COMPUTER SIMULATION OF A COMPLETE BIOLOGICAL TREATMENT PLANT

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

PINAR TOPKAYA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ENVIRONMENTAL ENGINEERING

JULY 2008

Approval of the thesis:

COMPUTER SIMULATION OF A COMPLETE BIOLOGICAL TREATMENT PLANT

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ABSTRACT

COMPUTER SIMULATION OF A COMPLETE BIOLOGICAL TREATMENT PLANT

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July 2008, 159 pages

Nitrogen and phosphorus removal is often required before discharge of treated wastewater to sensitive water bodies. Kayseri Wastewater Treatment Plant (KWWTP) is a biological wastewater treatment plant that includes nitrogen and phosphorus removal along with carbon removal. The KWWTP receives both municipal wastewater and industrial wastewaters. In this study, KWWTP was modeled by using a software called GPS-X, which is developed for modeling municipal and industrial wastewaters. The Activated Sludge Model No.2d (ASM2d) developed by the International Association on Water Quality (IAWQ) was used for the simulation of the treatment plant. In this model, carbon oxidation, nitrification, denitrification and biological phosphorus removal are simulated at the same time.

During the calibration of the model, initially, sensitivities of the model parameters were analyzed. After sensitivity analysis, dynamic parameter estimation (DPE) was carried out for the optimization of the sensitive parameters. Real plant data obtained from KWWTP were used for DPE. The calibrated model was validated by using different sets of data taken from various seasons after necessary temperature adjustments made on the model.

Considerably good fits were obtained for removal of chemical oxygen demand (COD), total suspended solids (TSS) and nitrogen related compounds. However, the results for phosphorus removal were not satisfactory, probably due to lack of information on volatile fatty acids concentration and alkalinity of the influent wastewater.

Keywords: activated sludge, biological nutrient removal, activated sludge models, GPS-X, ASM2d.

ÖZ

BİLGİSAYAR YARDIMIYLA KOMPLE BİR BİYOLOJİK ARITMA TESİSİNİN MODELLENMESİ

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Temmuz 2008, 159 sayfa

Arıtılmış atıksuların hassas alıcı ortamlara deşarjından önce genellikle azot ve fosfor arıtımı gerekmektedir. Kayseri Atıksu Arıtma Tesisi (KAAT) karbon arıtımı ile birlikte azot ve fosfor arıtımı içeren bir biyolojik atıksu arıtma tesisidir. KAAT'ye hem evsel hem de endüstriyel atıksu gelmektedir. Bu çalışmada, evsel ve endüstriyel atıksu modellemek üzere geliştirilmiş olan GPS-X isimli yazılım kullanılarak KAAT modellenmiştir. Uluslararası Su Kalitesi Birliği (IAWQ) tarafından geliştirilen Aktif Çamur Model No.2d (ASM2d) isimli model bu arıtma tesisinin modellenmesi için kullanılmıştır. Bu modelle karbon oksidasyonu, nitrifikasyon, denitrifikasyon ve biyolojik fosfor arıtımı aynı anda modellenebilmektedir.

Modelin kalibrasyonu sırasında, öncelikle, model parametrelerinin sensitiviteleri analiz edilmiştir. Sensitivite analizinin sonrasında, sensitivitesi yüksek olan parametrelerin optimizasyonu için dinamik parametre tahmini (DPT) yapılmıştır. DPT için KAAT'den alınan gerçek veriler kullanılmıştır. Kalibre edilmiş model, sıcaklıkla ilgili gerekli düzeltmeler yapıldıktan sonra farklı mevsimlere ait veri setleri ile test edilmiştir.

Kimyasal oksijen ihtiyacı (KOİ), askıda katı madde (AKM) ve azotla ilgili bileşiklerin arıtımına dair oldukça iyi sonuçlar elde edilmiştir. Ancak, ham atıksudaki uçucu yağ asitleri ve alkaliniteye dair veri olmaması nedeniyle, fosfor arıtımı ile ilgili tatmin edici sonuçlar elde edilememiştir.

Anahtar Kelimeler: aktif çamur, biyolojik besin tuzları arıtımı, aktif çamur modelleri, GPS-X, ASM2d.

To my family…

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor Prof. Dr. Celal F. Gökçay for his valuable guidance, advise, criticism and encouragements throughout this study.

I wish to express my appreciation to Hakan Ayyıldız for providing all the necessary information and data about Kayseri Wastewater Treatment Plant.

Finally, I would like to express my deepest appreciation to my family for their endless support, understanding and encouragement throughout my study.

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CHAPTER 1

INTRODUCTION

Removal of nutrients is often required before discharge of treated wastewater to sensitive water bodies. As the urban population keeps growing, the amount of wastewater generated increases and consideration is given to more stringent limits for nitrogen and phosphorus in wastewater discharge to lift the pressure over receiving waters.

The presence of nitrogen compounds is due to the protein metabolism in the human body and wastewater of domestic origin contains nitrogen in the organic and ammonium forms. In fresh municipal wastewater approximately 60% of the nitrogen is in organic form and 40% is in ammonium form. Normally, very little (less than 1%) of nitrogen is in the oxidized form of nitrate and nitrite in fresh municipal wastewater.

The presence of nitrogen in discharged wastewater is not desired for several reasons. Firstly, free ammonia is toxic to fish and many other aquatic organisms. Ammonium ion or ammonia is an oxygen-consuming compound which depletes dissolved oxygen in receiving water bodies. Nitrate ion is a potential public health hazard when it is consumed by infants. Furthermore nitrogen, in all forms, can be available as a nutrient to aquatic plants and eventually its presence causes eutrophication.

The presence of phosphorus in municipal wastewater is due to fecal and industrial sources and the use of synthetic detergents and household cleaning products. In municipal wastewaters the concentration of phosphorus is 4-16 mg/L as P. Wasting of excess sewage sludge from an activated sludge plant results in 10-30% removal of phosphorus since typical phosphorus content of microbial solids is 1.5-2% on dry weight basis. Nowadays, many wastewater treatment plants have biological phosphorus removal systems which result in the growth of a biological population that has much higher cellular phosphorus content. In these systems, the overall phosphorus content is in the range of 3-6% and this leads to lower effluent phosphorus concentrations [1]. Phosphorus is a limiting nutrient in most freshwater systems; therefore removal of phosphorus may be used to control eutrophication. Biological phosphorus removal can be achieved by making operational modifications to conventional treatment systems.

More stringent effluent standards for phosphorus and nitrogen are expected to take effect in future due to water quality problems [2]. For instance, an increasing number of nutrient-removing biological treatment plants are being built in Turkey or the existing ones are being modified for nutrient removal.

Mathematical modeling of these systems has many benefits. International Association on Water Quality (IAWQ) Task Group has developed several Activated Sludge Models for the simulation of carbon oxidation, nitrification, denitrification, and biological phosphorus removal. These models are not the final answer to biological treatment models. However, it is a compromise between complexity and simplicity. These models are tools for research (testing results or optimizing experiments), process optimization and troubleshooting at full-scale treatment plants, teaching and design assistance (for optimization of details). For instance, optimization for modern nutrient removal plants is very complicated due to the presence of many interacting processes. Therefore a model would be a valuable tool for optimizing the operation and for evaluating and implementing new procedures [3].

CHAPTER 2

AIM OF THE STUDY

The aim of the study is the modeling of Kayseri Wastewater Treatment Plant (WWTP) by using a simulation program called GPS-X. This simulation program is a multi-purpose modeling environment for the simulation of municipal and industrial wastewater treatment plants. For the modeling of Kayseri WWTP, which involves Biological Nutrient Removal processes, Activated Sludge Model No 2d (ASM2d) will be used. ASM2d is capable of simulating nitrogen and phosphorus removal processes.

Modeling can be used for various reasons. It can be used as a research tool to evaluate biological processes and to better understand important parameters that affect a certain type of performance. It can also be used during WWTP design and evaluating the treatment capacity of a given facility [4]. This way, the behavior of the treatment plant can be predicted before it is built.

It is aimed in this thesis to calibrate the GPS-X program with the real data from Kayseri WWTP and to check the calibration with a new set of data for validation. It is believed that computer simulations aid better plant operation and may facilitate visualization of effects of configuration changes on the plant performance without actually altering the plant.

CHAPTER 3

ACTIVATED SLUDGE MODELING

3.1. Biological Nutrient Removal

Nitrogen and phosphorus removal is often required when treated waters are discharged to sensitive water bodies. The discharge standards for nutrients are given in The Urban Wastewater Treatment Regulation as presented in Table 3.1.

Table 3.1 Discharge Standards in Urban Wastewater Treatment Regulation [5]

Parameter	Concentration
Total Phosphorus	2 mg/L (10000-100000 P.E.) 1 mg/L (>100000 P.E.)
Total Nitrogen	15 mg/L (10000-100000 P.E.) 10 mg/L (>100000 P.E.)

3.1.1. Biological Nitrogen Removal

Nitrogen exists in various forms. In ammonium and organic nitrogen compounds, which are the forms most closely associated with plants and animals, its oxidation state is -3. On the other hand, when nitrogen is in nitrate form, the oxidation state is +5. In municipal wastewaters that are predominantly from domestic origin, nitrogen is mostly in organic and ammonium forms.

Figure 3.1 shows the nitrogen transformation occurring during biological treatment processes.

Initially, organic nitrogen in raw wastewater is transformed into ammonia nitrogen through bacterial decomposition. In any biological treatment system some bacteria growth always take place. Since nitrogen is essential for microbial growth, any net growth of biomass will cause some nitrogen removal. Nitrogen constitutes 12% of cell dry mass, therefore nitrogen is assimilated by the newly formed cells. Depending on the treatment process, cell autooxidation and lysis also takes place. The remaining assimilated nitrogen may be removed from the system by growth and wasted in excess biological sludge. Ammonia nitrogen can be transformed into nitrate by nitrification.

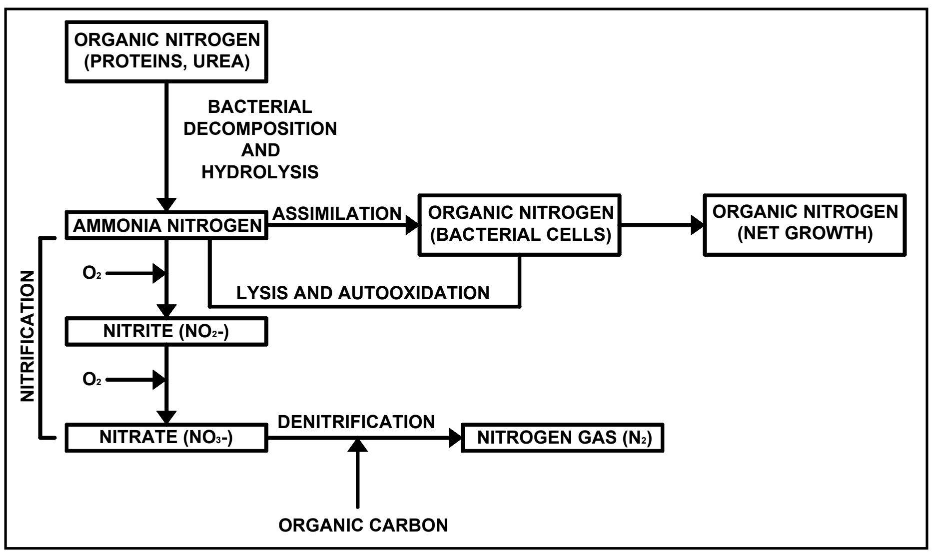

Figure 3.1 Nitrogen Transformation in Biological Treatment Processes

Nitrification is the biological oxidation of ammonia to nitrate with nitrite formation as an intermediate. Two autotrophic microorganisms *Nitrosomonas* and *Nitrobacter* carry out the reaction in two steps;

$$2\ NH_4^+ + 3\ O_2 \xrightarrow{\text{Nitrosomonas}} 2\ NO_2^- + 2\ H_2O + 4\ H^+ + \text{new cells}$$

$$2\,NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} 2\,NO_3^- + \text{new cells}$$

Finally, nitrates are transformed into nitrogen gas through denitrification. Denitrification is the biological conversion of nitrate-nitrogen into more reduced forms (N_2, N_2O, NO) by a variety of facultative heteretrophs that utilize nitrate instead of oxygen as the final electron acceptor.

3.1.2. Biological Phosphorus Removal

Biological phosphorus removal involves design or operational modifications on conventional treatment systems that result in the growth of a biological population having much higher cellular phosphorus content.

Biological phosphorus removal includes an anaerobic zone followed by an aerobic zone. It is based on the following facts;

- Bacteria are capable of storing excess amounts of phosphorus as polyphosphates,
- These bacteria are capable of removing simple fermentation substrates produced in the anaerobic zone and assimilating them into storage products within their cells. This process involves release of phosphorus,
- In the aerobic zone, energy is produced by the oxidation of storage products and polyphosphate storage occurs in the cells.

Anaerobic zone acts as a “biological selector” for phosphorus-storing microorganisms.

There are many factors that affect phosphorus removal efficiency. These factors are listed below;

- Environmental factors (such as DO, temperature, pH)
- Design parameters (such as solids retention time, anaerobic zone detention time, aerobic zone detention time, waste sludge handling methods)

- Substrate availability is affected by influent wastewater characteristics, the level of VFA production and the presence of nitrates [1].

3.2. Activated Sludge Models

3.2.1. Activated Sludge Model No.1

Knowing the benefits of mathematical modeling, the International Association on Water Quality (IAWQ) has formed a task group and developed Activated Sludge Model No.1 (ASM1). Large number of reactions between different components are sequentially or simultaneously take place in activated sludge systems. These reactions are related with carbon oxidation, nitrification, and denitrification.

In ASM1, four processes are considered: growth of biomass, decay of biomass, ammonification of organic nitrogen, and hydrolysis of particulate organics which are entrapped in bioflocs.

In this model, substrate is partitioned into two fractions: readily and slowly biodegradable substrate. The total COD in the influent wastewater is made up of:

$$\text{Total COD} = S_S + X_S + X_I + S_I \quad \text{eq. 3.1}$$

where;

S_S : readily biodegradable substrate,
X_S : slowly biodegradable substrate,
X_I : inert suspended organic matter,
S_I : inert soluble organic matter.

A matrix is developed to identify the biological processes occurring in the system, as presented in Table 3.2. The processes are listed in the leftmost column and the kinetic expressions or rate equations for each process are given in the rightmost column in the matrix format [6].

