      (g N/ m^3)

N_{BS} = Soluble biodegradable organic nitrogen S_{NS}
                      (g N/ m^3)

N_{O3} = Nitrate nitrogen S_{NO}
                      (g N/ m^3)

N_{H3} = Ammonium nitrogen S_{NH}
                      (g N/ m^3)

N_{US} = Un-biodegradable soluble nitrogen   -
                          (g N/ m^3)

This is the amount of nitrogen that is dissolved in solution but will not be utilized by nitrifying bacteria.   This amount is found in the influent thus the concentration depends on the waste source.

S_O = Oxygen (g / m^3) S_o

Due to the model's additional input parameters, ASM 2 also has additional constants. The ASM 2 has 33 stoichiometric parameters, which are organized into the three bacteria subsets that are modeled in the ASM 2. (Baker et al. 1997)
The parameters are as follows:

Non-polyP Heterotrophs

$Y_{H,AER}$ = 0.666 (g cell COD yield/ g COD utilized) Aerobic yield constant

$Y_{H,ANOX}$ = 0 666 (g cell COD yield/ g COD utilized) Anoxic yield constant

$Y_{H,ANA}$ = 0.100 (g cell COD yield/ g COD utilized) Anaerobic yield constant

Y_{AC} = 0.50 (g S_{BSA} COD/ g S_{BSC} COD) Fermentation S_{BSA} yield

E_{ANOX} = 0.90 (g S_{BSC} COD/ g S_{ENM} COD) Anoxic hydrolysis efficiency factor

E_{ANA} = 0.60 (g S_{BSC} COD/ g S_{ENM} COD) Anaerobic hydrolysis efficiency factor

$f_{N,ZH}$ = 0.068 (g N/ g COD active organisms) Nitrogen content of active mass

$f_{N,ZEH}$ = 0.068 (g N/ g COD endogenous residue) Nitrogen content of endogenous mass

$f_{P,ZH}$ = 0.021 (g P/ g COD active organisms) Phosphorus content of active mass

$f_{N,ZEH}$ = 0.021 (g P/ g COD endogenous residue) Phosphorus content of endogenous mass

$f_{EP,H}$ = 0.08 (g COD endogenous mass/ g COD active mass) Fraction of active mass remaining as endogenous residue

$f_{CV,H}$ = 1.48 (g COD/ g VSS) Ratio COD:VSS

PolyP Heterotrophs

Y_P = 0.639 (g cell COD yield/ g COD utilized) Yield constant

$f_{P,UPT1}$ = 0.95 (g P/ g stored COD) P uptake/ COD utilized in aerobic growth

$f_{P,UPT2}$ = 0.55 (g P/ g stored COD) P uptake/ COD utilized in anoxic growth

Y_{PHB} = 0.889 (g PHB COD/ g S_{BSA} COD) PHB yield on sequestration of S_{BSA}

$f_{N,ZP}$ = 0.070 (g N/ g COD active organisms) Nitrogen content of active mass

$f_{N,ZEP}$ = 0.070 (g N/ g COD endogenous residue) Nitrogen content of endogenous mass

$f_{N,SEP}$ = 0.070 (g N/ g COD endogenous residue) Nitrogen content of soluble un-biodegradable COD

$f_{P,ZP}$ = 0.021 (g P/ g COD active organisms) Phosphorus content of active mass excluding polyP content

$f_{P,ZEP}$ = 0.021 (g P/ g COD endogenous residue) Phosphorus content of endogenous mass

$f_{EP,P}$ = 0.25 (g COD endogenous mass/ g COD active mass) Fraction of active mass remaining as particulate un-bio. endogenous residue

$f_{ES,P}$ = 0.20 (g COD/ g COD active mass) Fraction of active mass remaining as soluble un-biodegradable residue

$f_{P,REL}$ = 0.52 (g P/ g S_{BSA} COD) P release/ SCFA COD uptake for sequestration

$f_{CV,P}$ = 1.42 (g COD/ g VSS) Ratio COD:VSS

f_{PP} = 0.94 (g P/ g P) Fraction of taken up P which can be released

Autotrophs

Y_A = 0.150 (g cell COD yield/ g N utilized) Yield constant

$f_{N,ZA}$ = 0.068 (g N/ g COD active organisms) Nitrogen content of active mass

$f_{N,ZEA}$ = 0.068 (g N/ g COD endogenous residue) Nitrogen content of endogenous mass

$f_{P,ZA}$ = 0.021 (g P/ g COD active organisms) Phosphorus content of active mass

$f_{P,ZEA}$ = 0.021 (g P/ g COD endogenous residue) Phosphorus content of endogenous mass

$f_{EP,A}$ = 0.08 (g COD endogenous mass/ g COD active mass) Fraction of active mass remaining as endogenous residue

$f_{CV,A}$ = 1.42 (g COD/ g VSS) Ratio COD:VSS

The model takes far greater organization because of its additional parameter inputs. The ASM 2 is attached as Figure 2 and Figure 3. Also, ASM 2 can be incorporated into Microsoft Excel. The model allows for switching function input as well. The switching functions are defined in the attached Figure 4. (Barker et al. 1997)

The use of the ASM 2 is exactly the same as the ASM 1. See Example 1-1, pg 7.

ASM 2 accurately predicts process and effluent values. Table 1, Table 2, and Table 3 are comparison of measured effluent values and ASM 2 predicted effluent values. (Barker et al. 1997) Also, the following tables compare the predicted aeration basin control values, such as the oxygen uptake rate (OUR) and the volatile suspended solids (VSS) with the measured values. Three different activated sludge processes were modeled. The percent error is the deviation of predicted ASM 2 values from the actual measured values. Model prediction error could be due to the unpredictable nature of biological organisms. Even with so many input values, the model still only designates three different kinds of organisms. This is done for a macro analysis of the system. When looking at a reactor sample under the microscope, there will be hundreds of different kinds of organisms. Error could be caused by parameter uncertainty. Input values are determined from experimental testing of the wastewater influent and activated sludge constituents. These systems can change very rapidly, thereby changing the input parameters and constants.

Table 1- Percent Error

Reactor	%
VSS (g VSS/m^3)	9.2
OUR (g O$_2$/m^3)	1.0
Effluent	
TKN (g N/m^3)	2.9
NO3 (g N/m^3)	4.5

(Barker et al. 1997)

Table 2- Percent Error

Reactor	%
VSS (g VSS/m^3)	2.9
OUR (g O$_2$/m^3)	5.8
Effluent	
TKN (g N/m^3)	5.2
NO3 (g N/m^3)	2.2

(Barker et al. 1997)

Table 3- Percent Error

Reactor	%
VSS (g VSS/m^3)	5.5
P VSS (g P / g VSS)	3.4
OUR (g O$_2$/m^3)	
Aerobic Reactor 1	3.2
Aerobic Reactor 2	11.3
Aerobic Reactor 3	7.4
Underflow Reactor	0.7
Effluent	
TKN (g N/m^3)	6.0
NO3 (g N/m^3)	21.4
P (g P/m^3)	23.5

(Barker et al. 1997)

ASM 2

Process component | Z_H | Z_A | Z_P | Z_E | S_{ENM} | S_{BSC} | S_{BSA} | S_{PHB} | S_{LP} | S_{LS} | $P_{PP=LO}$ | $P_{PP=HI}$ | P_{O4} | S_{BP} | S_{HS} | N_{O3} | N_{H3} | N_S | S_O | Rate equation

Aerobic growth of heterotrophs on S_{BSC} with NH3

Anoxic growth of heterotrophs on S_{BSC} with NH3

Aerobic growth of heterotrophs on S_{BSC} with NO3

Anoxic growth of heterotrophs on S_{BSC} with NO3

Aerobic growth of heterotrophs on S_{BSA} with NH3

Anoxic growth of heterotrophs on S_{BSA} with NH3

Aerobic growth of heterotrophs on S_{BSA} with NO3

Anoxic growth of heterotrophs on S_{BSA} with NO3

Decay of heterotrophs

Aerobic hydrolysis of stored/enmeshed COD

Anoxic hydrolysis of stored/enmeshed COD

Anaerobic hydrolysis of stored/enmeshed COD

Hydrolysis of organic nitrogen

Ammonification

Fermentation of S_{BSC} to S_{BSA}

Autotroph growth

Autotroph decay

Fig. 2- ASM 2

(Barker; Dold 1997)

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ASM 2

Fig. 3- ASM 2

(Barker; Dold 1997)

Switching Function

Switching Function	Equivalent Definition	
AirYesHet	$1 - $ AirNoHet	$\dfrac{S_O}{K_{OHET} + S_O}$
AirNoHet	$1 - $ AirYesHet	$\dfrac{K_{OHET}}{K_{OHET} + S_O}$
AirYesAut	$1 - $ AirNoAut	$\dfrac{S_O}{K_{OAUT} + S_O}$
AirNoAut	$1 - $ AirYesAut	$\dfrac{K_{OAUT}}{K_{OAUT} + S_O}$
NH_3Yes	$1 - NH_3$No	$\dfrac{N_{H3}}{K_{NA} + N_{H3}}$
NH_3No	$1 - NH_3$Yes	$\dfrac{K_{NA}}{K_{NA} + N_{H3}}$
NO_3Yes	$1 - NO_3$No	$\dfrac{N_{O3}}{K_{NO} + N_{O3}}$
NO_3No	$1 - NO_3$Yes	$\dfrac{K_{NO}}{K_{NO} + N_{O3}}$
PO_4GroYes	$1 - PO_4$GroNo	$\dfrac{P_{O4}}{K_{LP-GRO} + P_{O4}}$
PO_4GroNo	$1 - PO_4$GroYes	$\dfrac{K_{LP-GRO}}{K_{LP-GRO} + P_{O4}}$
PO_4UptYes	$1 - Po_4$UptNo	$\dfrac{P_{O4}}{K_{LP-UPT} + P_{O4}}$
Po_4UptNo	$1 - PO_4$UptYes	$\dfrac{K_{LP-GRO}}{K_{LP-UPT} + P_{O4}}$
S_{BSA}Yes	$1 - S_{BSA}$No	$\dfrac{S_{BSA}}{K_{SSEQ} + S_{BSA}}$
S_{BSA}No	$1 - S_{BSA}$Yes	$\dfrac{K_{SSEQ}}{K_{SSEQ} + S_{BSA}}$
PolyPYes	$1 - $ PolyPNo	$\dfrac{P_{PP-LO}}{K_{XP} + P_{PP-LO}}$
PolyPNo	$1 - $ PolyPYes	$\dfrac{K_{XP}}{K_{XP} + P_{PP-LO}}$

Fig. 4- ASM 2 Switching Functions
(Barker et al. 1997)