Table 3.2 Process Kinetics and Stoichiometry for Carbon Oxidation, Nitrification, and Denitrification in ASM1 [6]

Components → i / j ↓ Process	1 S_I	2 S_S	3 X_I	4 X_S	5 $X_{B,H}$	6 $X_{B,A}$	7 X_P	8 S_O	9 S_{NO}	10 S_{NH}	11 S_{ND}	12 X_{ND}	13 S_{ALK}	Process Rate, ρ_j [$ML^{-3}T^{-1}$]
1 Aerobic growth of heterotrophs		$-\frac{1}{Y_H}$			1			$-\frac{1-Y_H}{Y_H}$		$-i_{XB}$			$-\frac{i_{XB}}{14}$	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{O,H}+S_O}\right)X_{B,H}$
2 Anoxic growth of heterotrophs		$-\frac{1}{Y_H}$			1				$-\frac{1-Y_H}{2.86Y_H}$	$-i_{XB}$			$\frac{1-Y_H}{14\cdot 2.86Y_H} - i_{XB}/14$	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\eta_g X_{B,H}$
3 Aerobic growth of autotrophs						1		$\frac{4.57-Y_A}{Y_A}$	$\frac{1}{Y_A}$	$-i_{XB}-\frac{1}{Y_A}$			$-\frac{i_{XB}}{14}-\frac{1}{7Y_A}$	$\hat{\mu}_A\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_O}{K_{O,A}+S_O}\right)X_{B,A}$
4 Decay of heterotrophs				$1-f_P$	-1		f_P					$i_{XB}-f_P i_{XP}$		$b_H X_{B,H}$
5 Decay of autotrophs				$1-f_P$		-1	f_P					$i_{XB}-f_P i_{XP}$		$b_A X_{B,A}$
6 Ammonification of soluble organic nitrogen										1	-1		$\frac{1}{14}$	$k_a S_{ND} X_{B,H}$
7 Hydrolysis of entrapped organics		1		-1										$k_h \frac{X_S/X_{B,H}}{K_X+(X_S/X_{B,H})}\left[\left(\frac{S_O}{K_{O,H}+S_O}\right)+\eta_h\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\right]X_{B,H}$
8 Hydrolysis of entrapped organic nitrogen											1	-1		$\rho_7(X_{ND}/X_H)$
Observed Conversion Rates [$ML^{-3}T^{-1}$]	$r_i=\sum_j v_{ij}\rho_j$													
Stoichiometric Parameters: Heterotrophic yield: Y_H; Autotrophic yield: Y_A; Fraction of biomass yielding particulate products: f_P; Mass N/Mass COD in biomass: i_{XB}; Mass N/Mass COD in products from biomass: i_{XB}	Soluble inert organic matter [$M(COD)L^{-3}$]	Readily biodegradable substrate [$M(COD)L^{-3}$]	Particulate inert organic matter [$M(COD)L^{-3}$]	Slowly biodegradable substrate Soluble inert organic matter [$M(COD)L^{-3}$]	Active heterotrophic biomass [$M(COD)L^{-3}$]	Active autotrophic biomass [$M(COD)L^{-3}$]	Particulate products arising from biomass decay [$M(COD)L^{-3}$]	Oxygen (negative COD) [$M(COD)L^{-3}$]	Nitrate and nitrite nitrogen [$M(COD)L^{-3}$]	$NH_4^+ + NH_3$ nitrogen [$M(COD)L^{-3}$]	Soluble biodegradable organic nitrogen [$M(COD)L^{-3}$]	Particulate biodegradable organic nitrogen [$M(COD)L^{-3}$]	Alkalinity – Molar units	Kinetic Parameters: Heterotrophic growth and decay: $\hat{\mu}_H$, K_S, $K_{O,H}$, K_{NO}, b_H; Autotrophic growth and decay: $\hat{\mu}_A$, K_{NH}, $K_{O,A}$, b_A; Correction factor for anoxic growth of heterotrophs: η_g; Ammonification: k_a; Hydrolysis: k_h, K_X; Correction factor for anoxic hydrolysis: η_h

3.2.2. Activated Sludge Model No.2 and No.2d

Activated Sludge Model No.2 (ASM2) has been developed for the dynamic simulation of combined biological processes for COD, nitrogen, and phosphorus removal. The ASM2 is an extension of ASM1 which has proven to be an excellent tool for modeling nitrification-denitrification processes. The kinetics and stoichiometry used to describe the processes are mainly based on Monod kinetics for all the components involved.

More biological processes are added to the ASM1 to simulate biological phosphorus removal in ASM2. In addition to the biological processes, ASM2 includes two 'chemical processes' which may be used to model chemical precipitation of phosphorus.

Model components are distinguished between soluble (S) and particulate (X). Particulate components are assumed to be associated with the activated sludge (flocculated onto the activated sludge). Therefore, they can only be concentrated by sedimentation or thickening. On the other hand, soluble components are only transported with the wastewater.

ASM2d is a minor extension of ASM2 and it includes two more processes to simulate phosphorus removal during denitrification by phosphorus accumulating organisms (PAO).

<u>Definition of Soluble Components</u>

S_A : Fermentation products, considered to be acetate. Since fermentation is included in the biological processes, the fermentation products must be modeled separately from other soluble organic materials.

S_{ALK} : Alkalinity of the wastewater. Alkalinity is used to approximate the continuity of electrical charges in biological reactions.

S_F : Fermentable, readily biodegradable organic substances. This fraction of the soluble COD is directly available for biodegradation by heterotrophic organisms.

S_I : Inert soluble organic material. These organics cannot be further degraded by the microorganisms.

S_{N2} : Dinitrogen, N_2. It is assumed to be the only product of denitrification.

S_{NH4} : Ammonium plus ammonia nitrogen. For the electrical balance of the electrical charges, S_{NH4} is assumed to be all NH_4^+.

S_{NO3} : Nitrate plus nitrite nitrogen. For all stoichiometric computations S_{NO3} is considered to be NO_3^--N only.

S_{O2} : Dissolved oxygen. It may be subject to gas exchange.

S_{PO4} : Inorganic soluble phosphorus, primarily ortho-phosphates. For the balance of electrical charges, it is assumed that S_{PO4} consists of 50% $H_2PO_4^-$ and 50% HPO_4^{-2}, independent of pH.

S_S : Readily biodegradable substrate. This component was introduced in ASM1. In ASM2, it is replaced by the sum of $S_F + S_A$.

Definition of Particulate Components

X_{AUT} : Nitrifying organisms. Nitrifying organisms are responsible for nitrification. It is assumed that nitrifiers oxidize ammonium directly to nitrate.

X_H : Heterotrophic organisms. They may grow aerobically and anoxically (denitrification) and be active anaerobically (fermentation).

X_I : Inert particulate organic material. This material is not biodegradable. It is flocculated onto the activated sludge.

X_{MeOH} : Metal-hydroxides. This component represents the phosphorus-binding capacity of possible metal-hydroxides, which may be in the wastewater or may be added to the system.

X_{MeP} : Metal-phosphate, $MePO_4$. This component results from binding of phosphorus to the metal-hydroxides.

X_{PAO} : Phosphate-accumulating organisms, PAO. These organisms are assumed to be representative for all types of poly-phosphate-accumulating organism. In ASM2d, it is assumed that these organisms may grow in an anoxic environment as well as aerobic environment; whereas in ASM2 only aerobic growth is considered.

X_{PHA} : A cell internal storage product of phosphorus-accumulating organisms. It includes poly-hydroxy-alkanoates, glycogen, etc.

X_{PP} : Poly-phosphate. It is an internal inorganic storage product of PAO.

X_S : Slowly biodegradable substrates. Slowly biodegradable substrates are high molecular weight, colloidal and particulate organic substrates which must undergo cell external hydrolysis before they are available for degradation.

X_{TSS} : Total suspended solids, TSS. Total suspended solids include both inorganic and organics, and are introduced into the biokinetic models in order to compute their concentration via stoichiometry.

Definition of Kinetic Parameters

- Hydrolysis of particulate substrates: X_S
  K_h : Hydrolysis rate constant
  η_{NO3} : Anoxic hydrolysis reduction factor
  η_{fe} : Anaerobic hydrolysis reduction factor
  K_{O2} : Saturation/inhibition coefficient for oxygen
  K_{NO3} : Saturation/inhibition coefficient for nitrate
  K_X : Saturation coefficient for particulate COD

- Heterotrophic organisms: X_H

  μ_H : Maximum growth rate on substrate

  q_{fe} : Maximum rate for fermentation

  η_{NO3} : Reduction factor for denitrification

  b_H : Rate constant for lysis and decay

  K_{O2} : Saturation/inhibition coefficient for oxygen

  K_F : Saturation coefficient for growth on S_F

  K_{fe} : Saturation coefficient for fermentation of S_F

  K_A : Saturation coefficient for growth on acetate S_A

  K_{NO3} : Saturation/ inhibition coefficient for nitrate

  K_{NH4} : Saturation coefficient for ammonium (nutrient)

  K_P : Saturation coefficient for phosphate (nutrient)

  K_{ALK} : Saturation coefficient for alkalinity (HCO_3^-)

- Phosphorus-accumulating organisms: X_{PAO}

  q_{PHA} : Rate constant for storage of X_{PHA} (base X_{PP})

  q_{PP} : Rate constant for storage of X_{PP}

  μ_{PAO} : Maximum growth rate of PAO

  η_{NO3} : Reduction factor for anoxic activity

  b_{PAO} : Rate for lysis of X_{PAO}

  b_{PP} : Rate for lysis of X_{PP}

  b_{PHA} : Rate for lysis of X_{PHA}

  K_{O2} : Saturation/inhibition coefficient for oxygen

  K_{NO3} : Saturation coefficient for nitrate, S_{NO3}

  K_A : Saturation coefficient for acetate S_A

  K_{NH4} : Saturation coefficient for ammonium (nutrient)

  K_{PS} : Saturation coefficient for phosphorus in storage of PP

  K_P : Saturation coefficient for phosphate (nutrient)

  K_{ALK} : Saturation coefficient for alkalinity (HCO_3^-)

  K_{PP} : Saturation coefficient for poly-phosphate

  K_{MAX} : Maximum ratio of X_{PP}/X_{PAO}

K_{IPP} : Inhibition coefficient for PP storage

K_{PHA} : Saturation coefficient for PHA

- Nitrifying organisms (autotrophic organisms): X_{AUT}

  μ_{AUT} : Maximum growth rate of X_{AUT}

  b_{AUT} : Decay rate of X_{AUT}

  K_{O2} : Saturation coefficient for oxygen

  K_{NH4} : Saturation coefficient for ammonium (substrate)

  K_{ALK} : Saturation coefficient for alkalinity (HCO_3^-)

  K_P : Saturation coefficient for phosphorus (nutrient)

- Precipitation

  k_{PRE} : Rate constant for P precipitation

  k_{RED} : Rate constant for redissolution

  K_{ALK} : Saturation coefficient for alkalinity

Similar to ASM1, the biokinetic models of ASM2 and ASM2d are presented in matrix notation. Processes included in these models are: (1) hydrolysis processes, (2) processes of heterotrophic organisms, (3) processes of phosphorus accumulating organisms, (4) processes of nitrifying organisms (autotrophic organisms) and (5) simultaneous precipitation of phosphorus with ferric hydroxide $Fe(OH)_3$. The process rate equations for ASM2d are presented in Table 3.3.

ASM2 and ASM2d can be used for modeling simultaneous biological phosphorus uptake and nitrification-denitrification. However, ASM2d will improve the accuracy as compared to ASM2 as it includes both nitrate and phosphate treatment.

ASM2d has some limitations. These are: (1) the model is valid for only municipal wastewater, (2) the wastewater must contain sufficient Mg^{++} and K^+, (3) pH should be near neutral and (4) temperature is expected to be in the range of 10-25ºC [3,7].

Table 3.3 Process Rate Equations for ASM2d

j	Process	Process rate equation ρ_j. $\rho_j \geq 0$
Hydrolysis processes:		
1	Aerobic hydrolysis	$K_h \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{X_S/X_H}{K_X+X_S/X_H} X_H$
2	Anoxic hydrolysis	$K_h \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{X_S/X_H}{K_X+X_S/X_H} X_H$
3	Anaerobic hydrolysis	$K_h \eta_{fe} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{K_{NO3}}{K_{NO3}+S_{NO3}} \frac{X_S/X_H}{K_X+X_S/X_H} X_H$
Heterotrophic organisms: X_H		
4	Growth on fermentable substrates, S_F	$\mu_H \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_F}{K_F+S_F} \frac{S_F}{S_F+S_A} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
5	Growth on fermentation products, S_A	$\mu_H \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_A}{K_A+S_A} \frac{S_A}{S_F+S_A} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
6	Denitrification with fermentable substrates, S_F	$K_h \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_F}{K_F+S_F} \frac{S_F}{S_F+S_A} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
7	Denitrification with fermentation products, S_A	$K_h \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_A}{K_A+S_A} \frac{S_A}{S_F+S_A} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
8	Fermentation	$q_{fe} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{K_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_F}{K_F+S_F} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
9	Lysis	$b_H X_H$
Phosphorus accumulating organisms (PAO): X_{PAO}		
10	Storage of X_{PHA}	$q_{PHA} \frac{S_A}{K_A+S_A} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PP}/X_{PAO}}{K_{PP}+X_{PP}/X_{PAO}} X_{PAO}$
11	Aerobic storage of X_{PP}	$q_{PP} \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_{PO4}}{K_{PS}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}} \frac{K_{MAX}-X_{PP}/X_{PAO}}{K_{IPP}+K_{MAX}-X_{PP}/X_{PAO}} X_{PAO}$
12	Anoxic storage of X_{PP}	$\rho_{12} = \rho_{11} \eta_{NO3} \frac{K_{O2}}{S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}}$
13	Aerobic growth on X_{PHA}	$\mu_{PAO} \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}} X_{PAO}$
14	Anoxic growth on X_{PHA}	$\rho_{14} = \rho_{13} \eta_{NO3} \frac{K_{O2}}{S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}}$
15	Lysis of X_{PAO}	$b_{PAO} X_{PAO} S_{ALK}/(K_{ALK}+S_{ALK})$
16	Lysis of X_{PP}	$b_{PP} X_{PP} S_{ALK}/(K_{ALK}+S_{ALK})$
17	Lysis of X_{PHA}	$b_{PHA} X_{PHA} S_{ALK}/(K_{ALK}+S_{ALK})$
Nitrifying organisms (autotrophic organisms): X_{AUT}		
18	Aerobic growth of X_{AUT}	$\mu_{AUT} \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_{AUT}$
19	Lysis of X_{AUT}	$b_{AUT} X_{AUT}$
Simultaneous precipitation of phosphorus with ferric hydroxide $Fe(OH)_3$		
20	Precipitation	$k_{PRE} S_{PO4} X_{MeOH}$
21	Redissolution	$k_{RED} X_{MeP} S_{ALK}/(K_{ALK}+S_{AKL})$

3.2.3. Activated Sludge Model No.3

The Activated Sludge Model No.3 (ASM3) relates to ASM1 and corrects some inadequacies of ASM1 [8]. Therefore, ASM3 does not involve biological phosphorus removal processes that were presented in ASM2 and ASM2d.

3.3. Sedimentation Tank Modeling

Sedimentation is one of the most important unit processes in activated sludge treatment plants. The sedimentation models are either zero- or one-dimensional, and either reactive or nonreactive. The following models are available:

- Zero-dimensional, nonreactive: point
- One-dimensional, nonreactive: simple1d
- One-dimensional, reactive: mantis, asm1, asm2d, asm3, newgeneral.

In simple1d, it is assumed that there are no biological reactions in the primary clarifiers and the settler is divided into a number of layers of equal thickness. Figure 3.2 shows the sedimentation model.

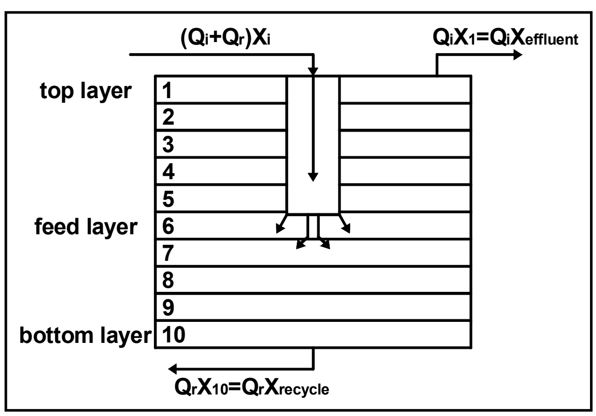

Figure 3.2 Sedimentation Model

Following assumptions are made in this model:

- Only vertical flow is considered,
- Incoming solids are distributed instantaneously and uniformly across the entire cross-sectional area of the feed.

The model is based on the solids flux concept: a mass balance is performed around each layer, providing for the simulation of the solids profile throughout the settling column under both steady-state and dynamic conditions.

In the simple1d sedimentation model, the only numerically integrated variable is the suspended solids concentration. The concentrations of the soluble state variables are not changed in the simple1d model.

The solid flux due to bulk movement of the liquid is a straightforward calculation based on the solids concentration times the liquid bulk velocity. The solids flux due to sedimentation is specified by a double exponential settling function (eq. 3.2), applicable to both hindered sedimentation and flocculant sedimentation conditions.

$$v_{sj} = v_{max}\, e^{-rhin*X^o_j} - v_{max}\, e^{-rfloc*X^o_j} \qquad \text{eq. 3.2}$$

where;

v_{sj} : settling velocity in layer j (m/d),
v_{max} : maximum Vesilind settling velocity (m/d),
$rhin$: hindered zone settling parameter (m^3/gTSS),
$rfloc$: flocculant zone settling parameter (m^3/gTSS).

$X^o_j = X_j - X_{min}$, where X_{min} is the minimum attainable suspended solids concentration, X_j is the suspended solids concentration in layer j.

The minimum attainable solids concentration in a layer, X_{min}, is calculated as a fraction (non-settlable fraction or *fns*) of the influent solids concentration to the settler:

$X_{min} = fns * X_{in}$ eq. 3.3

It is subject to a maximum value specified by the user; the maximum non-settleable solids or X_{minmax}. The settling velocity is also subject to a maximum value specified by the user; the maximum settling velocity or v_{bnd}.

The settling function is shown in Figure 3.3. The four regions depicted in this figure are explained as follows:

(I) the settling velocity equals to zero as the solids attain the minimum attainable concentration;

(II) the settling velocity is dominated by the flocculating nature of the particles;

(III) settling velocity has become independent of solids concentration;

(IV) settling velocity is affected by hindering.

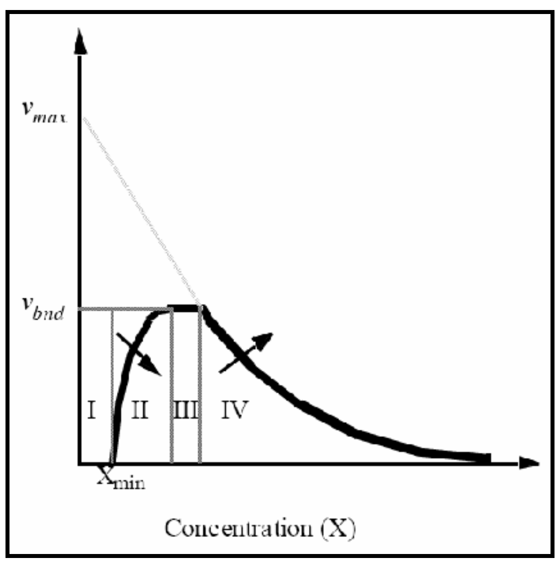

Figure 3.3 Settling Velocity vs. Concentration

In reactive models, biological reactions are taken into consideration and the Activated Sludge Models described previously may be used [8].

CHAPTER 4

DESCRIPTION OF KAYSERİ WASTEWATER TREATMENT PLANT

Kayseri WWTP is designed to treat wastewaters coming from the sewer system of Kayseri and has started operation in February 2004. The WWTP is built on an area of 367,490 m^2 and serves for 800,000 E.P. with a capacity of 110,000 m^3/day for dry weather and 215,000 m^3/day for rainy weather. The WWTP includes nitrogen and phosphorus removal along with carbon removal. The WWTP also receives industrial wastewaters [9]. The flow diagram of the treatment plant is shown in Figure 4.1.

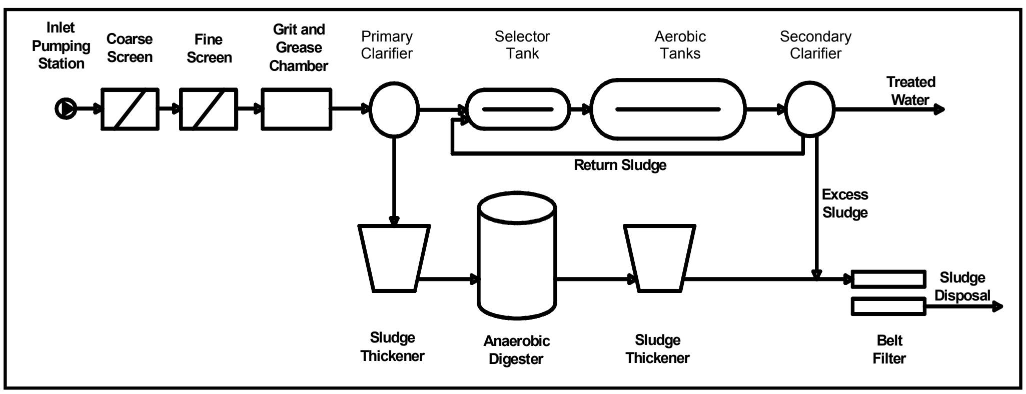

Figure 4.1 Flow Diagram of the Treatment Plant

Raw wastewater initially comes to the inlet pumping station. There are 3 pumps in the inlet pumping station.

After the inlet pumping station wastewater passes through screens to separate the coarse particles. There are 3 coarse screening and 3 fine screening bands in the pretreatment stage. The screenings are delivered by conveyors to a screening press, where they are compacted. The compacted screenings are then stored in containers which are removed from the site periodically.

After the screens wastewater flows in 4 aerated grit and grease chambers by gravity. In order to support the sedimentation of grit and the separation of oil/grease, aeration is applied by using 3 blowers.

Wastewater from the aerated grit and grease chambers then flows past the inlet venturi channel for flow measurement. There are sampling device, pH meter, temperature sensor and conductivity meter within the inlet venturi channel.

Following the inlet venturi channel, wastewater comes to primary clarifiers by gravity. Data related to the primary clarifiers are presented in Table 4.1.

Table 4.1 Information Related to Primary Clarifiers [10]

Dimensions Diameter (m) Depth (m)	32.7 2.98
Number of tanks	2
Detention time (hr)	0.75

After primary clarifiers wastewater is fed to the selector (bio-phosphorus) tank by gravity. Information related to the selector tank is given in Table 4.2. The aim of the selector tank is to provide biological phosphorus removal; therefore there is no aeration in this tank. Microorganisms in the anaerobic selector depolymerize polyphosphate storage materials and release soluble ortho-phosphate into the liquid. Subsequently microorganisms can take up more phosphate than they have released in the selector tank in the upcoming aerobic conditions.

Table 4.2 Information Related to the Selector Tank [10]

Dimensions Length (m) Width (m) Depth (m)	 85 24 6.3
Volume (m^3)	13,000
Number of tanks	1
Detention time (hr)	0.90
Return sludge (%)	100

The return activated sludge is given to the selector tank. The wastewater inlet is mixed with the return sludge by submersible agitators at the inlet chamber of the tank.

Passing the selector tank wastewater flows into the aeration tanks. Information related to these tanks is presented in Table 4.3.

Table 4.3 Information Related to Aeration Tanks [10]

Dimensions Length (m) Width (m) Depth (m)	 140 24 6.3
Volume (m^3)	20,375
Number of tanks	8

The aeration tanks are built as oxidation ditches. The dissolved oxygen in the tanks is measured at two points, one in the aeration zone, and the other in the anoxic zone.

The sludge age is set as 25 days in order to obtain combined nitrification-denitrification process. The required oxygen is delivered by a blower station to the oxic zones.

After the aeration tanks wastewater flows into the final clarifiers by gravity. Data related to the final clarifiers are given in Table 4.4.

Table 4.4 Information Related to Secondary Clarifiers [10]

Dimensions	
Diameter (m)	59.4
Depth (m)	5.22
Number of tanks	4
Detention time (hr)	2

The settled sludge is discharged from the central cone by gravity via regulated valves to the sludge pumping station. By means of submersible pumps sludge is pumped partly back to the selector tank as return activated sludge and partly to the sludge mixing tank before the sludge dewatering unit as excess sludge.

Water clarified passes through the outlet venturi channel where pH, temperature and conductivity of the water are measured continuously. After the outlet venturi channel, treated water is discharged to Karasu River.

Primary sludge collected is pumped to the primary sludge thickener. The sludge is thickened by gravity and by support of the installed rake device from 4% (dry solids) up to 7% (dry solids). Data related to the primary sludge thickener is given in Table 4.5.

Table 4.5 Information Related to the Primary Sludge Thickener [10]

Diameter (m)	19.5
Number of tanks	1
Flow rate of primary sludge (m^3/day)	590

The sludge from the thickener is pumped to the heat exchangers. The primary sludge is then mixed with the digested recirculating sludge at the entrance of the heat exchanger. The mixed sludge in the heat exchanger is pumped to the anaerobic digester. Information related to the anaerobic digester is given in Table 4.6.

Table 4.6 Information Related to the Anaerobic Digester [10]

Number of tanks	1
Volume (m^3)	6750
Diameter (m)	21
Temperature (ºC)	37
Raw sludge (m^3/day)	337
Oil/grease (m^3/day)	8

Digested primary sludge is delivered to the secondary sludge thickener and the sludge is thickened to 4.62% (dry solids). Information related to the secondary sludge thickener is presented in Table 4.7.

Biogas produced in the anaerobic digester is stored in a gas storage tank or disposed off by burning in a flare on a stack.

Table 4.7 Information Related to the Secondary Sludge Thickener [10]

Diameter (m)	19.5
Number of tanks	1
Flow rate of primary sludge (m^3/day)	345

The digested sludge from the secondary sludge thickener and excess sludge from biological treatment are mixed in a mixing tank and delivered to belt filters. Sludge is thickened normally to 20% (dry solids) but may be thickened up to 35% (dry solids) after lime addition [11, 12, 13].

CHAPTER 5

METHODS

In this study, modeling of Kayseri WWTP was carried out by using a municipal and industrial wastewater treatment simulation software developed by Hydromantis Co. of Canada, called GPS-X. It is claimed as the world's premier wastewater treatment plant simulation platform. The GPS-X uses an advanced graphical user interface to facilitate dynamic modeling and simulation.

By using properly calibrated GPS-X software it is possible to assess impacts of increased organic and hydraulic loading on an existing plant.

The software offers options for converting an existing activated sludge plant into a BNR plant or provides options for testing configuration changes to affect higher removal rates. Modeling can also be used to confirm if current plant operational strategies are appropriate.

The impact of internal recirculation rates, sizes of anoxic and anaerobic zones on nitrification, denitrification and on overall treatability can be assessed. By using future organic and hydraulic loading estimates, GPS-X can be used to determine plant expansion and/or upgrade needs [14].

Different libraries exist in GPS-X, which are a collection of wastewater process models using a set of basic wastewater components, or state variables. The term 'state variable' refers to the basic variables that are continuously integrated over time.

The ‘composite variables’ are those variables that are calculated from (or composed of) the state variables. The process libraries in GPS-X are as follows;

- Carbon – Nitrogen (cnlib): Basic library used for modeling carbon oxidation, nitrification and denitrification.

- Advanced Carbon – Nitrogen (cn2lib): Similar to the carbon - nitrogen library, but nitrate and nitrite are modeled separately.

- Carbon – Nitrogen – Phosphorus (cnplib): Builds on the carbon - nitrogen library, by including models for biological and chemical phosphorus removal.

- Carbon – Nitrogen – Industrial Pollutant (cniplib): Combines the carbon - nitrogen library with 30 undefined customizable components.

- Advanced Industrial Pollutants (cn2iplib): Combines the advanced carbon - nitrogen library with 30 undefined customizable components.

- Carbon – Nitrogen – Phosphorus – Industrial Pollutant (cnpiplib): Combines the carbon - nitrogen - phosphorus library with 30 undefined customizable components.

In this study, Carbon – Nitrogen – Phosphorus (cnplib) Library is used and the state variables of this library are listed in Table 5.1.