Activated Sludge Model No. 3

Activated Sludge Model No. 3 (ASM 3) was developed in 1999 as a solution to the short comings of ASM 1. ASM 1 does not have the necessary limitations built into the model to deal with nitrogen and alkalinity inputs. This can lead the user to negative concentrations of ammonium. ASM 3 eliminates the soluble and particulate nitrogen from the model as two separate variables. ASM 3 also eliminates the kinetics of ammonification. These eliminations were due to the difficulty in measuring specific parameters. ASM 3 differentiates the decay rates of nitrifiers under different processes within different stages of the reactor. ASM 3 also incorporates an observable section of the model to directly predict the mixed liquor suspended solids (MLSS) concentration. These changes were to simplify the model and, to a certain extent, to allow for easier use by the user. Fig. 5 is a visual representation of the model. (Gujer et al. 1999) (Koch et al. 2000)
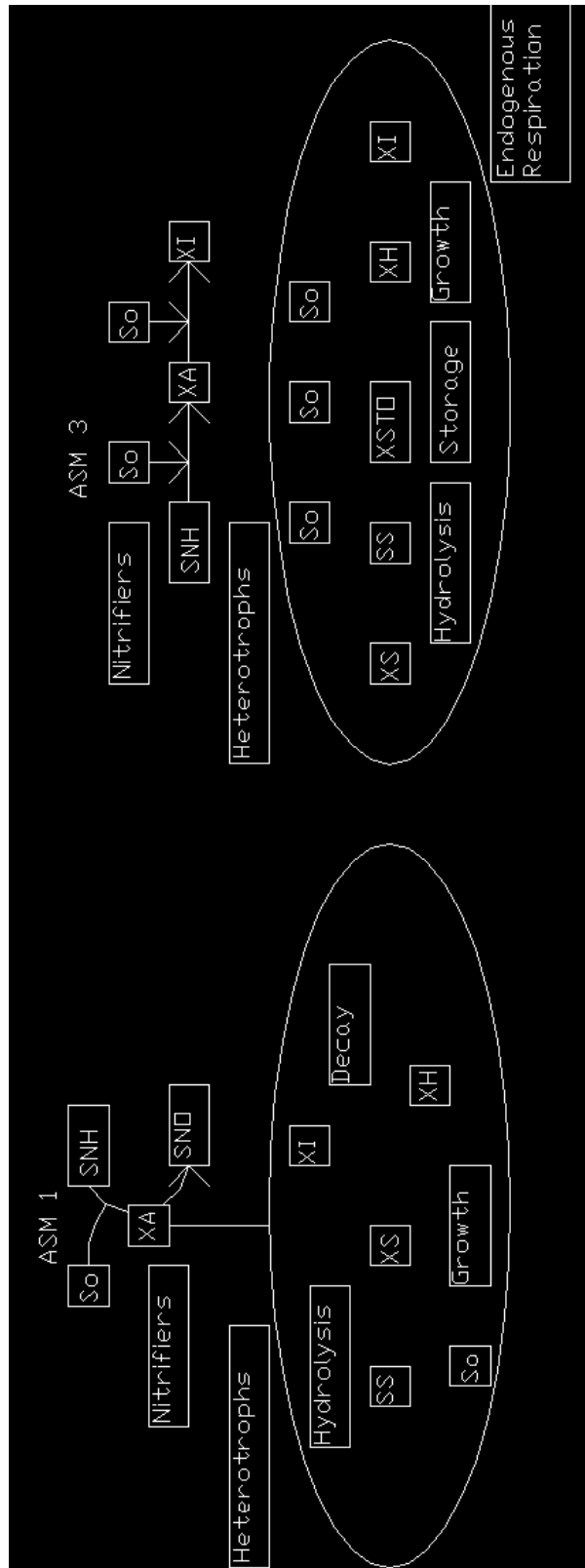
Fig. 5- Flow of COD in ASM 1 and ASM 3
(Gujer et al. 1999)

ASM 3 has 13 model inputs, 21 kinetic parameters and 16 stoichmetric parameters. The input parameters are segregated into two categories: soluble and particulate. The first letter of the input variable is either X (particulate) or S (soluble). The subscripted second letter represents the specific component it represents. See below for input variable definitions.

This model was input into Microsoft Excel. Microsoft Excel was used as the platform for ASM 3 because of its ease of use and is highly available for any user. The format that was chosen separates the model into sheets. The first sheet is the model inputs. This is where the user can change any of the inputs they wish. Different applications of the model require different model inputs.

Table 4- ASM 3 Model Inputs

Model Inputs			
SO	1	0 g O2 m-3	Dissolved Oxygen
SI	52	g COD m-3	Inert Soluble Material
SS	80	g COD m-3	Readily Biodegradable Organic Substrate
SNH	28	g N m-3	Ammonium Plus Ammonia Nitrogen
SN2	0	g N m-3	Dinitrogen
SNO	0	g N m-3	Nitrate Plus Nitrite Nitrogen
SHCO	5	mole HCO3- m-3	Alkalinity
XI	30	g COD m-3	Inert Particulate Organic Material
XS	96	g COD m-3	Slowly Biodegradable Organic Material
XH	1415	g COD m-3	Heterotrophic Organisms
XSTO	0.25	g COD m-3	A Cell Internal Storage Product of Heterotrophic Organisms
XA	88	g COD m-3	Nitrifying Organisms
XTS	3000	g TSS m-3	Total Suspended Solids

(Gujer et al. 1999)

The second sheet is the kinetic and stoichmetric input parameters. The input parameters listed are typical values. These typical values come from a typical municipal waste stream. For a more accurate use of ASM 3 the user should use case specific input parameters. Each waste stream can vary depending on region or demographics. Waste streams can also vary depending on if the source is residential, commercial or industrial. These can be determined through batch analysis. Batch analysis is an acceptable way to determine the parameters if there are no existing reactor data. If there are reactor data then the stoichmetric parameters can be determined mathematically.

Table 5- ASM 3 Kinetic Parameters

Model Constants
Kinetic Parameters

Symbol	Characterization	Value	Units
kH	Hydrolysis rate constant	3	g XS g-1 XH d-1
KX	Hydrolysis saturation constant	1	g XS g-1 XH
Heterotrophic organisms, denitrification, XH			
kSTO	Storage rate constant	5	g SS g-1 XH d-1
nNO	Anoxic reduction factor	0.6	
KO	Saturation constant for SO	0.2	g O2 m-3
KNO	Saturation constant for SNO	0.5	g NO3- - Nm-3
KS	Saturation constant for substrate SS	2	g COD m-3
KSTO	Saturation constant for XSTO	1	g XSTO g-1 XH
uH	Heterotrophic max. growth rate	1	d-1
KNH	Saturation constant for ammonium, SNH	0.01	g N m-3
KHCO	Bicarbonate saturation constant of XH	0.1	mole HCO3- m-3
bH,O2	Aerobic endog. respiration rate of XH	0.2	d-1
bH,NO	Anoxic endog. respiration rate of XH	0.1	d-1
bSTO,O2	Aerobic respiration rate of XSTO	0.2	d-1
bSTO,NO	Anoxic respiration rate for XSTO	0.1	d-1
Autotrophic organisms, nitrification, XA			
uA	Autotrophic max. growth rate XA	1	d-1
KA,NH	Ammonium substrate saturation for XA	1	g N m-3
KA,O	Oxygen saturation for nitrifiers	0.5	g O2 m-3
KA,HCO	Bicarbonate saturation for nitrifiers	0.5	mole HCO3- m-3
bA,O2	Aerobic endog. respiration rate of XA	0.15	d-1
bA,NO	Anoxic endog. respiration rate of XA	0.05	d-1

Note: All values are at 20 degrees C
(Gujer et al. 1999)

Table 6- ASM 3 Stoichiometric Parameters

Stoichiometric parameters					
Symbol	Characterization	Value	Units		
f_{SI}	Production of SI in Hydrolysis	0	g SI g-1 XS		
fXI	Production of XI in endog. Biomass respiration	0.1	g SI g-1 XS		
YSTO,O2	Aerobic yield of stored product per SS	0.85	g XSTO g-1 SS		
YSTO,NO	Anoxic yield of stored product per SS	0.8	g XSTO g-1 SS		
YH,O2	Aerobic yield of heterotrophic biomass	0.63	g XH g-1 XSTO		
YH,NO	Anoxic yield of heterotrophic biomass	0.54	g XH g-1 XSTO		
YA	Yield of autotrophic biomass per NO3-N	0.24	g XA g-1 SNO		
iNSI	N content of SI	0.01	g N g-1 SI		
INSS	N content of SS	0.03	g N g-1 SS		
iNXI	N content of XI	0.02	g N g-1 XI		
iNXS	N content of XS	0.04	g N g-1 XS		
iNBM	N content of biomass, XH, XA	0.07	g N g-1 XH or A	VSS	
iTSXI	TSS to COD ratio for XI	0.75	g TS g-1 XI	0.75	g VSS g-1 XI
iTSXS	TSS to COD ratio for XS	0.75	g TS g-1 XS	0.75	g VSS g-1 XS
iTSBM	TSS to COD ratio for biomass, XH, XA	0.9	g TS g-1 XH or A	0.75	g VSS g-1 XH or A
iTSSTO	TSS to COD ratio for XSTO based on PHB	0.6	g TS g-1 XSTO	0.6	g VSS g-1 XSTO

(Gujer et al. 1999)