Table 5.1 Carbon – Nitrogen – Phosphorus Library State Variables

	State Variables	GPS-X Cryptic Symbols	Units
1	Soluble inert organics	si	$gCOD/m^3$
2	Readily biodegradable (soluble) substrate	ss	$gCOD/m^3$
3	Particulate inert organics	xi	$gCOD/m^3$
4	Slowly biodegr. (stored, particulate) substrate	xs	$gCOD/m^3$
5	Active heterotrophic biomass	xbh	$gCOD/m^3$
6	Active autotrophic biomass	xba	$gCOD/m^3$
7	Unbiodegradable particulates from cell decay	xu	$gCOD/m^3$
8	Dissolved oxygen	so	gO_2/m^3
9	Nitrate and nitrite N	sno	gN/m^3
10	Free and ionized ammonia	snh	gN/m^3
11	Soluble biodegradable organic nitrogen (in ss)	snd	gN/m^3
12	Particulate biodegradable organic nitrogen (in xs)	xnd	gN/m^3
13	Polyphosphate accumulating biomass	xbp	$gCOD/m^3$
14	Poly-hydroxy-alkanoates (PHA)	xbt	$gCOD/m^3$
15	Stored polyphosphate	xpp	gP/m^3
16	Volatile fatty acids	slf	$gCOD/m^3$
17	Soluble phosphorus	sp	gP/m^3
18	Alkalinity	salk	$mole/m^3$
19	Dinitrogen	snn	gN/m^3
20	Soluble unbiodegradable organic nitrogen (in si)	sni	gN/m^3
21	Fermentable readily biodegradable substrate	sf	$gCOD/m^3$
22	Stored glycogen	xgly	$gCOD/m^3$
23	Stored polyphosphate (releasable)	xppr	gP/m^3
24	Metal-hydroxides	xmeoh	g/m^3
25	Metal-phosphate	xmep	g/m^3
26	Cell internal storage product	xsto	$gCOD/m^3$
27	Inert inorganic suspended solids	xii	g/m^3

The steps followed in the modeling study are explained below;

Determination of influent wastewater characteristics:

The wastewater characteristics were obtained from Kayseri Wastewater Treatment Plant. The parameters that are daily measured are settleable solids, NH_4-N, NO_3-N, total nitrogen, BOD_5, suspended solids, COD, PO_4-P and total phosphorus. Significant consideration must be given to wastewater characterization, so that the model's ability to predict the dynamic behavior of the plant would not be limited. Hydromantis has developed a Microsoft Excel based utility tool called 'Influent

Advisor' based on material balances which can help users improve influent wastewater characterization.

Treatment plant layout build-up:

Initially, a plant flowsheet needs to be created on the graphical interface by selecting unit processes and connecting the flow lines between them. Code for the dynamic computer model is prepared automatically based on the layout specified. A layout in GPS-X contains data on the physical objects being modeled. For instance, the model(s) being used, physical dimensions of the units, and the connectivity between unit processes should be determined [15].

Data input:

After building-up the plant layout, the input data needs to be entered by setting up input controls in GPS-X. This way, dynamic input data (measured daily) obtained from the treatment plant can be used.

Sensitivity analysis:

Initially, the model parameters that serve as independent variables need to be specified. For these parameters, sensitivity analysis should be carried out. The minimum, maximum and increment value for an independent variable needs to be entered during sensitivity testing. Following the sensitivity testing GPS-X presents an output graph showing the parameter values versus selected output parameter. According to the output graph the user can decide on the sensitivity of the parameter. For example if the response curve runs parallel to the X axis this indicates a very low sensitivity that may be attributed to the particular parameter.

Parameter optimization:

After sensitivity analysis, the sensitive parameters should be optimized. Parameter optimization is an essential step since model parameters can vary significantly from one treatment plant to another. Therefore, a model that has been fitted to actual plant data will be more useful for predicting actual plant behavior.

In GPS-X, all optimization is formulated as data fitting problems. The user provides the data in a file and chooses an objective function, the parameters of interest, and selects the model response variables that will be fitted. The selected parameters are adjusted until the objective function is minimized.

GPS-X provides dynamic parameter estimation which is designed for the estimation of time-varying parameters. Five objective functions are available in GPS-X. These are absolute difference, relative difference, sum of squares, relative sum of squares and maximum likelihood objective function. The equations for these objective functions are presented below;

Absolute Difference: $$F = \sum_{j=1}^{m} \sum_{i=1}^{n_j} \left| z_{i,j} - f_{i,j} \right|$$ eq. 5.1

Relative Difference: $$F = \sum_{j=1}^{m} \sum_{i=1}^{n_j} \left| \frac{z_{i,j} - f_{i,j}}{z_{i,j}} \right|$$ eq. 5.2

Sum of Squares: $$F = \sum_{j=1}^{m} \sum_{i=1}^{n_j} \left(z_{i,j} - f_{i,j} \right)^2$$ eq. 5.3

Relative Sum of Squares: $$F = \sum_{j=1}^{m} \sum_{i=1}^{n_j} \left(\frac{z_{i,j} - f_{i,j}}{z_{i,j}} \right)^2$$ eq. 5.4

Maximum Likelihood:

$$F = \frac{1}{2} \sum_{j=1}^{m} \left[n_j (\ln(2\pi) + 1) + n_j \ln \left(\frac{1}{n_j} \sum_{i=1}^{n_j} \frac{(z_{i,j} - f_{i,j})^2}{f_{i,j}^{\gamma_j}} \right) + \gamma_j \sum_{i=1}^{n_j} \ln f_{i,j} \right]$$ eq. 5.5

where,

$z_{i,j}$: the measured value of response j in experiment i,

$f_{i,j}$: the value of response variable j predicted by the process model in experiment i,

γ_j : the heteroscedasticity parameter for response j,

m : the number of measured response variables,

n_j : the number of experiments for response j [8].

In this study, dynamic parameter estimation will be performed for each objective function. For the results obtained for each objective function, average of the ratio of predicted to measured values and standard deviation were calculated by using eq. 5.6 and eq. 5.7, respectively. The value of $\bar{x}$ should be close to 1, therefore, the objective function that provides $\bar{x}$ value closest to 1 will be selected. The standard deviation is a measure of the dispersion of x values or spread and it must be close to zero for optimum fit.

$$\bar{x} = \frac{\sum x}{n} \qquad \text{eq. 5.6}$$

$$\sigma = \sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}} \qquad \text{eq. 5.7}$$

where,

x : ratio of the predicted values to the measured values,

$\bar{x}$: mean of x values,

n : number of data points,

σ : standard deviation.

Validation:

The parameters optimized should be validated at the end of the modeling study by using different sets of data. It is expected that the model predictions would run close to the actual values for most of the time. For instance, biological treatment plants may behave different in different seasons. A successful model clearly should be able to predict the necessary parameters reasonably well all round the year. Therefore calibration for a set of data should be validated by using different sets of data taken from other seasons after necessary temperature adjustments made on the model.

CHAPTER 6

RESULTS AND DISCUSSION

6.1. Wastewater Characterization

The real wastewater characteristics of February 2004 – January 2005 were obtained from Kayseri Wastewater Treatment Plant. This period corresponds to the most accurate data period when the constructor company was operating the plant for start-up. For the calibration of the model, data obtained in March 2004 was used. Settleable solids, NH_4-N, NO_3-N, total nitrogen, BOD_5, suspended solids, COD, PO_4-P and total phosphorus parameters were measured daily. The data for March 2004 is given in Appendix A [16].

The model is based on COD fractions and on several stoichiometric coefficients (such as VSS/TSS ratio, soluble fraction of total COD etc.) which need to be determined to achieve better wastewater characterization. For this purpose, the Influent Advisor developed by Hydromantis Co. was used by inserting the average concentrations of March 2004 into the table. All other data were calculated by the advisor basing on material balance.

Initially, the parameters indicated in Table 6.1 were inserted in the Influent Advisor.

The default and modified values of the stiochiometric coefficients are presented in Table 6.2. These values were modified using the influent advisor according to the average concentrations of influent total BOD_5 and total suspended solids, which were obtained from the treatment plant, and their concentrations were 355 gO_2/m^3 and 312 g/m^3, respectively.

Table 6.1 Influent Wastewater Characteristics Inserted in the Influent Advisor [16]

Parameter	Unit	Concentration
Total COD	$gCOD/m^3$	570.00
Total TKN	$gTKN\text{-}N/m^3$	55.80
Total phosphorus	gP/m^3	8.40
Dissolved oxygen	gO_2/m^3	0.00
Soluble ortho-phosphate	$gPO_4\text{-}P/m^3$	6.20
Free and ionized ammonia	$gNH4\text{-}N/m^3$	36.80
Nitrate and nitrite	$gNO_3\text{-}N/m^3$	0.50
Dinitrogen	gN/m^3	0.00

* Total = Filtered + Particulate

Table 6.2 Stoichiometric Coefficients Given in the Influent Advisor

Stoichiometric Coefficient	Unit	Default Value	Modified Value
VSS/TSS ratio	gVSS/gTSS	0.60	0.58
Soluble fraction of total COD	-	0.35	0.30
Inert fraction of soluble COD	-	0.35	0.13
VFA fraction of soluble COD	-	0.00	0.00
Substrate fraction of particulate COD	-	0.75	0.90
Unbiodegradable fraction of particulate COD	-	0.00	0.00
Heterotrophic biomass fraction of particulate COD	-	0.00	0.00
Autotrophic biomass fraction of particulate COD	-	0.00	0.00
Poly-P biomass fraction of particulate COD	-	0.00	0.00
PHA fraction of particulate COD	-	0.00	0.00
Stored fraction of particulate COD	-	0.00	0.00
Glycogen fraction of particulate COD	-	0.00	0.00
Ortho-phosphate fraction of soluble phosphorus	-	0.90	0.90
xpp fraction of particulate phosphorus	-	0.00	0.00
xppr fraction of particulate phosphorus	-	0.00	0.00
Ammonium fraction of soluble TKN	-	0.90	0.90
Inert fraction of soluble TKN	-	0.00	0.00
Metal-hydroxide fraction of inorganic suspended solids	-	0.00	0.00
Metal-phosphate fraction of inorganic suspended solids	-	0.00	0.00
X_{COD}/VSS ratio	gCOD/gVSS	2.20	2.20
$BOD_5/BOD_{ultimate}$ ratio	-	0.66	0.70

* X : Particulate

By doing this modification, the concentrations presented in Table 6.3 were obtained.

Table 6.3 Concentrations Obtained by Using the Influent Advisor

Parameter	Unit	Concentration
Filtered COD	$gCOD/m^3$	171.00
Particulate COD	$gCOD/m^3$	399.00
Total COD	$gCOD/m^3$	570.00
Filtered carbonaceous BOD_5	gO_2/m^3	104.14
Particulate carbonaceous BOD_5	gO_2/m^3	251.37
Total carbonaceous BOD_5	gO_2/m^3	355.51
Filtered ultimate carbonaceous BOD_5	gO_2/m^3	148.77
Particulate ultimate carbonaceous BOD_5	gO_2/m^3	359.10
Total ultimate carbonaceous BOD_5	gO_2/m^3	507.87
Filtered TKN	gN/m^3	40.89
Particulate TKN	gN/m^3	14.91
Total TKN	gN/m^3	55.80
Total nitrogen	gN/m^3	56.30
Filtered phosphorus	gP/m^3	6.89
Particulate phosphorus	gP/m^3	1.51
Total phosphorus	gP/m^3	8.40
Total inorganic suspended solids	g/m^3	131.33
Volatile suspended solids	g/m^3	181.36
Total suspended solids	g/m^3	312.70

* Shaded values represent the measured concentrations, others are those calculated by the advisor.

The concentrations of total BOD_5 and total suspended solids obtained by using the Influent Advisor were 355.51 gO_2/m^3 and 312.70 g/m^3, respectively; as can be seen extremely close to the actual data from the plant.

6.2. Calibration of the Primary Clarifiers

For the calibration of the primary clarifiers, the layout shown in Figure 6.1 was built. Simple1d sedimentation model was used. Settler was divided into 10 layers of equal thickness, which is the default value given in GPS-X.

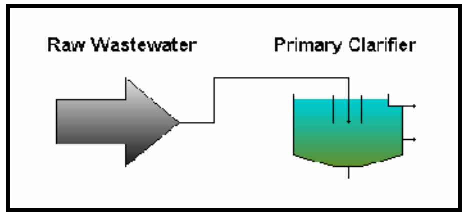

Figure 6.1 Layout for Primary Clarifier

Initially, sensitivity analysis was performed with respect to the underflow suspended solids concentration. The settling parameters that were analyzed were maximum settling velocity, maximum Vesilind settling velocity, hindered zone settling parameter, flocculant zone settling parameter, non-settleable fraction, maximum non-settleable solids, quiescent zone maximum upflow velocity, and complete mix maximum upflow velocity. The results are presented in Figures 6.2 to 6.9.

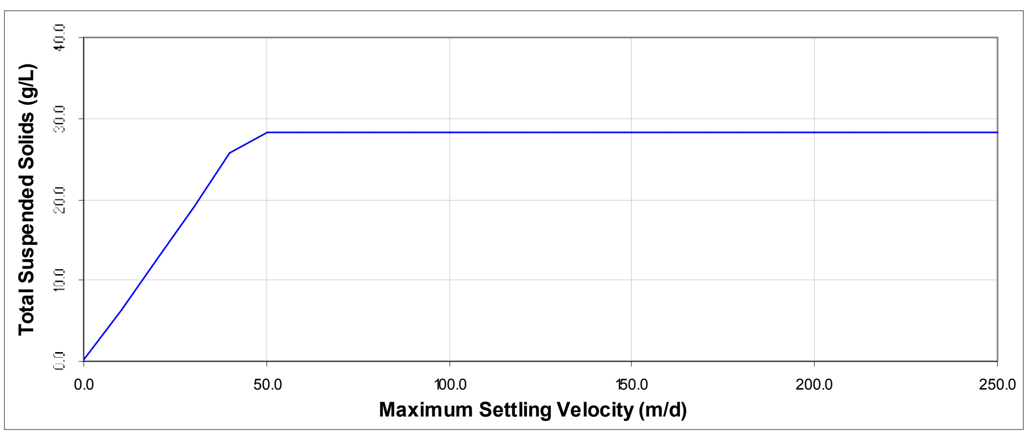

Figure 6.2 Sensitivity Analysis for Maximum Settling Velocity

As can be seen in Figure 6.2, primary clarifier underflow total suspended solids concentration is rather sensitive to maximum settling velocity, since the average total suspended solids concentration was approximately 11 g/L in the plant.

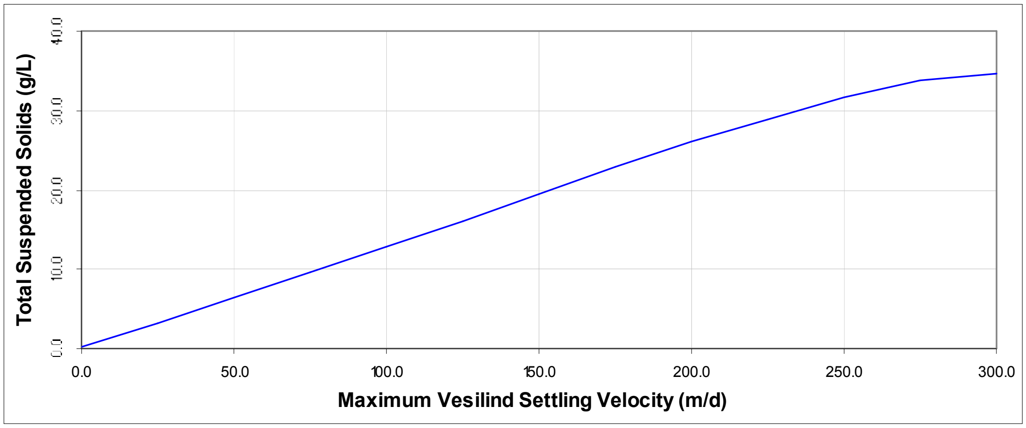

Figure 6.3 Sensitivity Analysis for Maximum Vesilind Settling Velocity

Figure 6.3 shows that underflow total suspended solids concentration is very sensitive to maximum Vesilind settling velocity.

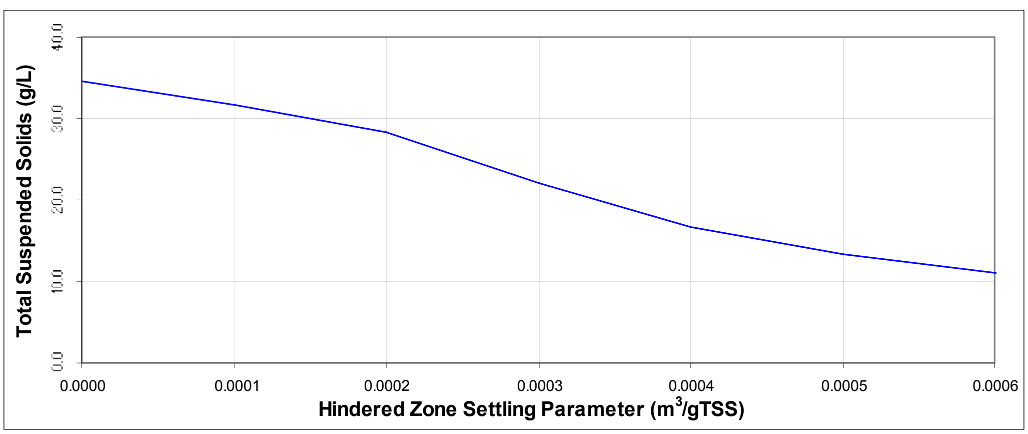

Figure 6.4 Sensitivity Analysis for Hindered Zone Settling Parameter

As can be seen in Figure 6.4, underflow total suspended solids concentration is sensitive to hindered zone settling parameter too.

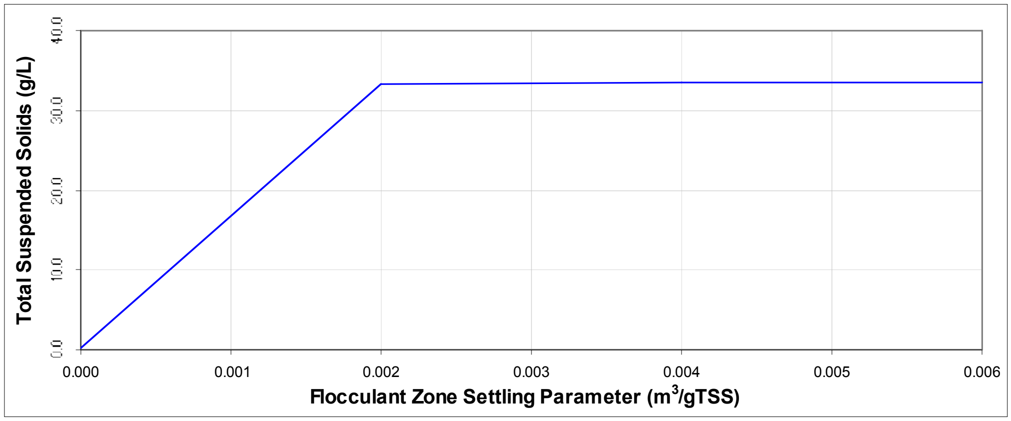

Figure 6.5 Sensitivity Analysis for Flocculant Zone Settling Parameter

Sensitivity analysis presented in Figure 6.5 shows that underflow total suspended solids concentration is also sensitive to flocculant zone settling parameter.

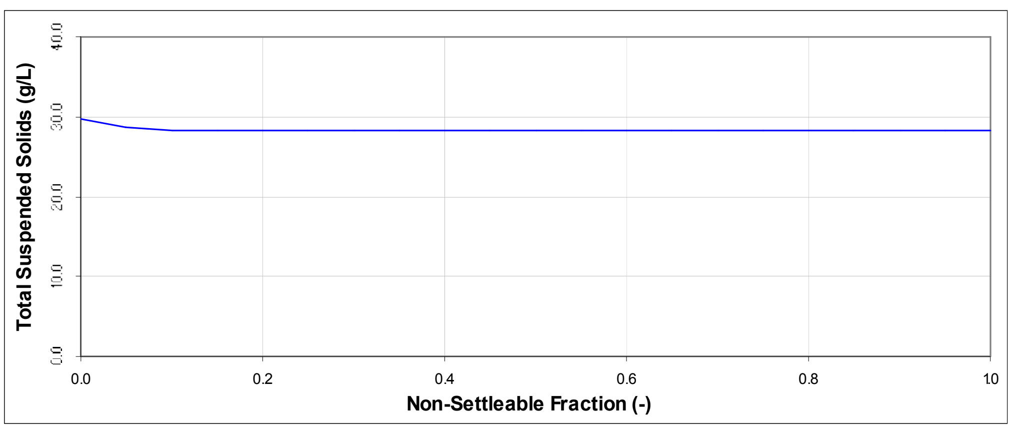

Figure 6.6 Sensitivity Analysis for Non-Settleable Fraction

According to Figure 6.6, underflow total suspended solids concentration is not sensitive to non-settleable fraction. Therefore this parameter was not considered in parameter estimation and the default value of the parameter was used for the modeling of the primary clarifiers.

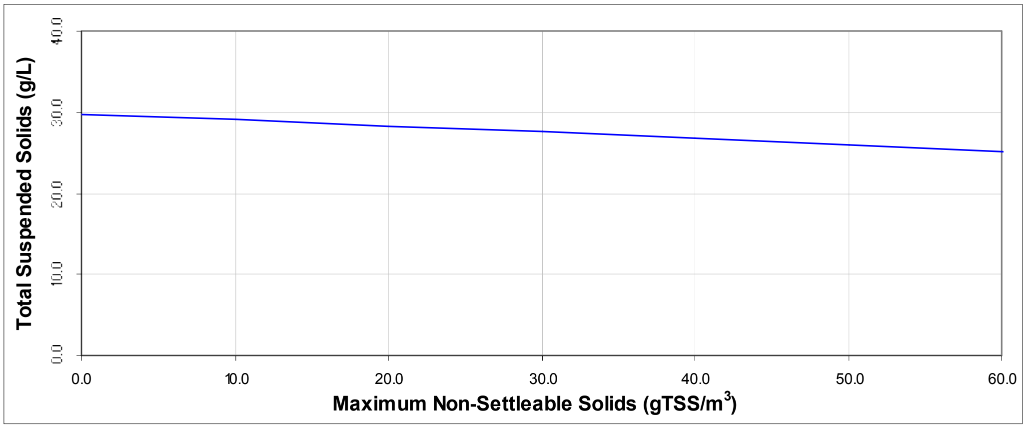

Figure 6.7 Sensitivity Analysis for Maximum Non-Settleable Solids

Figure 6.7 shows that underflow total suspended solids concentration is not very sensitive to maximum non-settleable solids either; therefore this parameter was not considered in parameter estimation. The default value of 20 $gTSS/m^3$ was used for the parameter during model runs.

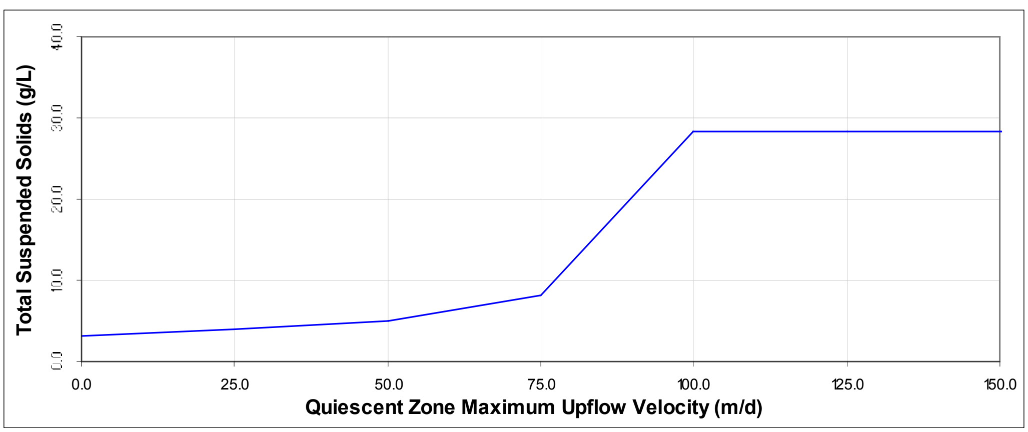

Figure 6.8 Sensitivity Analysis for Quiescent Zone Maximum Upflow Velocity

Figure 6.8 shows that quiescent zone maximum upflow velocity is very sensitive to underflow total suspended solids concentration between 9-29 g/L concentrations. Therefore this parameter needs adjusting during parameter estimation trials.

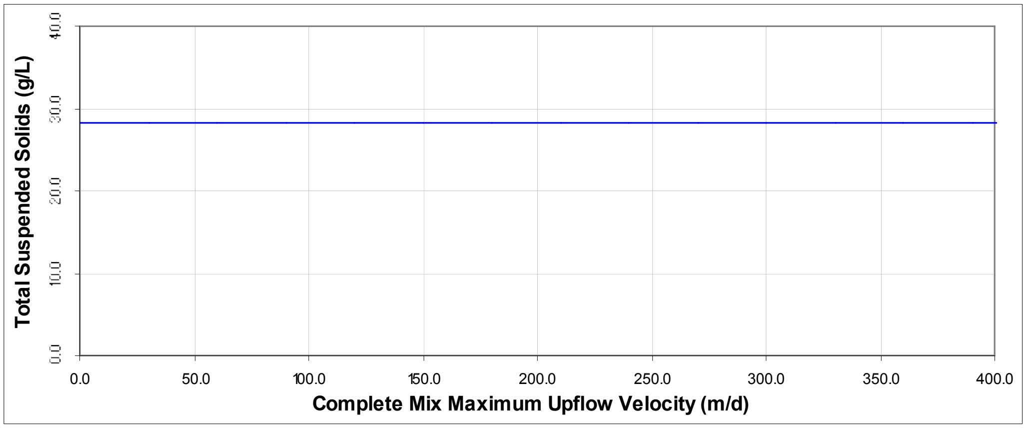

Figure 6.9 Sensitivity Analysis for Complete Mix Maximum Upflow Velocity

As can be seen in Figure 6.9, underflow total suspended solids concentration was not sensitive to complete mix maximum upflow velocity. Therefore, default value of 300 m/d was used for this parameter in the simulations.

According to the results of sensitivity analysis, the settling parameters that need optimization are maximum settling velocity, maximum Vesilind settling velocity, hindered zone settling parameter, flocculant zone settling parameter, and quiescent zone maximum upflow velocity.

After determining the sensitive parameters, dynamic parameter estimation was performed by using different objective functions. The results and the ranges inserted for each parameter are presented in Table 6.4. The calibrated parameter values were those calculated on the absolute difference column in Table 6.4.

Table 6.4 Dynamic Parameter Estimation Results for the Primary Clarifiers

	Range	Default	Absolute Difference	Relative Difference	Sum of Squares	Relative Sum of Squares	Maximum Likelihood
Maximum settling velocity (m/d)	150 - 250	200	248.9	192.5	248.5	232.2	249.5
Maximum Vesilind settling velocity (m/d)	150 - 250	220	249.3	226.9	249.9	221.0	250.0
Hindered zone settling parameter (m^3/gTSS)	0 – 0.001	0.0002	0.00016	0.00023	0.00027	0.00031	0.00025
Flocculant zone settling parameter (m^3/gTSS)	0 - 0.05	0.001	0.00035	0.00095	0.00093	0.00050	0.00093
Quiescent zone maximum upflow velocity (m/d)	50 - 150	100	134.2	67.3	82.2	100.8	82.0
$\bar{x}$		2.97	1.01	0.74	1.11	0.78	1.11
σ		1.48	0.46	0.37	0.63	0.40	0.63

$\bar{x} = \frac{\sum(\text{predicted TSS / measured TSS})}{n}$, *σ = standard deviation*

$\bar{x}$ value obtained by using absolute difference objective function was closest to 1. $\bar{x}$ and σ values for this objective function were 1.01 and 0.46, respectively. Therefore, the values obtained by this function will be used instead of the default values. The results obtained by using the default values and the modified values after the dynamic parameter estimation are presented in Figure 6.10 and Figure 6.11, respectively. The results for all the objective functions are presented in Appendix B.