ASM 3 (Gujer et al. 1999) — stoichiometric and kinetic matrix

Process	SO	SI	SS	SNH	SN2	SNO	SHCO	Xt	XS	XH	XSTO	XA	XTS		Process Rate Equation
Hydrolysis		fSI	1+fSI	iN,XS-iN,SS*(1+fSI)-iN,SI*fSI			Z1		-1				iTS:XS		kH*((XS/XH)/(KX+(XS/XH)))*XH
Heterotrophic organisms, denitrification															
Aerobic storage of COD	(YSTO,O2)*-1		-1	-iN,SS			Z2				YSTO,O2			T2	kSTO*(SO/(KO+SO))*(SS/(KS+SS))*XH
Anoxic storage of COD			-1	-iN,SS	(1-YSTO,NO)/2.86	-(1-YSTO,NO)/2.86	Z3				YSTO,NO			T3	kSTO*nNO*(KO/(KO+SO))*(SNO/(KNO+SNO))*(SS/(KS+SS))*XH
Aerobic growth	1-1/YH,O2			(-iN,BM)			Z4			1	(-1/YH,O2)			T4	uH*(SO/(KO+SO))*(SNH/(KNH+SNH))*(SHCO/(KHCO+SHCO))*((XSTO/XH)/(KSTO+(XSTO/XH)))*XH
Anoxic growth (denitrification)				(-iN,BM)	-(1/(YH,NO*-1))/2.86	(1/(YH,NO*-1))/2.86	Z5			1	(-1/YH,NO)			T5	uH*nNO*(KO/(KO+SO))*(SNH/(KNH+SNH))*(SHCO/(KHCO+SHCO))*(SNO/(KNO+SNO))*((XSTO/XH)/(KSTO+(XSTO/XH)))*XH
Aerobic endog. respiration	-(1-fXI)			iN,BM-fXI*iNXI			Z6	fXI		-1				T6	bH,O2*(SO/(KO+SO))*XH
Anoxic endog. Respiration				iN,BM-fXI*iNXI	-(1-fXI)/2.86	(1-fXI)/2.86	Z7	fXI		-1				T7	bH,O2*(SO/(KO+SO))*(SNO/(KNO+SNO))*XH
Aerobic respiration of XSTO	-1										-1			T8	bSTO,O2*(SO/(KO+SO))*XSTO
Anoxic respiration of XSTO					(-1/2.86)	1/2.86	Z9				-1			T9	bSTO,O2*(SO/(KO+SO))*(SNO/(KNO+SNO))*XSTO
Autotrophic organisms, nitrification															
Nitrification	(1-4.57/YA)			(-1/YA)-iN,BM		1/YA	Z10					1		T10	uA*(SO/(KA,O+SO))*(SNH/(KA,NH+SNH))*(SHCO/(KA,HCO+SHCO))*XA
Aerobic endog. respiration	-(1-fXI)			iN,BM-fXI*iNXI			Z11	fXI				-1		T11	bA,O2*(SO/(KO+SO))*XA
Anoxic endog. Respiration				iN,BM-fXI*iNXI	(1-fXI)/2.86	-(1-fXI)/2.86	Z12	fXI				-1		T12	bA,NO*(KO/(KO+SO))*(SNO/(KNO+SNO))*XA
Composition matrix															
Conservatives															
COD (g COD)	-1	1	1		(-24/16)	(-64/14)		1	1	1	1	1			
Nitrogen (g N)		iNSI	iNSS	1		1		iNXI	iNXS	iNBM		iNBM			
Ionic Charge (Mole +)				(1/14)	1	(-1/14)	-1								
Observables															
TSS (g TSS)								iTS:XI	iTS:XS	iTS:BM	0.6	iNBM			

Fig. 6- ASM 3 (Gujer et al. 1999)

Application of Activated Sludge Model No. 3

Over the last 20 years the Activated Sludge Models have a proven record for predicting reasonably well the desired output parameters. In more recent years, ASM 3 has been specifically applied to the prediction of nitrification and denitrification. Activated Sludge Model No. 3 (ASM 3) has been utilized almost exclusively for modeling of municipal waste treatment. (Iacopozzi et al. 2007)

ASM 3 is a model that can require case specific input parameters to be added. In recently released papers, nitrification-denitrification was modeled as a two-step process. Due to the increased complexity, the model kinetics and stoichiometric parameters have to be adjusted. This has been done to account for the more complex treatment options such as the Single reactor High activity Ammonia Removal Over Nitrite (SHARON) and the Sequencing Batch Reactor (SBR). Additionally, special consideration has been taken to optimize operational costs and discharge limits. Other attempts have been made to expand specifically ASM 3 into accurately predicting biological phosphorus removal. The BIO-P addition to ASM 3 expanded the model by an additional 13 process components and 4 variables. The expansion of ASM has been successful in predicting and optimizing treatment operations. (Iacopozzi et al. 2007) (Rieger et al. 2001)

Attempts to analytically model industrial processes have been limited and have usually been case specific. Recently an empirical model was used to evaluate biological treatment of petrochemical plant. This model incorporated physical stripping of volatile organic carbons (VOC's) and biological removal of chemical oxygen demand (COD). This model did have limited success in removal prediction. The limited success can be attributed to a rather simple model to describe a complex treatment situation. (Maqueda et al. 2006)

There has been limited use of the Activated Sludge Models when applied to industrial treatment processes. Two reasons for this are due to the increased temperature of the waste stream and the usual toxic nature of industrial wastes. Recently, however, there has been an application of ASM 3 to oil refinery's wastewater treatment facilities. The goals of the research project were: to apply the general model constants to the refinery influent wastewater characteristics; to evaluate ASM 3 when applied to oil refinery wastewater treatment; to evaluate the kinetic and stoichiometric parameters through the use of batch tests; and to optimize the wastewater treatment plant performance. The treatment facility is arranged with three aeration basins in a series that empties into a single clarifier. The refinery influent temperature averages 34 degree C. Six sampling points were used to evaluate the model performance. (Pinzon Pardo et al. 2007)

Modifications were made to the default values of ASM 3. The particulate COD of the total COD was reduced to 10% for this application. Therefore, readily biodegradable COD was much higher for the oil refinery influent. Additionally, the autotrophic yield constant was lowered to .5 d-1. This change was appropriate due to the toxic nature of the waste stream.

Overall, the general model constants were appropriate when applied to the oil refinery waste treatment. The model prediction became much closer when the four stoichiometric parameters were modified. The four modified stoichiometric parameters were nitrogen content of particulate inert, autotrophic maximum growth rate, anoxic yield of stored products and the anoxic reduction factor. Modifications to these parameters are demonstrated in Table 7. Table 8 is a comparison between the ASM 3 predicted treatment values. The research used ASM 3 to accurately predict treatment values. (Pinzon Pardo et al. 2007)

Table 7- Adjusted Model Parameters

Parameter	Symbol	Study	ASM default	Unit
Nitrogen content of particulate inert	iN,Xi	.030	.020	gN gXi^-1
Autotrophic maximum growth rate	YA	0.50	1.0	d^-1
Anoxic yield of stored products	YSTO,NO	0.50	0.80	gCOD(XSTO) gCOD^-1
Anoxic reduction factor	nNO	0.30	0.60	-

(Pinzon Pardo et al. 2007)

Table 8- Measured and Predicted Treatment Values

	Effluent			Biomass		
	COD	NH4-N	NO3-N	TSS	VSS	TKN
Measured Average	34+/-9	1+/-1	3+/-3	6573+/- 458	4009+/- 438	206
After Calibration	41	0.2	4	6269	3823	206

(Pinzon Pardo et al. 2007)

The Activated Sludge Model No. 3 has had limited use in describing the fate of organic material and nutrients. Although, ASM 3 has not experienced as wide spread use as the analytical model in academia or in engineering practice. Therefore, it is necessary to understand the more common method of describing the fate of organic material and nutrients in an activated sludge process. The analytical model is the most common way of modeling biological removal of BOD and nutrients.

Analytical Model

The analytical modeling used in biological treatment uses a mass balance approach with a fixed volume. The model for biomass in the system assumes accumulation = inflow – outflow + net growth. Fig. 8 is a visual representation of the model approach.
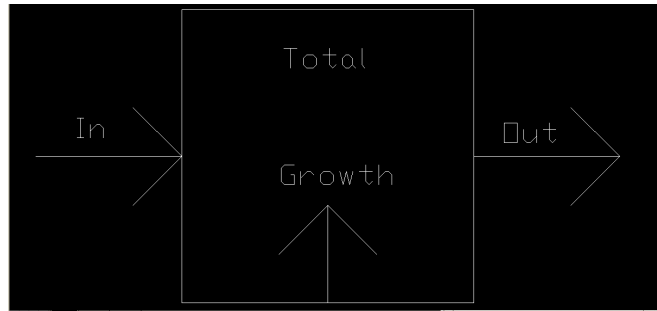
Fig. 7- Box Model
(Metcalf et al. 2003)

The box model approach is used in many other applications to simplify calculations. This approach is specific to the activated sludge process by creating a boundary system around the aeration basin and clarifier. Fig. 9 demonstrates the approach.
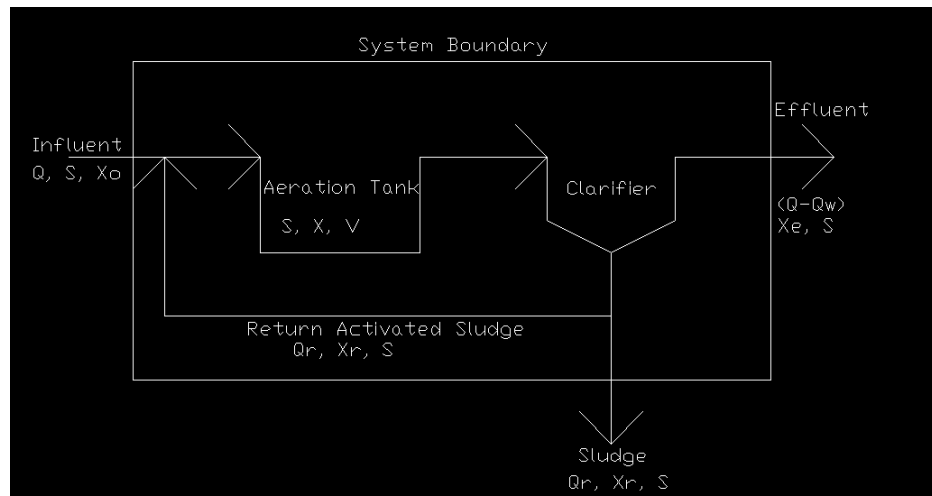
Fig. 8- Analytical Model-Wastewater Treatment Process
(Metcalf et al. 2003)

Biomass Mass Balance

$$\frac{dx}{dt}V = QX_o - (Q - Q_w)X_e - Q_w X_R + r_s V$$

Parameters

$\frac{dx}{dt}V$ = Rate of change of biomass concentration in reactor (gVSS/m^3-day)

V = Reactor volume (m^3)

Q = Influent flow (m^3/day)

X_o = Concentration of biomass in influent (gVSS/m^3)

Q_w = Waste sludge flowrate (m^3/day)

X_e = Concentration of biomass in effluent (gVSS/m^3)

X_R = Concentration of biomass in return line from clarifier (gVSS/m^3)

r_s = Net rate of biomass production (gVSS/m^3-day)

Assume steady-state and initial microorganism concentration can be neglected

$$\frac{dx}{dt} = 0$$

$$r_s V = (Q - Q_w) \cdot X_e - Q_w \cdot X_R$$

Combine with growth rate of biomass

$$-Y \cdot \frac{r_{su}}{X} - k_d = \frac{(Q - Q_w) \cdot X_e - Q_w \cdot X_R}{VX}$$

X = Concentration of the biomass in the reactor (gVSS/m^3)

Solids retention time (SRT = days) equal to the inverse of the left side of the equation

$$SRT = \frac{1}{\left(-Y \cdot \dfrac{r_{su}}{X} - k_d\right)}$$

Combine the solids retention time with equation

$$SRT = \frac{VX}{(Q - Q_W) \cdot X_e + Q_W \cdot X_R}$$

(Metcalf et al. 2003)

Substrate Mass Balance

The same method for developing a biomass mass balance can be used for substrate utilization.

$$\frac{ds}{dt} V = Q \cdot S_o - Q \cdot S - r_{su} \cdot V$$

Parameters

Q = Influent flow (m^3/day)

V $\qquad$ = Reactor volume (m^3)

r_{su} $\qquad$ = Rate of substrate concentration change due to utilization (g/m^3-day)

S_o $\qquad$ = Influent substrate concentration (g/m^3)

S $\qquad$ = Effluent substrate concentration (g/m^3)

Assume steady-state

$$\frac{ds}{dt} = 0$$

Rate of substrate utilization is:

$$r_{su} = \frac{-k \cdot X \cdot S}{k_s + S}$$

X $\qquad$ = Concentration of the biomass in the reactor (gVSS/m^3)

k $\qquad$ = maximum specific substrate utilization rate (g S / g VSS)

k_s $\qquad$ = Half velocity constant (g/m^3)

Combine the rate of substrate utilization and rearrange

$$S_o - S = \left(\frac{V}{Q}\right) \cdot \frac{(k \cdot X \cdot S)}{k_S + S}$$

(Metcalf et al. 2003)

These presented equations are the basic equations that have been used to model the fate of biomass and substrate through a wastewater treatment process. Other equations have been developed by expanding the basic biomass and substrate equations.