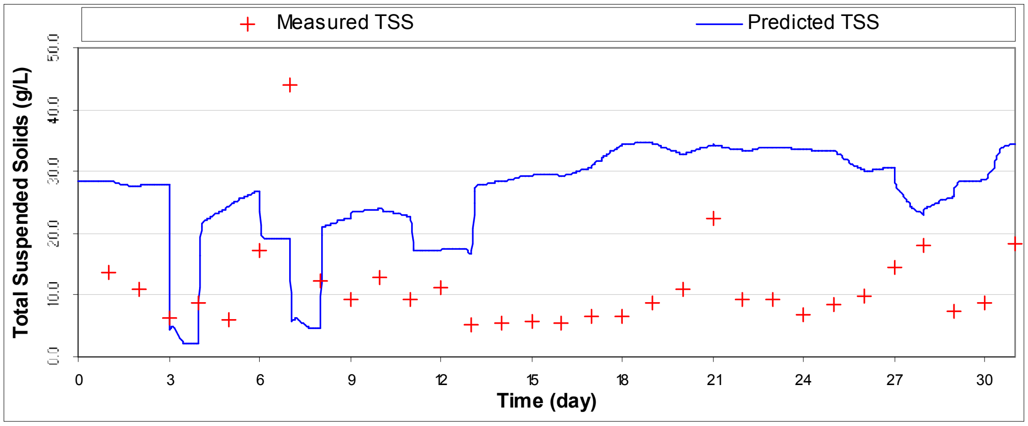

Figure 6.10 Dynamic Run for Primary Clarifiers by Using Default Values

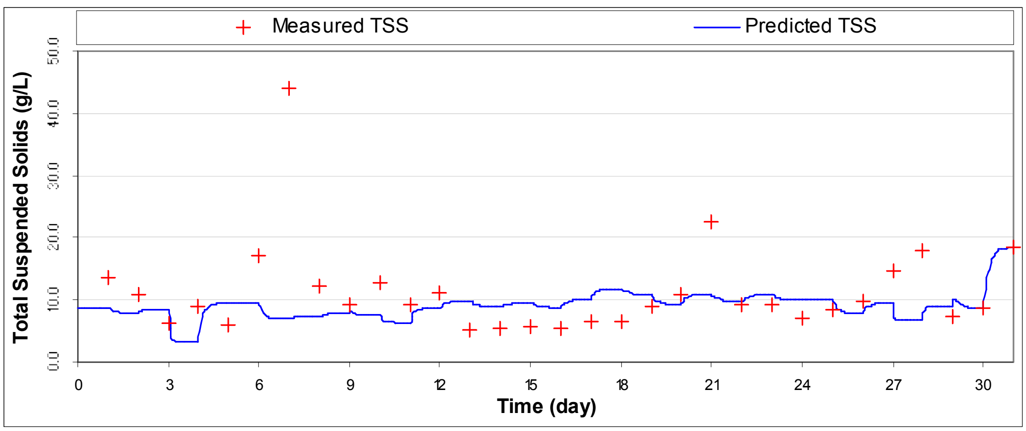

Figure 6.11 Dynamic Run for Primary Clarifiers by Using Optimized Values

As can be seen in Figure 6.10, before calibration, the predicted TSS concentration in the primary sludge were much higher than those measured. The results obtained after calibration, which are shown in Figure 6.11, show that the obtained fit is reasonably good for that period of time.

The measured underflow TSS concentration on the 7th day was very high (43.91 g/L). This might have been due to the high TSS concentration in the influent wastewater on the 6th day, which was 976 mg/L. This sudden change could not be simulated by the model and considered an artifact.

6.3. Calibration of the Secondary Clarifiers

For the calibration of the secondary clarifiers, the layout shown in Figure 6.12 was built. Simple1d sedimentation model was used and settler was divided into 10 layers of equal thickness. As can be seen in Figure 6.12, the model was built for a single secondary clarifier and return activated sludge (RAS) was given by using a separate influent object.

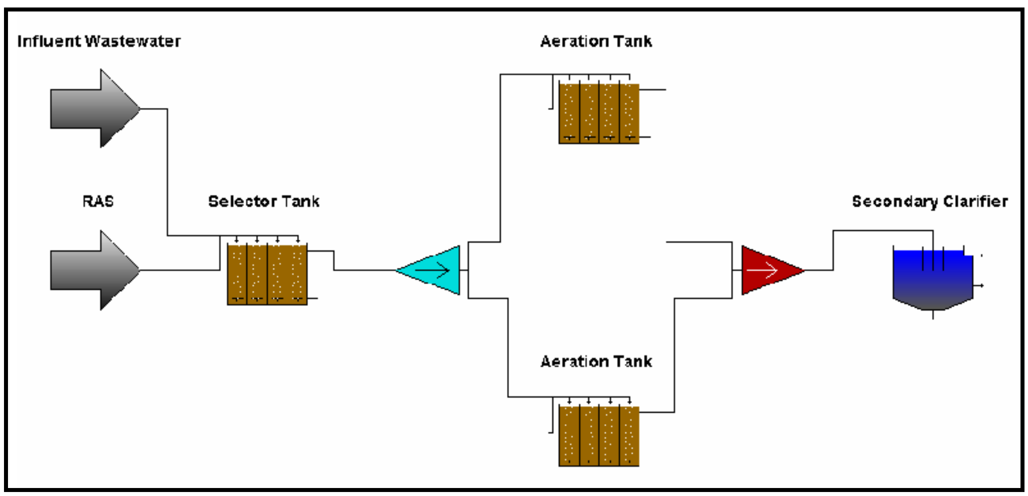

Figure 6.12 Layout for Secondary Clarifier

Sensitivity analysis was carried out with respect to the underflow suspended solids concentration coming from the secondary clarifier. The settling parameters that were analyzed were maximum settling velocity, maximum Vesilind settling velocity, hindered zone settling parameter, flocculant zone settling parameter, non-settleable fraction, maximum non-settleable solids, quiescent zone maximum upflow velocity, and complete mix maximum upflow velocity. The results are presented in Figures 6.13 to 6.20.

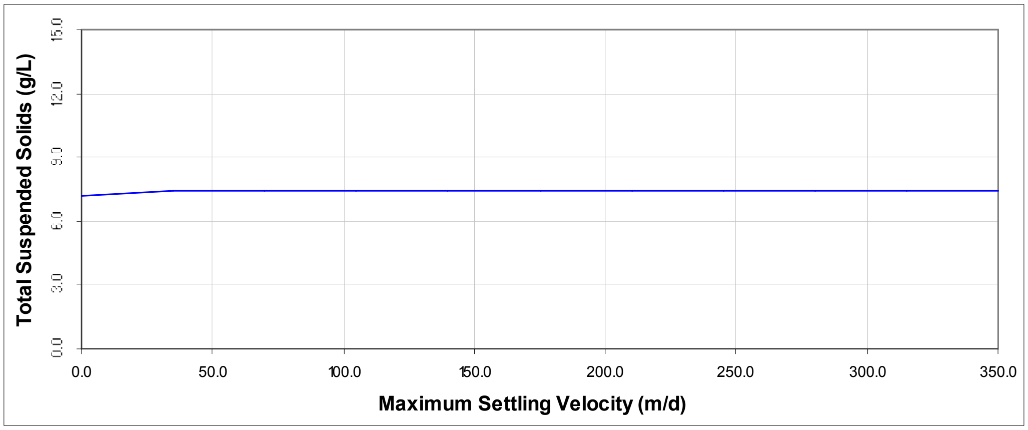

Figure 6.13 Sensitivity Analysis for Maximum Settling Velocity

According to Figure 6.13, maximum settling velocity will be considered in dynamic parameter estimation; since underflow total suspended solids concentration is slightly sensitive to this parameter.

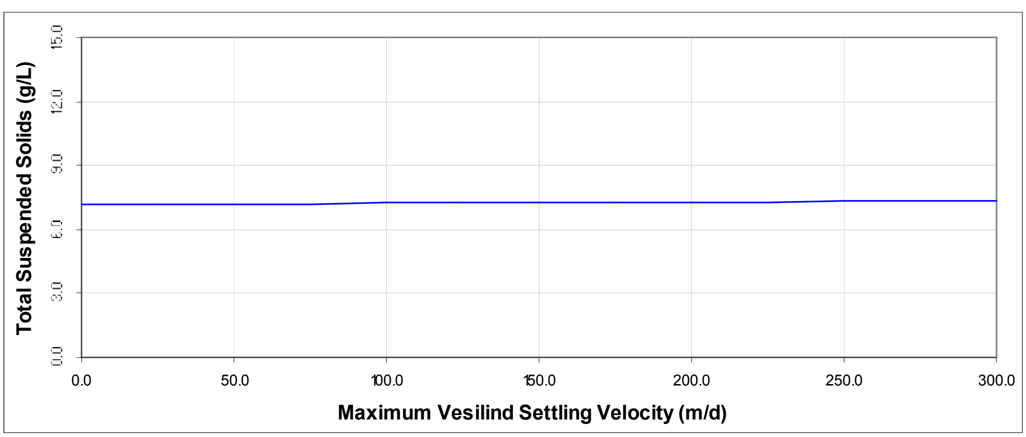

Figure 6.14 Sensitivity Analysis for Maximum Vesilind Settling Velocity

As can be seen in Figure 6.14, underflow suspended solids concentration is slightly sensitive to maximum Vesilind settling velocity, therefore, this parameter will be considered in dynamic parameter estimation.

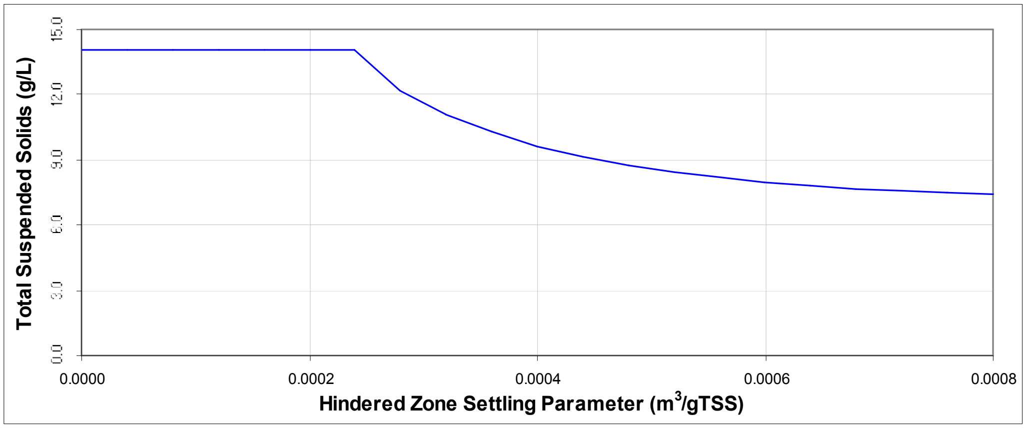

Figure 6.15 Sensitivity Analysis for Hindered Zone Settling Parameter

Figure 6.15 shows that underflow suspended solids concentration is rather sensitive to hindered zone settling parameter.

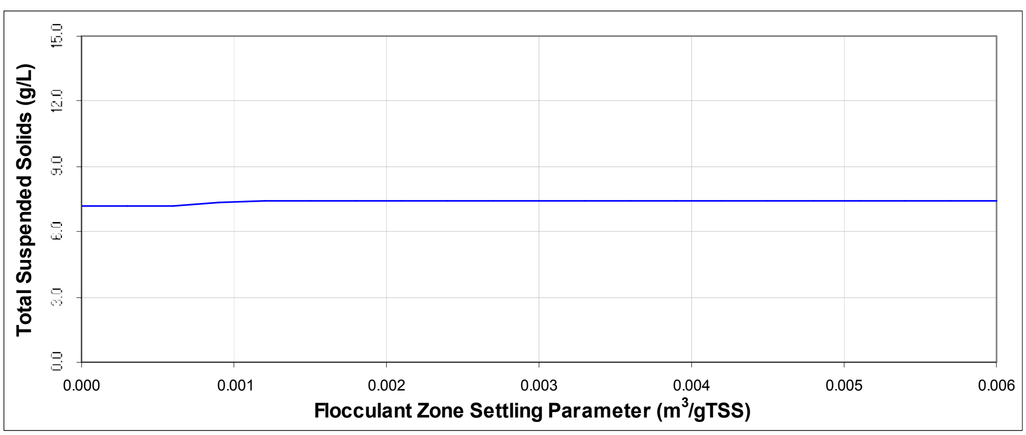

Figure 6.16 Sensitivity Analysis for Flocculant Zone Settling Parameter

As can be seen in Figure 6.14, underflow suspended solids concentration is slightly sensitive to flocculant zone settling parameter, therefore, this parameter was considered in dynamic parameter estimation.

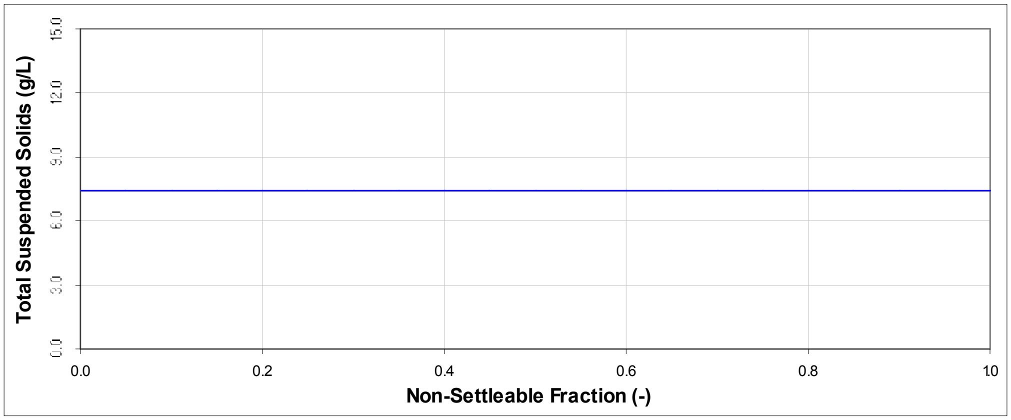

Figure 6.17 Sensitivity Analysis for Non-Settleable Fraction

As can be seen in Figure 6.17, underflow total suspended solids concentration is not sensitive to non-settleable fraction. This parameter was not considered in dynamic parameter estimation and the default value of 0.001 was used.