Additionally this model has been adapted to predict the fate of nitrogen in a wastewater treatment process.

Nitrification

$$\mu_n = \left[\frac{(\mu_{nm} \cdot N)}{K_n + N}\right]\left(\frac{DO}{K_o + DO}\right) - k_{dn}$$

Parameters

μ_n $\qquad$ = Specific growth rate of nitrifying bacteria (g cells/ g cells)

μ_{nm} = Maximum specific growth rate of nitrifying bacteria (g cells/ g cells)

N = Nitrogen concentration (g/m^3)

K_n = Half velocity constant (g/m^3)

k_{dn} = Endogenous decay coefficient for nitrifying bacteria (g VSS/ g VSS-day)

DO = Dissolved oxygen concentration (g/m^3)

D_o = Half saturation coefficient (g/m^3)

(Metcalf et al. 2003)

Denitrification

$$Y_n = \frac{Y}{1 + k_{dn} \cdot SRT}$$

$$\frac{gbsCOD}{gNO_3 - N} = \frac{2.86}{1 - 1.42Y_n}$$

Parameters

Y_n = Nitrifying biomass yield (g VSS/ g bcCOD)

Y = Total biomass yield (g VSS/ g bcCOD)

(Metcalf et al. 2003)

Overall, the analytical model is the more common way to predict the fate of wastewater constituents. The analytical model is used for optimization and design of wastewater treatment processes. The accuracy of the model depends on how precisely the constants represent the biological activity. Parameter constants can introduce error into the model. Constants can be chosen using accepted values or can be determined through experimental analysis. The model has been well proven through years of trial and error. In the United States the overwhelming majority of wastewater treatment facilities were designed using the analytical model. (Metcalf et al. 2003)

Chapter III will determine the validity of ASM 3 when incorporated into Microsoft Excel and apply ASM 3 to a case specific industrial activated sludge unit to determine if the model accurately predicts the effluent ammonium concentration. Additionally, Chapter III will investigate changes in model inputs to reduce the effluent concentration of ammonium.

CHAPTER III

METHODOLOGY

Activated Sludge Model No. 3 (ASM 3) Validation

ASM 3 was validated through a peer review process. ASM 3 is accepted in the scientific community but does not experience wide-spread use in the design community. The analytical model has been more widely used for reactor design. (Koch et al. 2000)

This section will investigate how accurate ASM 3 predicts reactor tank design. It was not reasonable to use ASM 3 to design a treatment facility and then construct a full scale treatment facility. It also was not reasonable to construct a pilot treatment facility. Therefore, design investigation was done exclusively on paper to compare ASM 3 and the analytical model reactor design. For this investigation, accepted Metcalf and Eddy design examples were used. These design examples are completed by using the analytical method. Example 8-2 and Example 8-5 in Metcalf and Eddy are common reactor design examples that are widely used in academia for upper level wastewater process design classes. Example 8-2 and Example 8-5 are found in the appendix section of this paper. Example 1 and Example 2 are based on Example 8-2 and Example 8-5 from Metcalf and Eddy, respectively. (Metcalf et al. 2003)

Example 1 Complete-Mixed Activated Sludge Process Design for BOD Removal Only and for BOD Removal with Nitrification

Example 1 focuses on the design of the reactor tank only. The constituents used for the design are given municipal primary effluent values. Flows, dissolved oxygen, oxygen transfer efficiency, SRT, and MLSS used for the design are all given values. (Metcalf et al. 2003)

The first part of Example 1 is to predict the hydraulic retention time (HRT) for BOD removal only. The model expressed organic substrate in terms of chemical oxygen demand (COD) not biological oxygen demand (BOD). Therefore, BOD must be converted into biodegradable COD. The influent biodegradable COD was estimated to be 224 g COD m-3. This estimation was done by using a typical multiplier of 1.6 times the BOD. The goal is to find the required hydraulic retention time (HRT) to convert 224 g COD m-3 of organic material into additional biomass, water, and carbon dioxide. The parameter inputs are presented in Table 9 and the model inputs are demonstrated in Table 10. (Metcalf et al. 2003)

Table 9- Example 1 ASM 3 Parameter Inputs

Model Constants

Kinetic Parameters			
Symbol	Characterization	Value	Units
kH	Hydrolysis rate constant	1	g XS g-1 XH d-1
KX	Hydrolysis saturation constant	1	g XS g-1 XH
Heterotrophic organisms, denitrification, XH			
kSTO	Storage rate constant	1	g SS g-1 XH d-1
nNO	Anoxic reduction factor	0.6	
KO	Saturation constant for SO	0.2	g O2 m-3
KNO	Saturation constant for SNO	0.5	g NO3- - Nm-3
KS	Saturation constant for substrate SS	2	g COD m-3
KSTO	Saturation constant for XSTO	1	g XSTO g-1 XH
uH	Heterotrophic max. growth rate	0.65	d-1
KNH	Saturation constant for ammonium, SNH	0.01	g N m-3
KHCO	Bicarbonate saturation constant of XH	0.1	mole HCO3- m-3
bH,O2	Aerobic endog. respiration rate of XH	0.2	d-1
bH,NO	Anoxic endog. respiration rate of XH	0.1	d-1
bSTO,O2	Aerobic respiration rate of XSTO	0.2	d-1
bSTO,NO	Anoxic respiration rate for XSTO	0.1	d-1
Autotrophic organisms, nitrification, XA			
uA	Autotrophic max. growth rate XA	0.12	d-1
KA,NH	Ammonium substrate saturation for XA	1	g N m-3
KA,O	Oxygen saturation for nitrifiers	0.5	g O2 m-3
KA,HCO	Bicarbonate saturation for nitrifiers	0.5	mole HCO3- m-3
bA,O2	Aerobic endog. respiration rate of XA	0.15	d-1
bA,NO	Anoxic endog. respiration rate of XA	0.05	d-1

Note: All values are at 20 degrees C

Stoichiometric parameters			
Symbol	Characterization	Value	Units
f_{SI}	Production of SI in Hydrolysis	0	g SI g-1 XS
fXI	Production of XI in endog. Biomass respiration	0.06	g SI g-1 XS
YSTO,O2	Aerobic yield of stored product per SS	0.8	g XSTO g-1 SS
YSTO,NO	Anoxic yield of stored product per SS	0.13	g XSTO g-1 SS
YH,O2	Aerobic yield of heterotrophic biomass	0.65	g XH g-1 XSTO
YH,NO	Anoxic yield of heterotrophic biomass	0.54	g XH g-1 XSTO
YA	Yield of autotrophic biomass per NO3-N	0.12	g XA g-1 SNO
iNSI	N content of SI	0	g N g-1 SI
INSS	N content of SS	0	g N g-1 SS
iNXI	N content of XI	0.02	g N g-1 XI
iNXS	N content of XS	0.04	g N g-1 XS
iNBM	N content of biomass, XH, XA	0.12	g N g-1 XH or A
iTSXI	TSS to COD ratio for XI	0.75	g TS g-1 XI
iTSXS	TSS to COD ratio for XS	0.75	g TS g-1 XS
iTSBM	TSS to COD ratio for biomass, XH, XA	0.9	g TS g-1 XH or A

iTSSTO	TSS to COD ratio for XSTO based on PHB	0.6	g TS g-1 XSTO

Table 10- Example 1 ASM 3 Inputs

Model Inputs			
SO	2	0 g O2 m-3	Dissolved Oxygen
SI	52	g COD m-3	Inert Soluble Material
SS	80	g COD m-3	Readily Biodegradable Organic Substrate
SNH	28	g N m-3	Ammonium Plus Ammonia Nitrogen
SN2	0	g N m-3	Dinitrogen
SNO	0	g N m-3	Nitrate Plus Nitrite Nitrogen
SHCO	5	mole HCO3- m-3	Alkalinity
XI	30	g COD m-3	Inert Particulate Organic Material
XS	62	g COD m-3	Slowly Biodegradable Organic Material
XH	1415	g COD m-3	Heterotrophic Organisms
XSTO	0.25	g COD m-3	A Cell Internal Storage Product of Heterotrophic Organisms
XA	88	g COD m-3	Nitrifying Organisms
XTS	3000	g TSS m-3	Total Suspended Solids

The model prediction results are presented in Chapter IV Table 18.

The second part of Example 1 is to predict the HRT for BOD removal and nitrification. For this part of the example, focus is put on the removal of ammonium by conversion into nitrate. For this section of the example, the same parameter inputs and model inputs (demonstrated in Table 9 and Table 10) will be used to predict the required HRT to convert 28 g N m-3 of ammonium to nitrate. The model prediction results are demonstrated in Chapter IV Table 19. (Metcalf et al. 2003)

Example 2 Anoxic/ Aerobic Process Design

Example 2 is a continuation of Example 1. Example 3 is the denitrification step utilizing the same wastewater constituents as Example 1. The differences to ASM 3 are that the model input's dissolved oxygen and nitrate concentration have been changed. The dissolved oxygen is inputted as 0 to represent the anoxic zone of the reactor basin. The nitrate concentration is 28 g N m-3 because the ammonium concentration has been converted to nitrate in the nitrification process in Example 1. The goal is to calculate the required HRT of the anoxic zone required to convert 22 g N m-3 of nitrate to nitrogen gas and oxygen. The parameter inputs and model inputs are presented in Table 11 and Table 12.

Table 11- Example 2 Parameter Inputs

Model Constants

Kinetic Parameters			
Symbol	Characterization	Value	Units
kH	Hydrolysis rate constant	1	g XS g-1 XH d-1
KX	Hydrolysis saturation constant	1	g XS g-1 XH
Heterotrophic organisms, denitrification, XH			
kSTO	Storage rate constant	1	g SS g-1 XH d-1
nNO	Anoxic reduction factor	0.6	
KO	Saturation constant for SO	0.2	g O2 m-3
KNO	Saturation constant for SNO	0.5	g NO3- - Nm-3
KS	Saturation constant for substrate SS	2	g COD m-3
KSTO	Saturation constant for XSTO	1	g XSTO g-1 XH
uH	Heterotrophic max. growth rate	0.65	d-1
KNH	Saturation constant for ammonium, SNH	0.01	g N m-3
KHCO	Bicarbonate saturation constant of XH	0.1	mole HCO3- m-3
bH,O2	Aerobic endog. respiration rate of XH	0.2	d-1
bH,NO	Anoxic endog. respiration rate of XH	0.1	d-1
bSTO,O2	Aerobic respiration rate of XSTO	0.2	d-1
bSTO,NO	Anoxic respiration rate for XSTO	0.1	d-1
Autotrophic organisms, nitrification, XA			
uA	Autotrophic max. growth rate XA	0.12	d-1
KA,NH	Ammonium substrate saturation for XA	1	g N m-3
KA,O	Oxygen saturation for nitrifiers	0.5	g O2 m-3
KA,HCO	Bicarbonate saturation for nitrifiers	0.5	mole HCO3- m-3
bA,O2	Aerobic endog. respiration rate of XA	0.15	d-1
bA,NO	Anoxic endog. respiration rate of XA	0.05	d-1

Note: All values are at 20 degrees C

Stoichiometric parameters			
Symbol	Characterization	Value	Units
f_{SI}	Production of SI in Hydrolysis	0	g SI g-1 XS
fXI	Production of XI in endog. Biomass respiration	0.06	g SI g-1 XS
YSTO,O2	Aerobic yield of stored product per SS	0.8	g XSTO g-1 SS
YSTO,NO	Anoxic yield of stored product per SS	0.13	g XSTO g-1 SS
YH,O2	Aerobic yield of heterotrophic biomass	0.65	g XH g-1 XSTO
YH,NO	Anoxic yield of heterotrophic biomass	0.54	g XH g-1 XSTO
YA	Yield of autotrophic biomass per NO3-N	0.12	g XA g-1 SNO
iNSI	N content of SI	0	g N g-1 SI
INSS	N content of SS	0	g N g-1 SS
iNXI	N content of XI	0.02	g N g-1 XI
iNXS	N content of XS	0.04	g N g-1 XS
iNBM	N content of biomass, XH, XA	0.12	g N g-1 XH or A
iTSXI	TSS to COD ratio for XI	0.75	g TS g-1 XI
iTSXS	TSS to COD ratio for XS	0.75	g TS g-1 XS
iTSBM	TSS to COD ratio for biomass, XH, XA	0.9	g TS g-1 XH or A

iTSSTO	TSS to COD ratio for XSTO based on PHB	0.6	g TS g-1 XSTO

Table 12- Example 2 ASM 3 Inputs

Model Inputs			
SO	0	0 g O2 m-3	Dissolved Oxygen
SI	52	g COD m-3	Inert Soluable Material
SS	80	g COD m-3	Readily Biodegradable Organic Substrate
SNH	0	g N m-3	Ammonium Plus Ammonia Nitrogen
SN2	0	g N m-3	Dinitrogen
SNO	28	g N m-3	Nitrate Plus Nitrite Nitrogen
SHCO	5	mole HCO3- m-3	Alkalinity
XI	30	g COD m-3	Inert Particulate Organic Material
XS	62	g COD m-3	Slowly Biodegradable Organic Material
XH	1415	g COD m-3	Heterotrophic Organisms
XSTO	0.25	g COD m-3	A Cell Internal Storage Product of Heterotrophic Organisms
XA	88	g COD m-3	Nitrifying Organisms
XTS	3000	g TSS m-3	Total Suspended Solids

The model prediction of the required HRT is presented in Chapter IV Table 20. (Metcalf et al. 2003)

The comparison of the analytical model and ASM 3 is complete. Now ASM 3 will be applied to the activated sludge unit at the industrial wastewater treatment facility. In order to gain a better understanding of the industrial wastewater treatment facility a description has been provided.

Description of Wastewater Treatment Process

All wastes from refining process end up at the headworks of the industrial treatment facility. As the process diagram shows there are different waste streams that enter the treatment facility. Some waste streams are from processes and others are from groundwater/ stormwater. Due to the site contamination, the groundwater and stormwater are treated along with the refining waste products.

The industrial wastewater treatment facility of study operates somewhat similarly to a secondary municipal wastewater treatment facility. The activated sludge units (ASUs), is where the aerobic biological treatment occurs. From the ASUs the waste stream travels to a secondary clarifier. In the secondary clarifier the endogenous and active bacteria, as well as any solid material, are settled out of solution. This mixture of solids is called sludge. Some of the sludge is then recycled back into the aeration basins, while the rest is pumped out of the system.

For this paper the activated sludge units' (ASUs) biodegradation will be modeled exclusively. Due to presence of an equalization basin, each of the ASUs experiences the same flow and organic loading. The ASUs are exactly the same volumes. Additionally, each ASU experiences the same mixed liquor concentration and dissolved oxygen.

Therefore, it is reasonable to say that they will have very similar biodegradation characteristics. Figure 9 is a process flow diagram of the biological treatment process.
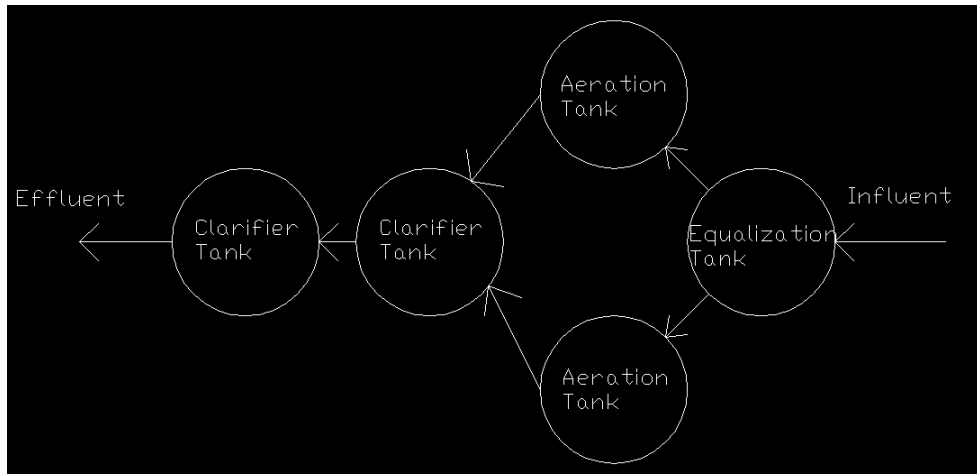
Fig. 9- Process Flow Diagram

Utilizing ASM 3 to Model the ASU at the Industrial Wastewater Treatment Facility

The known ASU input parameters for the industrial wastewater treatment facility are presented in Table 13. The hydraulic parameters and the MLVSS data are from the operators of the industrial wastewater treatment facility. All other data was determined through experimentation by a field technician.

Table 13- Known ASU Parameters

Hydraulic Parameters		
Volume	4896	m3
Flow	4940	m3 d-1
HRT	0.99	D
Influent Parameters		
BOD	141	g BOD m-3
sCOD	225	g COD m-3
NH3-N	8.6	g N m-3
tCOD	370	g COD m-3
Reactor Parameters		
DO	0.8	0 g O2 m-3
MLVSS	2600	g VSS m-3

The ASU parameters are not typical for an industrial wastewater. As previously stated, industrial wastewaters are typically higher in BOD and are lower in flow. This is all the data that is given to describe the ASU. Not all the information required is given. Therefore, engineering assumptions and estimations will need to be made in order to model accurately the existing ASU. The approach will be to input all necessary data into ASM 3 in order to accurately predict effluent concentrations of BOD and ammonium.

The effluent ammonium concentration is being focused on because ammonium lowers the dissolved oxygen concentration in receiving waters. Therefore the industrial wastewater treatment facility has a discharge permit. Currently the facility meets the requirements of its discharge permit. In the future, the allowable ammonium discharge could be lowered. The industrial wastewater treatment facility would like to model their ASUs to determine if there are any process controls that can be adjusted to ensure that they meet any future regulation.

Assumptions and Estimations

This waste stream would not be considered a typical municipal waste stream. This treatment facility likely experiences a high concentration of potentially toxic substances as well as complex organic compounds. Toxic and complex organic substances usually slow down the degradation of BOD.   A typical design value for a municipal wastewater SRT is 12.5 days to ensure nitrification. Nitrification does occur at the facility currently. Therefore, a longer SRT of 14 days was chosen in order to ensure that nitrification occurred even under toxic loadings. The lower end of the heterotrophic and autotrophic yield range was chosen to represent the nature of the wastewater. Estimation of the active heterotrophic biomass was made by utilizing an equation from the analytical model. The following equation was used for the estimation

$$X_b \qquad = \qquad \frac{Q(SRT)}{V} \cdot \frac{Y(S_o - S)}{1 + k_d \cdot SRT}$$

Q $\qquad$ = Flow (m3 d-1)

SRT $\qquad$ = Sludge Retention Time (d)

V $\qquad$ = Volume (m3)

Y $\qquad$ = Hetertrohpic Yield (g VSS/ g COD)

S_o $\qquad$ = Influent COD (g COD m-3)

S $\qquad$ = Effluent COD (g COD m-3)

k_d $\qquad$ = Endogenous Decay (d-1)

Typically, the autotrophic organisms concentration represents 3.7% of the active biomass. (Metcalf et al. 2003) Due to the reduction of the autrotrophic yield coefficient, the percentage was lowered to 2.9%. The upper limit of the endogenous decay term was chosen due to the likely toxicity of the waste stream. A slowed substrate storage and utilization rate was chosen due to the presence of complex organic compounds. Assumptions were made on the nature of the influent COD. It was assumed that there is twice as much inert soluble material as there is readily biodegradable substrate. This was

done to estimate more accurately the nature of the waste stream. This is significantly different than a typical municipal waste stream. The assumed and known inputs are presented in Table 14 and Table 15.