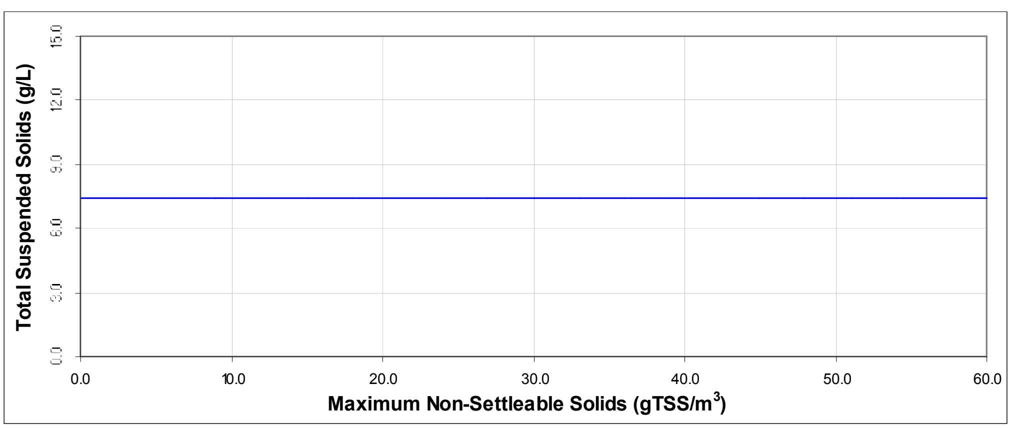

Figure 6.18 Sensitivity Analysis for Maximum Non-Settleable Solids

Figure 6.18, shows that underflow total suspended solids concentration is not sensitive to maximum non-settleable solids. Therefore, it was not taken into consideration in dynamic parameter estimation and the default value of 20 $gTSS/m^3$ was used.

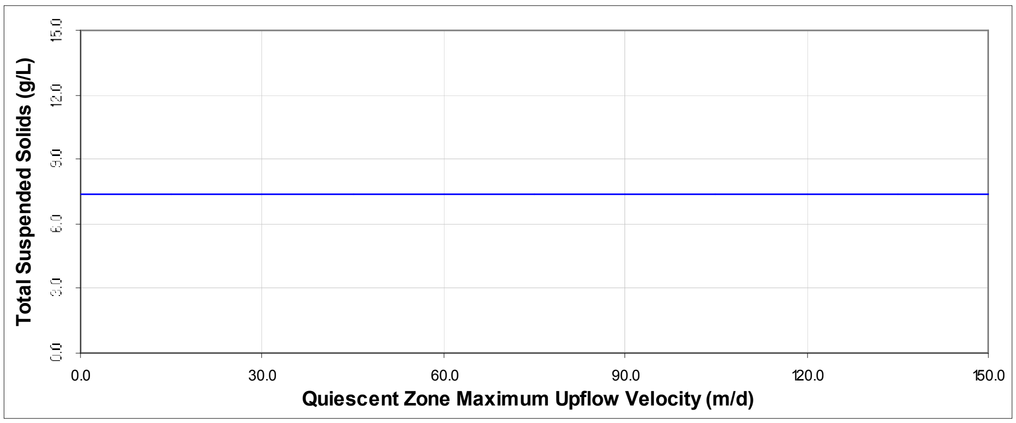

Figure 6.19 Sensitivity Analysis for Quiescent Zone Maximum Upflow Velocity

According to Figure 6.19, underflow total suspended solids concentration is not sensitive to quiescent zone maximum upflow velocity. For this parameter, the default value of 100 m/d was used.

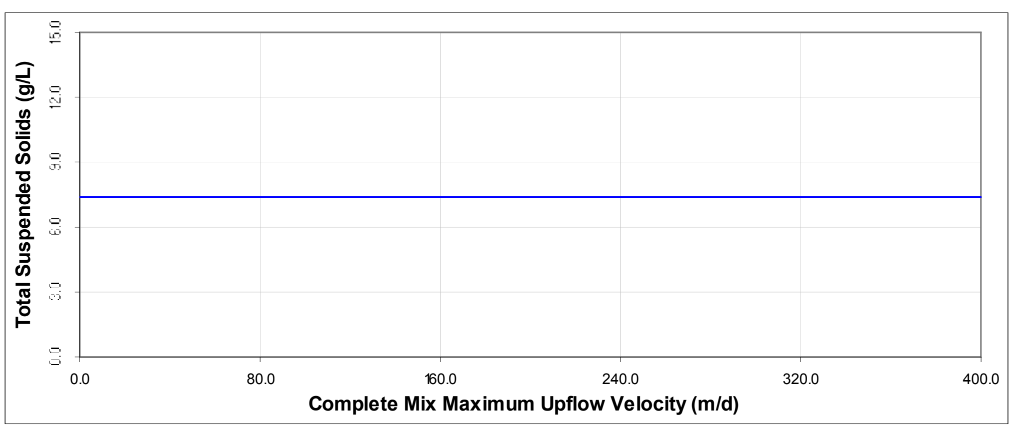

Figure 6.20 Sensitivity Analysis for Complete Mix Maximum Upflow Velocity

Figure 6.20 shows that underflow total suspended solids concentration is not sensitive to complete mix maximum upflow velocity. Therefore, it will not be taken into consideration in dynamic parameter estimation and the default value of 300 m/d was used.

According to the results of the sensitivity analysis, the parameters that need to be taken into consideration in dynamic parameter estimation are maximum settling velocity, maximum Vesilind settling velocity, hindered zone settling parameter and flocculant zone settling parameter.

Dynamic parameter estimation was carried out assuming all suspended solids from the aeration tanks were settled in the secondary clarifier. The underflow suspended solids concentrations for this assumption were calculated from the material balance written around this tank as shown in eq. 6.1.

$$\text{Target TSS} = \frac{(Q_{Influent} + Q_{RAS})\,TSS_{Aeration}}{Q_{RAS} + Q_{Excess}} \qquad \text{eq. 6.1}$$

where,

$Q_{Influent}$: flow rate of influent wastewater,

Q_{RAS} : flow rate of return activated sludge,

Q_{Excess} : flow rate of excess sludge,

$TSS_{Aeration}$: TSS concentration in the aeration tank.

The parameter estimation was then performed basing on these concentrations. These calculated concentrations will be called as *target concentrations* since they were not actually measured in the plant. The calculated target concentrations are presented in Appendix C.

Results of dynamic parameter estimation by using different objective functions are presented in Table 6.5.

Table 6.5 shows that $\bar{x}$ values are the same for objective functions. However the lowest value for standard deviation were obtained by using absolute difference and sum of squares objective functions. The values obtained by using absolute difference objective function were used instead of the default values. The results obtained by using the default and modified values are shown in Figure 6.21 and Figure 6.22. The results for all objective functions are presented in Appendix C.

Table 6.5 Dynamic Parameter Estimation Results for the Secondary Clarifiers

	Range	Default	Absolute Difference	Relative Difference	Sum of Squares	Relative Sum of Squares	Maximum Likelihood
Maximum settling velocity (m/d)	250 – 300	274	257.9	258.4	259.1	259.7	258.2
Maximum Vesilind settling velocity (m/d)	390 – 430	410	417.5	416.7	418.4	414.1	418.3
Hindered zone settling parameter (m^3/gTSS)	0 – 0.0006	0.0004	0.00021	0.00021	0.00021	0.00021	0.00021
Flocculant zone settling parameter (m^3/gTSS)	0 – 0.006	0.0025	0.00221	0.00210	0.00210	0.00204	0.00208
$\bar{x}$		0.67	1.00	1.00	1.00	1.00	1.00
σ		0.05	0.08	0.09	0.08	0.09	0.09

$\bar{x} = \frac{\Sigma(predicted\ TSS / target\ TSS)}{n}$, σ = standard deviation

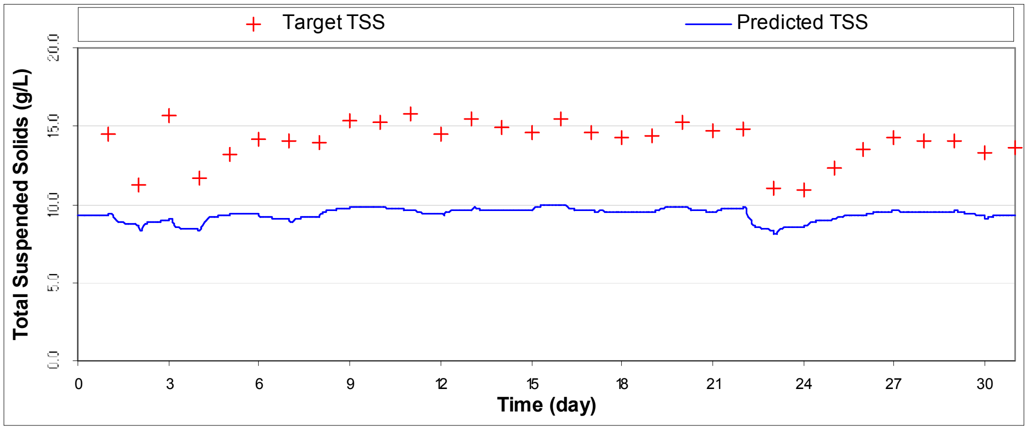

Figure 6.21 Dynamic Run for Secondary Clarifiers by Using Default Values

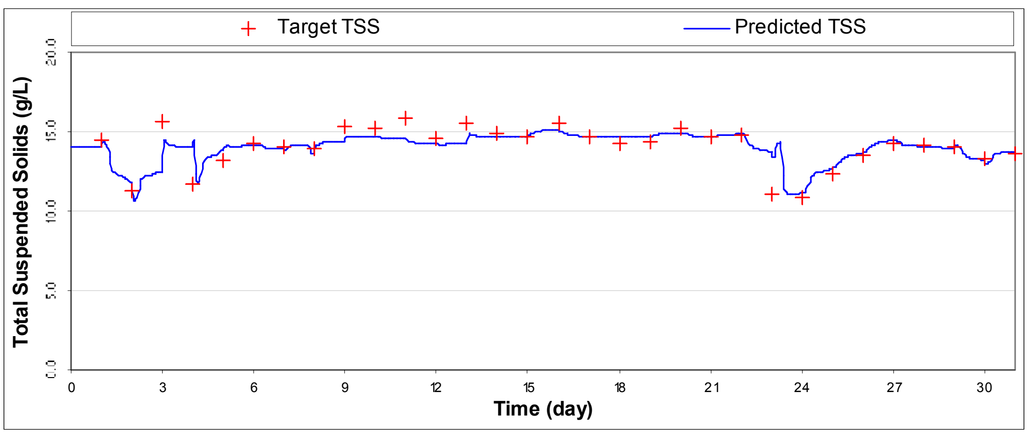

Figure 6.22 Dynamic Run for Secondary Clarifiers by Using Optimized Values

As can be seen in Figure 6.21, the predicted underflow TSS concentrations were lower than the target concentrations. Figure 6.22 shows that after calibration model results fitted perfectly to the target concentrations.

The underflow TSS concentration needs to be checked finally by using the measured underflow TSS concentrations after calibration of all the units is complete.

6.4. Calibration of the Aeration Tanks

For the calibration of the aeration tanks, the layout shown in Figure 6.23 was built. As can be seen in Figure 6.23, the model was built for a single secondary clarifier and only two aeration tanks were taken into consideration. The return activated sludge was no longer given by a separate influent object, but recycled from the secondary clarifier to the selector tank. The internal recirculation in the aeration tanks was taken as 100%.

Activated Sludge Model No.2d was used to model the biokinetic processes and the tank was simulated by using 10 CSTRs connected in series to represent a truly plug-flow reactor hydraulics. The layout of the visualized aeration tanks is shown in Figure 6.24. One third of each aeration tank was being aerated and these sections were shaded in Figure 6.24. Dissolved oxygen concentrations for the aerated sections and for the anoxic sections were set to 1.35 mg/L and 0.30 mg/L, respectively.

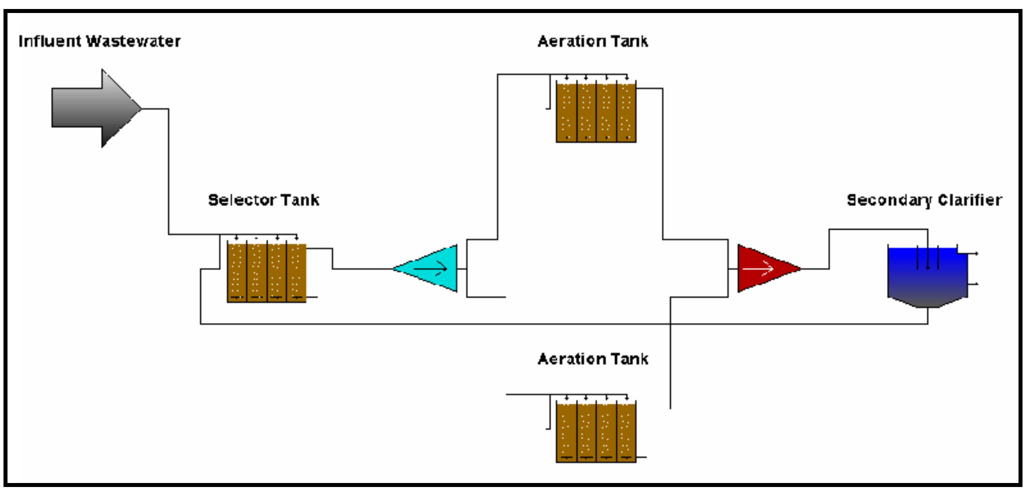

Figure 6.23 Layout for Selector Tank and Aeration Tanks

Volume of each section and CSTRs involved were as follows;

$V_1 = V_5 = V_6 = V_{10} = 1698 \text{ m}^3$

$V_2 = V_3 = V_4 = V_7 = V_8 = V_9 = 2264 \text{ m}^3$

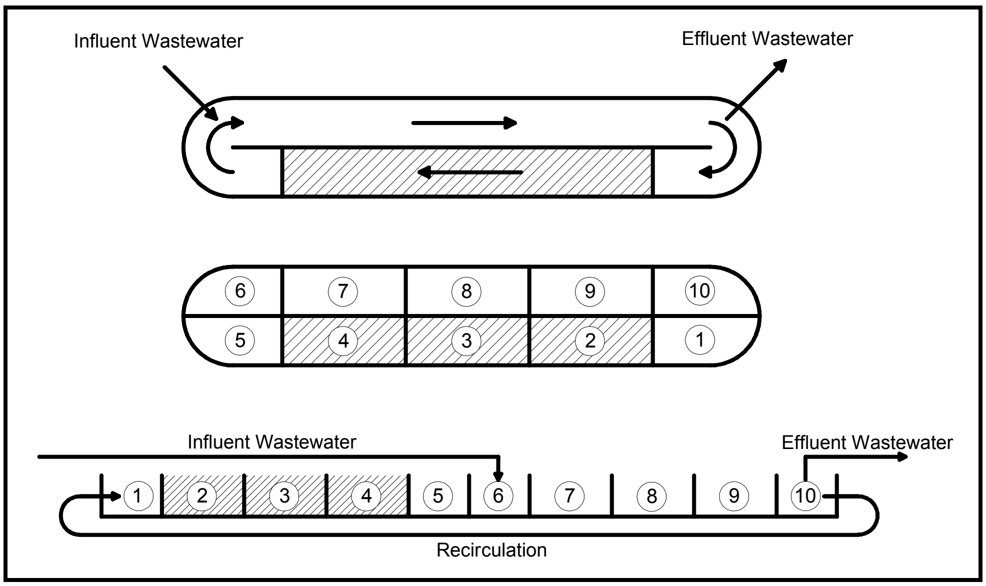

Figure 6.24 Conceptual Internal Layout of the Aeration Tanks

6.4.1. Calibration of the Aeration Tanks with Respect to MLSS

Sensitivity analysis was initially carried out with respect to the effluent MLSS from the aeration tanks. The sensitivities of all the kinetic parameters were analyzed. The results of the sensitivity analyses for the sensitive kinetic parameters are presented in Figures 6.25 to 6.27 and the sensitivity analyses for the rest of the kinetic parameters are given in Appendix D.