Table 14-ASU ASM 3 Input Parameters

Model Constants

Kinetic Parameters			
Symbol	Characterization	Value	Units
kH	Hydrolysis rate constant	1.00	g XS g-1 XH d-1
KX	Hydrolysis saturation constant	1.00	g XS g-1 XH
Heterotrophic organisms, denitrification, XH			
kSTO	Storage rate constant	0.53	g SS g-1 XH d-1
nNO	Anoxic reduction factor	0.3	
KO	Saturation constant for SO	0.2	g O2 m-3
KNO	Saturation constant for SNO	0.5	g NO3- -Nm-3
KS	Saturation constant for substrate SS	2	g COD m-3
KSTO	Saturation constant for XSTO	1	g XSTO g-1 XH
uH	Heterotrophic max. growth rate	0.65	d-1
KNH	Saturation constant for ammonium, SNH	0.01	g N m-3
KHCO	Bicarbonate saturation constant of XH	0.1	mole HCO3- m-3
bH,O2	Aerobic endog. respiration rate of XH	0.2	d-1
bH,NO	Anoxic endog. respiration rate of XH	0.1	d-1
bSTO,O2	Aerobic respiration rate of XSTO	0.2	d-1
bSTO,NO	Anoxic respiration rate for XSTO	0.1	d-1
Autotrophic organisms, nitrification, XA			
uA	Autotrophic max. growth rate XA	0.07	d-1
KA,NH	Ammonium substrate saturation for XA	1	g N m-3
KA,O	Oxygen saturation for nitrifiers	0.6	g O2 m-3
KA,HCO	Bicarbonate saturation for nitrifiers	0.5	mole HCO3- m-3
bA,O2	Aerobic endog. respiration rate of XA	0.15	d-1
bA,NO	Anoxic endog. respiration rate of XA	0.05	d-1

Stoichiometric parameters			
Symbol	Characterization	Value	Units
fSI	Production of SI in Hydrolysis	0	g SI g-1 XS
fXI	Production of XI in endog. Biomass respiration	0.12	g SI g-1 XS
YSTO,O2	Aerobic yield of stored product per SS	0.6	g XSTO g-1 SS
YSTO,NO	Anoxic yield of stored product per SS	0.5	g XSTO g-1 SS

YH,O2		Aerobic yield of heterotrophic biomass		0.295	g XH g-1 XSTO
YH,NO		Anoxic yield of heterotrophic biomass		0.2	g XH g-1 XSTO
YA		Yield of autotrophic biomass per NO3-N		0.1	g XA g-1 SNO
iNSI		N content of SI		0	g N g-1 SI
INSS		N content of SS		0	g N g-1 SS
iNXI		N content of XI		0.03	g N g-1 XI
iNXS		N content of XS		0.04	g N g-1 XS
iNBM		N content of biomass, XH, XA		0.12	g N g-1 XH or A
iTSXI		TSS to COD ratio for XI		0.75	g TS g-1 XI
iTSXS		TSS to COD ratio for XS		0.75	g TS g-1 XS
iTSBM		TSS to COD ratio for biomass, XH, XA		0.9	g TS g-1 XH or A
iTSSTO		TSS to COD ratio for XSTO based on PHB		0.6	g TS g-1 XSTO

Table 15-ASU ASM 3 Model Inputs

Model Inputs			
SO	0.8	0 g O2 m-3	Dissolved Oxygen
SI	80	g COD m-3	Inert Soluble Material
SS	53	g COD m-3	Readily Biodegradable Organic Substrate
SNH	8.6	g N m-3	Ammonium Plus Ammonia Nitrogen
SN2	0	g N m-3	Dinitrogen
SNO	0	g N m-3	Nitrate Plus Nitrite Nitrogen
SHCO	5	mole HCO3- m-3	Alkalinity
XI	30	g COD m-3	Inert Particulate Organic Material
XS	62	g COD m-3	Slowly Biodegradable Organic Material
XH	528	g COD m-3	Heterotrophic Organisms
XSTO	0.25	g COD m-3	A Cell Internal Storage Product of Heterotrophic Organisms
XA	15.5	g COD m-3	Nitrifying Organisms
XTS	3000	g TSS m-3	Total Suspended Solids

The predicted BOD and ammonium concentration are presented in Chapter IV Table 21.

ASM 3 has been applied to the activated sludge units of the industrial waste treatment facility. ASM 3 will now be used to investigation effluent concentration through process control. Only process control inputs will be varied to maximize ammonium removal.

ASM 3 Input Parameter Sensitivity Analysis

The goal of this section is to change certain input parameters to determine how sensitivity the effluent ammonium concentration is when input parameters are varied. The focus will be on stoichiometric input parameters. The parameters of interest are the aerobic yield of heterotrophic biomass (YH, O2) and the yield of autotrophic biomass per NO3-N (YA).

The aerobic yield of heterotrophic biomass (YH, O2) will be varied from .295 to .5 g biomass per g COD in increments of .05 g biomass per g COD. This will be conducted to determine how sensitive ASM 3 effluent ammonium concentration is to the effects of changes in the aerobic yield of heterotrophic biomass.

Additionally, the yield of autotrophic biomass per NO3-N (YA) will be varied from .1 to .15 g biomass per g NH3-N with increments of .01 g biomass per g NH3-N. This will be conducted to determine how sensitive ASM 3 effluent ammonium concentration is to the effects of changes in the yield of autotrophic biomass.

Utilizing ASM 3 to Estimate the Reduction of Effluent Ammonium Concentration

The focus of this section is to change the process control reactor inputs to reduce the effluent ammonium concentration. The focus will be on two process control inputs. The dissolved oxygen concentration and the SRT can be controlled by ASU operator. The operator can increase or decrease the dissolved oxygen concentration by increasing or decreasing the diffused air blowers. The SRT can be increased or decreased by increasing or decreasing the waste sludge pumping rate. ASM 3 will be modified through the following options:

Option 1:   Increase the dissolved oxygen from 0.8 to 2 g O2 m-3 in increments of .1 g O2 m-3 only.
              Use the same parameter inputs demonstrated in Table 14.

Increasing the dissolved oxygen concentration creates a situation where more available oxygen would be available to the nitrifying bacterial culture. With more available oxygen the nitrifiers could then utilize more ammonium to create more nitrates.

Table 16- Model Inputs- Increase Dissolved Oxygen

Model Inputs			
SO	2	0 g O2 m-3	Dissolved Oxygen
SI	80	g COD m-3	Inert Soluable Material
SS	53	g COD m-3	Readily Biodegradable Organic Substrate
SNH	8.6	g N m-3	Ammonium Plus Ammonia Nitrogen
SN2	0	g N m-3	Dinitrogen
SNO	0	g N m-3	Nitrate Plus Nitrite Nitrogen
SHCO	5	mole HCO3- m-3	Alkalinity
XI	30	g COD m-3	Inert Particulate Organic Material
XS	62	g COD m-3	Slowly Biodegradable Organic Material
XH	528	g COD m-3	Heterotrophic Organisms
XSTO	0.25	g COD m-3	A Cell Internal Storage Product of Heterotrophic Organisms
XA	15.5	g COD m-3	Nitrifying Organisms
XTS	3000	g TSS m-3	Total Suspended Solids

The increase in the dissolved oxygen is represented in the change in variable SO. All other model inputs are held constant from Table 15.

The predicted effluent ammonium concentration is demonstrated in Chapter IV Table 22.

Option 2:   Reduce the SRT from 14 to 10 days in increments of 1 day only.
             Use the same model inputs as presented in Table 15.

Reducing the SRT will create a more overall active biomass. The overall biomass includes the nitrifying bacterial culture. If the nitrifiers are more active then they will utilize more ammonium to create more nitrates. Although, if the SRT is to low then nitrification will not occur under typical dissolved oxygen concentrations. For a dissolved oxygen concentration of .8 g O2 m-3 the theoretical SRT should not be lower than 8 days. (Metcalf et al. 2003)

Table 17- Parameter Inputs- Reduced SRT

Model Constants			
Kinetic Parameters			
Symbol	Characterization	Value	Units
kH	Hydrolysis rate constant	1.00	g XS g-1 XH d-1
KX	Hydrolysis saturation constant	1.00	g XS g-1 XH
Heterotrophic organisms, denitrification, XH			
kSTO	Storage rate constant	0.53	g SS g-1 XH d-1
nNO	Anoxic reduction factor	0.3	
KO	Saturation constant for SO	0.2	g O2 m-3
KNO	Saturation constant for SNO	0.5	g NO3- -Nm-3
KS	Saturation constant for substrate SS	2	g COD m-3
KSTO	Saturation constant for XSTO	1	g XSTO g-1 XH
uH	Heterotrophic max. growth rate	0.65	d-1
KNH	Saturation constant for ammonium, SNH	0.01	g N m-3
KHCO	Bicarbonate saturation constant of XH	0.1	mole HCO3- m-3
bH,O2	Aerobic endog. respiration rate of XH	0.2	d-1
bH,NO	Anoxic endog. respiration rate of XH	0.1	d-1
bSTO,O2	Aerobic respiration rate of XSTO	0.2	d-1
bSTO,NO	Anoxic respiration rate for XSTO	0.1	d-1
Autotrophic organisms, nitrification, XA			
uA	Autotrophic max. growth rate XA	0.1	d-1
KA,NH	Ammonium substrate saturation for XA	1	g N m-3
KA,O	Oxygen saturation for nitrifiers	0.6	g O2 m-3
KA,HCO	Bicarbonate saturation for nitrifiers	0.5	mole HCO3- m-3
bA,O2	Aerobic endog. respiration rate of XA	0.15	d-1

	Anoxic endog. respiration rate of XA	0.05	d-1
bA,NO			

Stoichiometric parameters			
Symbol	Characterization	Value	Units
f_{SI}	Production of SI in Hydrolysis	0	g SI g-1 XS
fXI	Production of XI in endog. Biomass respiration	0.12	g SI g-1 XS
YSTO,O2	Aerobic yield of stored product per SS	0.6	g XSTO g-1 SS
YSTO,NO	Anoxic yield of stored product per SS	0.5	g XSTO g-1 SS
YH,O2	Aerobic yield of heterotrophic biomass	0.295	g XH g-1 XSTO
YH,NO	Anoxic yield of heterotrophic biomass	0.2	g XH g-1 XSTO
YA	Yield of autotrophic biomass per NO3-N	0.1	g XA g-1 SNO
iNSI	N content of SI	0	g N g-1 SI
INSS	N content of SS	0	g N g-1 SS
iNXI	N content of XI	0.03	g N g-1 XI
iNXS	N content of XS	0.04	g N g-1 XS
iNBM	N content of biomass, XH, XA	0.12	g N g-1 XH or A
iTSXI	TSS to COD ratio for XI	0.75	g TS g-1 XI
iTSXS	TSS to COD ratio for XS	0.75	g TS g-1 XS
iTSBM	TSS to COD ratio for biomass, XH, XA	0.9	g TS g-1 XH or A
iTSSTO	TSS to COD ratio for XSTO based on PHB	0.6	g TS g-1 XSTO

The reduction in the SRT is represented in the change in variable uA (uA = 1/SRT). All other parameter inputs are held constant from Table 14.

The predicted effluent ammonium concentration is presented in Chapter IV Table 23.

CHAPTER IV

FINDINGS

Activated Sludge Model No. 3 (ASM 3) Validation

As presented in Chapter III, the validation process was completed by comparing the traditional analytical model with ASM 3. The purpose was to predict through ASM 3 a required HRT to remove a given concentration of substrate. The required HRT is then compared to the analytical model which is a more accepted way of predicting a required HRT. The results of the investigation are presented in Table 18 for BOD removal only and BOD removal with nitrification is presented in Table 19. The results of investigation are presented in Table 20 for denitrification.

Example 1 Complete-Mixed Activated Sludge Process Design for BOD Removal Only and for BOD Removal with Nitrification

Table 18- Example 1 Required HRT Comparison

Example 1 BOD Removal Only			
	ASM 3	Analytical	% Deviation
Influent sCOD	224 mg/L	224 mg/L	
Effluent sCOD	0	0	
Predicted HRT	4.29 hrs	4.3 hrs	0.34

ASM 3 accurately predicts the same required HRT as the analytical model. This HRT can then be used for reactor design. The .34 % deviation would be considered negligible.

Table 19- Example 1 Required HRT Comparison

Example 1 BOD Removal and Nitrification			
	ASM 3	Analytical	% Deviation
Influent NH3-N	28 mg/L	28 mg/L	
Effluent NH3-N	0	0	
Predicted HRT	9.9 hrs	9 hrs	10

ASM 3 predicts a longer required HRT than the analytical model. This does not mean that the required HRT that ASM 3 predicted is incorrect. ASM 3 is more conservative than the analytical model when modeling nitrification. ASM 3 incorporates 13 model inputs, 21 kinetic parameters and 16 stoichiometric parameters. The analytical model utilizes 4 equations with 5 stoichiometric parameters and 5 input variables. The conservatism that is incorporated into ASM 3 could be due to the complexity of the model. Although the simplicity of the analytical model is one of the reasons it is more widely accepted in the engineering profession and in academia. The 10 % additional conservatism would be considered acceptable in the engineering profession.

Example 2 Anoxic/ Aerobic Process Design

Table 20- Example 2 Required HRT Comparison

Example 2 Denitrification			
	ASM 3	Analytical	% Deviation
Influent NO3-N	28 mg/L	28 mg/L	
Effluent NO3-N	6 mg/L	6 mg/L	
Predicted HRT	2.1 hrs	1.5 hrs	41

ASM 3 predicts a longer required HRT than the analytical model. The ASM 3 predicted minimum HRT for denitrification appears to be overly conservative. Since the analytical model answer stated that an HRT of 2.5 hrs is acceptable, this leads the user to believe that an acceptable answer is between 1.5 and 2.5 hrs. The predicted ASM 3 HRT is acceptable under the range standard.

Utilizing ASM 3 to Model the ASU at the Industrial Wastewater Treatment Facility

As presented in Chapter III, ASM 3 was utilized to predict the effluent concentration of soluble COD (sCOD) and ammonium (NH3-N) in an industrial waste treatment process. The predicted effluent concentrations were then compared to measured effluent data. The goal was to use ASM 3 to accurately predict the measured effluent values. The results of the investigation are presented in Table 21.

Table 21- Effluent Prediction Comparison

ASU			
	ASM 3	Measured	% Error
Influent sCOD	225 mg/L	225 mg/L	
Effluent sCOD	11.4 mg/L	12.3 mg/L	7.2
Influent NH3-N	8.6 mg/L	8.6 mg/L	
Effluent NH3-N	3.1 mg/L	3.6 mg/L	13.8
HRT	.99 days	.99 days	

ASM 3 accurately predicts ammonium and COD removal when compared to the measured data. The error could be attributed to the estimated inputs, the unpredictable nature of microorganisms and the toxicity of the waste stream. Additionally the error could be to due to error introduced during collection of the measured data.

ASM 3 Input Parameter Sensitivity Analysis

As presented in Chapter III, an investigation was conducted into ASM 3 effluent ammonium concentration sensitivity when stoichiometric parameters are varied. As previously stated, YH, O2 was varied from .295 to .5 g biomass per g COD in increments of .05 g biomass per g COD. The results are presented in Figure 10.
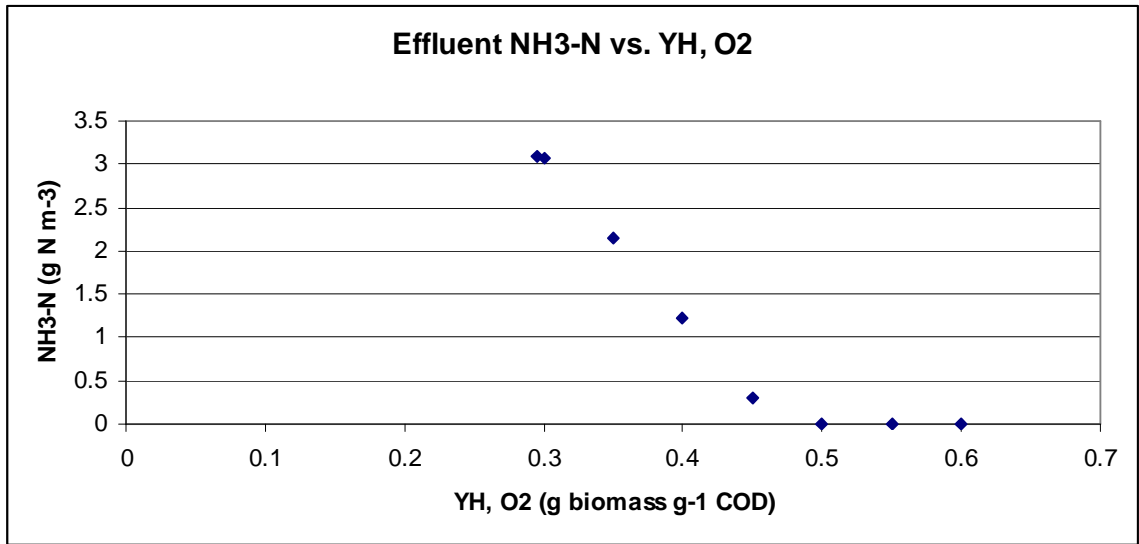
Figure 10- Sensitivity analysis- Aerobic yield of heterotrophic biomass (YH, O2)

Effluent ammonium concentration is very sensitive to changes in YH, O2. This is what was expected because YH, O2 is a stoichiometric parameter that is the ratio of biomass yield to COD concentration. If a culture of bacteria has a higher ratio then more biomass will be created, thus increasing the concentration of active nitrifying bacteria. This will lower the effluent concentration of ammonium. Also a culture of bacteria with a high YH, O2 places more emphasis on producing more bacteria. A bacterial culture with a lower YH, O2 places more emphasis on cell maintenance. An industrial wastewater used for this study would encourage a bacterial culture to perform more cell maintenance.

As previously stated, YA was varied from .1 to .15 g biomass per g NH3-N with increments of .01 g biomass per g NH3-N. The results are presented in Figure 11.
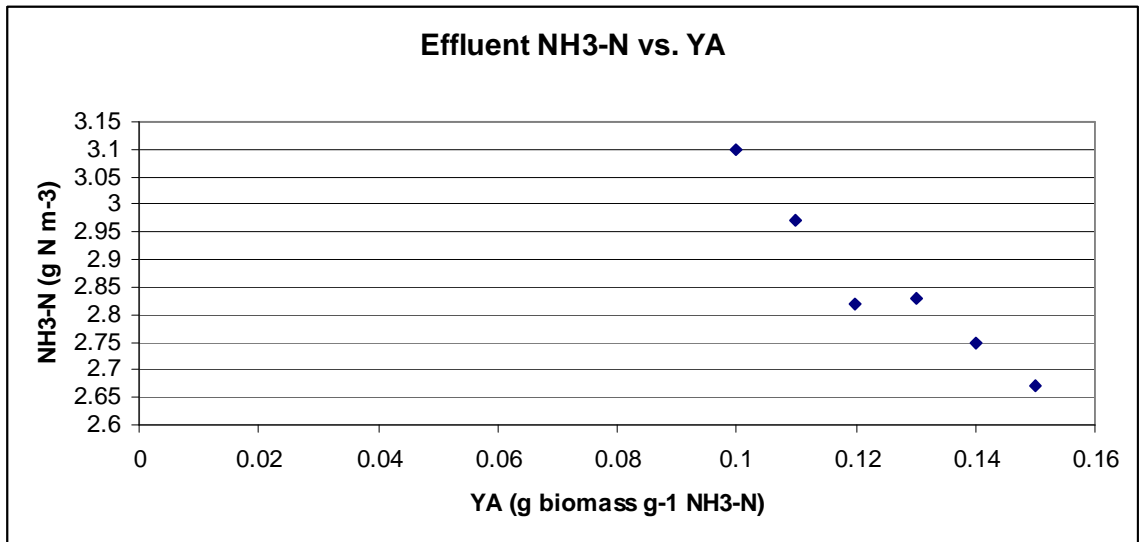
Fig. 11- Sensitivity analysis- Yield of autotrophic biomass per NO3-N (YA)

Effluent ammonium concentration is sensitive to changes in YA. This is what was expected because YA is a stoichiometric parameter that is the ratio of autotrophic biomass yield to NH3-N concentration. If a culture of bacteria has a higher ratio then more biomass will be created, thus increasing the concentration of active nitrifying bacteria. This will lower the effluent concentration of ammonium. Also a culture of bacteria with a high YA places more emphasis on producing more bacteria. A bacterial culture with a lower YA places more emphasis on cell maintenance. An industrial wastewater used for this study would encourage a bacterial culture to perform more cell maintenance. What was not expected is that when YH, O2 was varied the effluent concentration of NH3-N decrease at a faster than YA was varied.

Utilizing ASM 3 to Estimate the Reduction of Effluent Ammonium Concentration

As presented in Chapter III, ASM 3 was then used to predict the effluent ammonium concentration by varying process control variables. Specifically the dissolved oxygen concentration and SRT were varied.

The dissolved oxygen was increased from .8 to 2 g O2 m-3 by increments of .1 g O2 m-3. The results are presented in Figure 12 and Table 22.
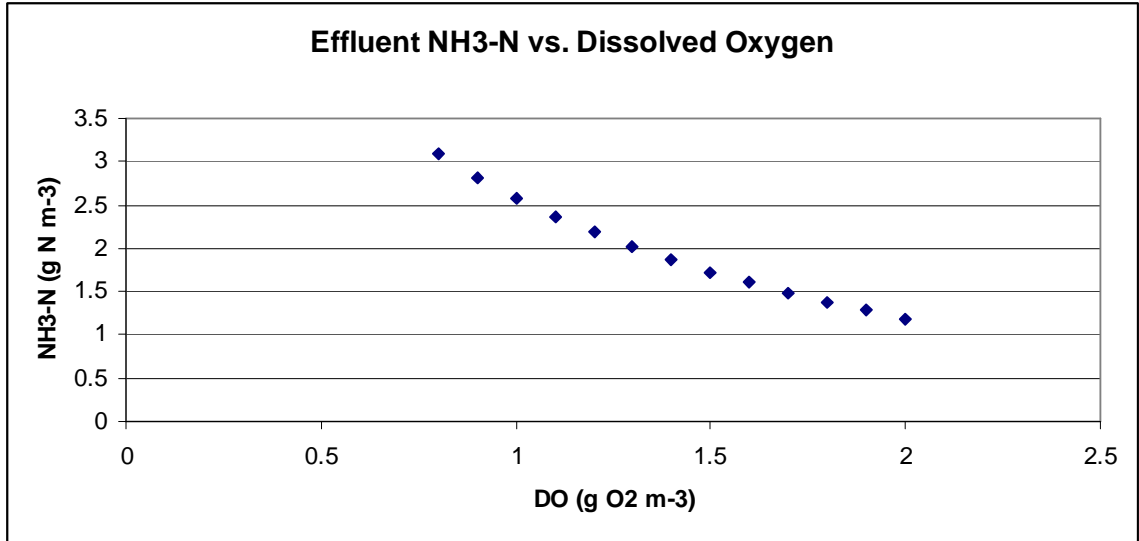

Fig. 12- Predicted Effluent Ammonium Concentration- Increased Dissolved Oxygen

Figure 12 demonstrates that as the DO is increased the ammonium concentration decreases. This is what is typically observed in wastewater treatment facilities. As previously stated in Chapter III, creating an environment where more oxygen is available will convert more ammonium to nitrate.

Table 22- Predicted Effluent Ammonium Concentration- Increased Dissolved Oxygen

ASU			
	ASM 3	ASM 3	% Ammonium Reduction (Theoretical)
Dissolved Oxygen	0.8 mg/L	2 mg/L	
Influent NH3-N	8.6 mg/L	8.6 mg/L	
Effluent NH3-N	3.1 mg/L	1.19 mg/L	61.3
HRT	.99 days	.99 days	

ASM 3 predicts that an increase of dissolved oxygen concentration from 0.8 to 2 g O2 m-3 will reduce the effluent ammonium concentration by 61.3%. This is a theoretical ammonium reduction percentage. 63.1 % reduction would be a signifgant reduction in ammonium concentration. In an industrial wastewater treatment facility the actual reduction could be more or less. The reason the reduction could be more or less is due to the difficulties in predicting the behavior of microorganisms.

The SRT was decreased from 14 to 10 days by increments of 1 day. The results are presented in Figure 13 and Table 23.
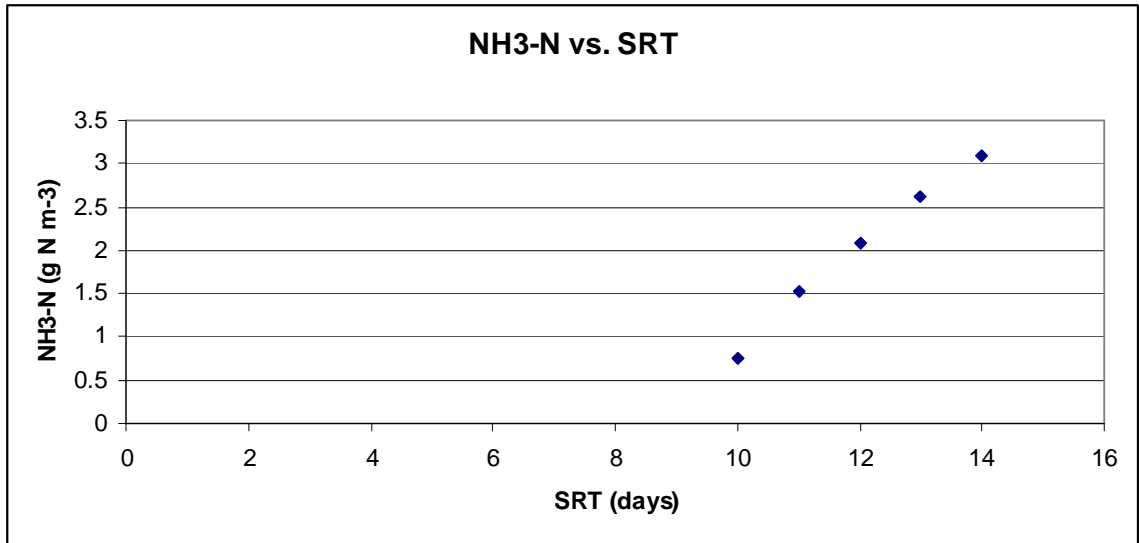

NH3-N vs. SRT

Fig. 13- Predicted Effluent Ammonium Concentration- Reduction in SRT

The Figure 13 indicates that if the SRT is reduced the ammonium concentration will be reduced also. As previously stated in Chapter III there is a theoretical minimum SRT. For the dissolved oxygen concentration of .8 g O2 m-3 the theoretical minimum SRT is 8 days. ASM 3 has incorporated a minimum SRT in the form of nitrifying organism concentration (XA). If the minimum SRT drops below 8 days, the ASM 3 user should input XA is equal to 0. If XA is equal to 0, nitrification will not occur in ASM 3. In ASM 3 the SRT and concentration of nitrifying bacteria are independent input parameters. In an activated sludge treatment facility they are dependent input parameters. The user of ASM 3 must recognize that this is the case.

ASU			
	ASM 3	ASM 3	% Ammonium Reduction (Theoretical)
SRT	14	10	
Influent NH3-N	8.6 mg/L	8.6 mg/L	
Effluent NH3-N	3.1 mg/L	.75 mg/L	75.8
HRT	.99 days	.99 days	

Table 23- Predicted Effluent Ammonium Concentration- Reduction in SRT

ASM 3 predicts that a reduction in the SRT from 14 to 10 days will reduce the effluent ammonium concentration by 75.8%. This is a theoretical ammonium reduction percentage. 75.8 % reduction would be a signifgant reduction in ammonium concentration. As previously stated in Chapter III, only the input parameter uA was adjusted. In the industrial wastewater treatment facility, an adjustment of the SRT would

also adjust other input parameters. It is unknown which input parameters would adjust, other than XA, as the SRT is lowered.

CHAPTER V

CONCLUSION

Conclusion

As previously stated in Chapter IV, the validation process was completed by comparing the analytical model with ASM 3. ASM 3 was utilized to predict the effluent concentration of soluble COD (sCOD) and ammonium (NH3-N); an investigation was conducted into ASM 3 effluent ammonium concentration sensitivity when stoichiometric parameters are varied; and ASM 3 was then used to predict the effluent ammonium concentration by varying process control variables. This section of the paper will discuss conclusions that can be drawn from the Chapter IV. The section will highlight the significant findings of the paper.

ASM 3 Validation

- ASM 3 can be used for the design of an activated sludge reactor basin that is for BOD removal only and BOD removal with nitrification.
- ASM 3 is more conservative than the analytical model for a design of reactor basins.
- It was hypothesized that ASM 3 conservatism could be attributed to ASM 3 complexities when compared to the analytical model.
- The analytical model is easy to use and more widely accepted in the engineering profession. However, it appears that ASM 3 has potential for design applications.

Utilizing ASM 3 to Model the ASU at the Industrial Wastewater Treatment Facility

- The nature of the waste stream led to an assumption of slowed microorganism activity. This assumption appears to have been validated by the performance of the model.
- ASM 3 successfully modeled the effluent BOD and ammonium concentration of the ASU.
-

ASM 3 Input Parameter Sensitivity Analysis

- The model is sensitive to changes to aerobic yield of heterotrophic biomass (YH, O2) and the yield of autotrophic biomass per NO3-N (YA).
- The effluent ammonium concentration decreases at a faster rate with changes to YH, O2 than with changes to YA.

Utilizing ASM 3 to Estimate the Reduction of Effluent Ammonium Concentration

- ASM 3 predicts that increasing the dissolved oxygen from .8 to 2 g O2 m-3 will decrease the effluent ammonium concentration.
- ASM 3 predicts that reducing the SRT from 14 to 10 days will decrease the effluent ammonium concentration.

- Nitrification within ASM 3 is particularly sensitive to the SRT and dissolved oxygen.
- In ASM 3, the SRT is independent of autotrophic biomass concentration.
- If adjusting the SRT, special care must be taken to ensure the nitrifying biomass concentration is reasonable.
- The model must be used with care as small changes in the SRT or dissolved oxygen could significantly change the model inputs and stoichiometric parameters.

Recommendations for Future Work

- To ensure accuracy of the ASM 3, batch tests should be conducted to develop model and parameter inputs.
- Future work could be conducted into the area of developing more specific input parameters.

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APPENDICES

VITA

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Master of Science

Thesis: THE USE OF ACTIVATED SLUDGE MODEL NO. 3 TO MODEL AN
ACTIVATED SLUDGE UNIT AT A PETROLEUM REFINERY
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Major Field: Environmental Engineering

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Completed the requirements for the Bachelor of Science Civil and
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Title of Study: THE USE OF ACTIVATED SLUDGE MODEL NO. 3 TO MODEL AN
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Pages in Study: 54   Candidate for the Degree of Master of Science

Major Field: Environmental Engineering

Scope and Method of Study:

The objective of this research is to (I) introduce the Activated Sludge Models (ASM), (II) examine the validity of Activated Sludge Model No. 3 (ASM 3), (III) apply ASM 3 to a specific industrial activated sludge unit to determine if the model accurately predicts the effluent ammonium concentration, (IV) determine the ammonium concentration sensitivity when stoichiometric parameters are varied, and (V) investigate changes in model inputs to reduce the effluent concentration of ammonium.

To achieve the objectives of the paper, this work will (I) review literature pertaining to the Activated Sludge Models, (II) apply Activated Sludge Model No. 3 to example problems from environmental engineering literature, (III) apply ASM 3 to the industrial activated sludge unit to replicate the measured effluent, (IV) change stoichiometric parameters within ASM 3 to determine what occurs to the effluent ammonium concentration, and (V) change input parameters that can be controlled through process control to determine what occurs to the effluent ammonium concentration.

Findings and Conclusions:

Through this work, it was found that ASM 3 can be used for the design of an activated sludge reactor basin that is for BOD removal only and BOD removal with nitrification. ASM 3 can be used to model an ASU at an industrial wastewater treatment facility. The model is sensitive to changes to aerobic yield of heterotrophic biomass (YH, O2) and the yield of autotrophic biomass per NO3-N (YA). For this ASU, the general trend is that if the dissolved oxygen is increased and the SRT is reduced then the effluent ammonium concentration should be reduced.

ADVISER'S APPROVAL: Dr. Greg Wilber