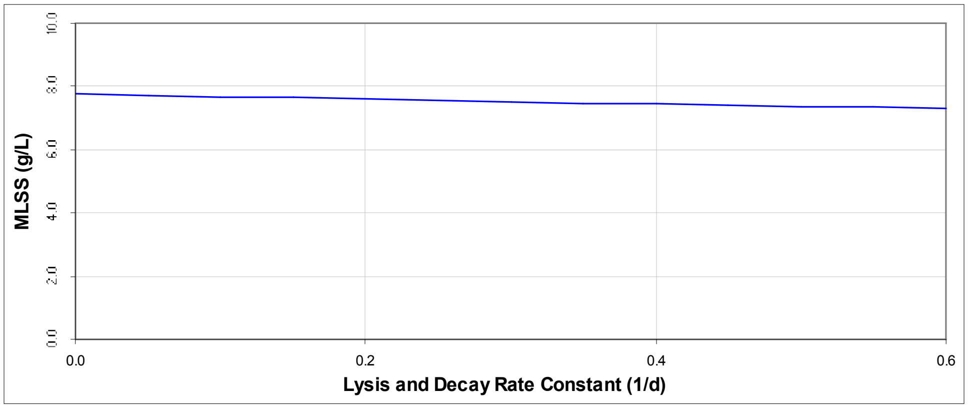

Figure 6.25 Sensitivity Analysis for Lysis and Decay Rate Constant

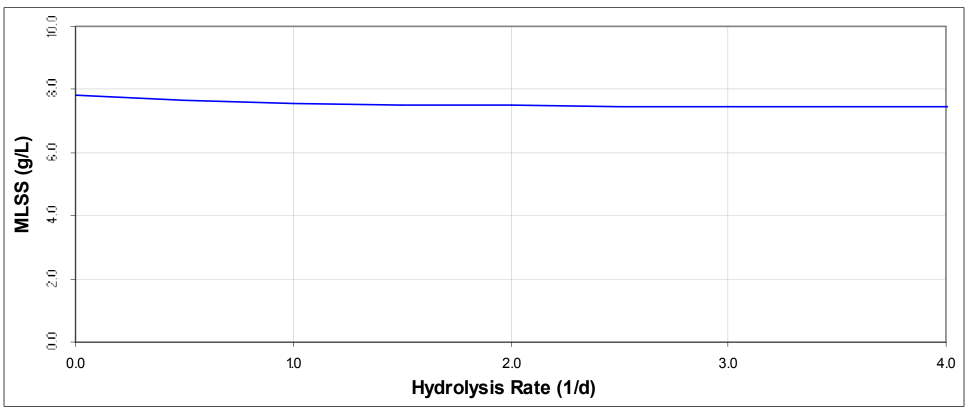

Figure 6.26 Sensitivity Analysis for Hydrolysis Rate

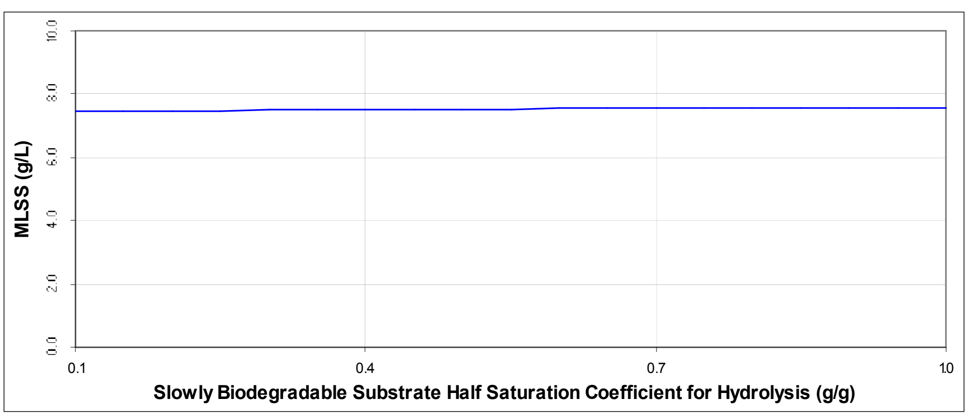

Figure 6.27 Sensitivity Analysis for Slowly Biodegradable Substrate Half Saturation Coefficient for Hydrolysis

Dynamic parameter estimation was decided to be carried out for the lysis and decay rate constants, as well as for hydrolysis rate constant and slowly biodegradable substrate half saturation coefficient for hydrolysis.

Table 6.6 Dynamic Parameter Estimation Results for the Aerobic Tanks (MLSS)

	Range	Default	Absolute Difference	Relative Difference	Sum of Squares	Relative Sum of Squares	Maximum Likelihood
Lysis and decay rate constant (1/d)	0 – 0.6	0.4	0.22	0.23	0.26	0.28	0.26
Hydrolysis rate (1/d)	1 – 4	3	3.58	3.53	3.44	3.30	3.30
Slowly biodegradable substrate half saturation coefficient for hydrolysis (g/g)	0.1 - 1	0.1	0.21	0.21	0.18	0.18	0.18
$\bar{x}$		0.96	1.02	1.02	1.00	1.00	1.00
σ		0.07	0.07	0.07	0.07	0.07	0.07

$\bar{x} = \frac{\sum(\textit{predicted MLSS / measured MLSS})}{n}$, σ = *standard deviation*

The $\bar{x}$ and standard deviation values obtained by using sum of squares, relative sum of squares and maximum likelihood objective functions were 1.00 and 0.07, respectively. The values obtained by using sum of squares objective function was decided to be used instead of the default values for the simulation. The results obtained by using the default and modified values are shown in Figure 6.28 and Figure 6.29. The results for all objective functions are presented in Appendix D.

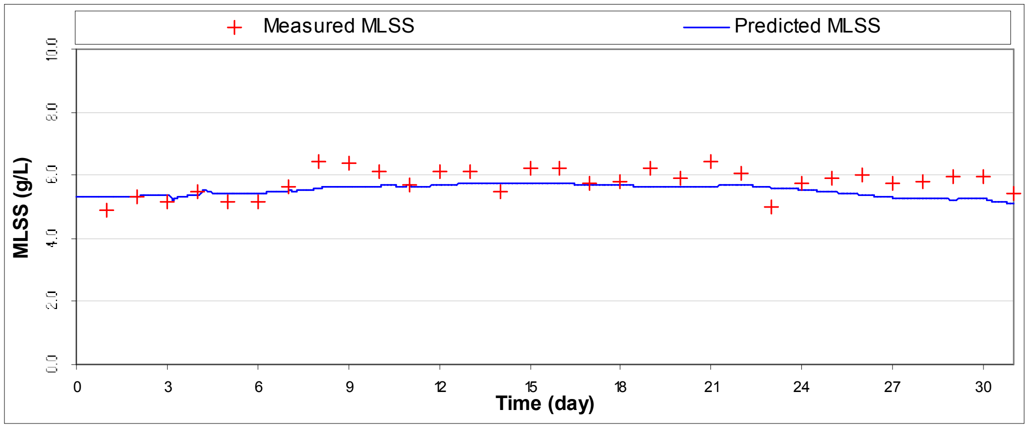

Figure 6.28 Dynamic Run for Aeration Tanks by Using Default Values (MLSS)

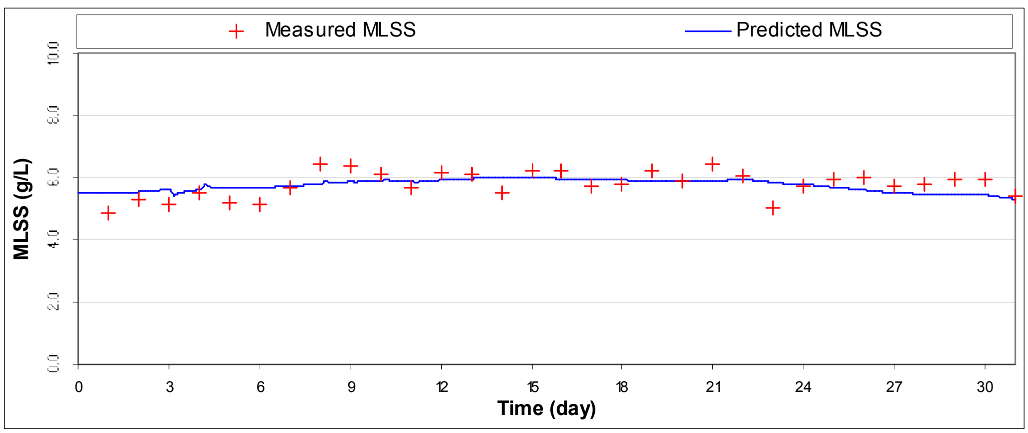

Figure 6.29 Dynamic Run for Aeration Tanks by Using Optimized Values (MLSS)

Figure 6.29 shows that the calibrated model has perfect fit to the predicted effluent measured MLSS concentrations.

6.4.2. Calibration of the Aeration Tanks with Respect to Total Nitrogen

Sensitivity analysis was then carried out with respect to the total nitrogen concentration in the secondary clarified wastewater. The sensitivities of all the kinetic parameters were analyzed with respect to the total nitrogen concentration in the clarified wastewater from the secondary clarifiers.

The results of the sensitivity analyses for the sensitive kinetic parameters are presented in Figures 6.30 to 6.37 and the sensitivity analyses for the rest of the kinetic parameters are given in Appendix E.

Sensitivities of the three kinetic parameters that were optimized with respect to MLSS were not analyzed again with respect to total nitrogen concentration.

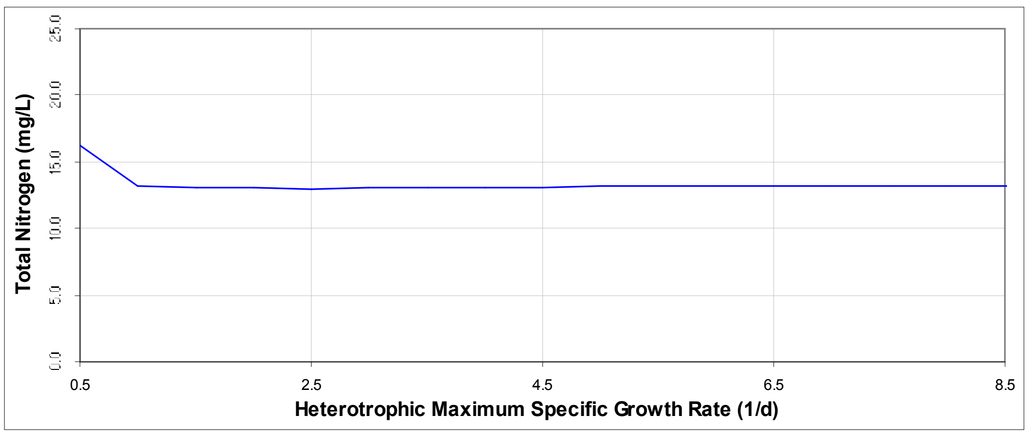

Figure 6.30 Sensitivity Analysis for Heterotrophic Maximum Specific Growth Rate

Figure 6.30 shows that effluent total nitrogen concentration is not very sensitive to heterotrophic maximum specific growth rate. Therefore, this parameter was not considered in the dynamic parameter estimation and the default value of 6 day^{-1} was used during simulations.

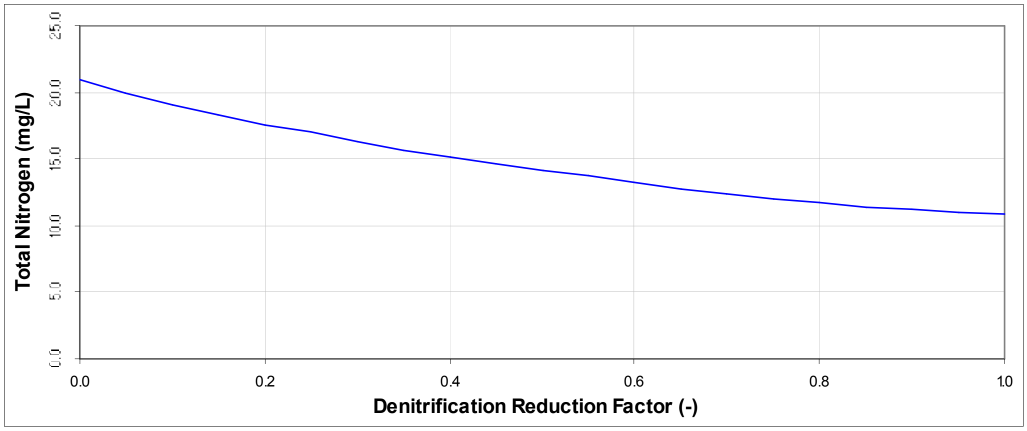

Figure 6.31 Sensitivity Analysis for Denitrification Reduction Factor

As can be seen in Figure 6.31, effluent total nitrogen concentration is rather sensitive to denitrification factor, therefore this parameter was considered in the dynamic parameter estimation.

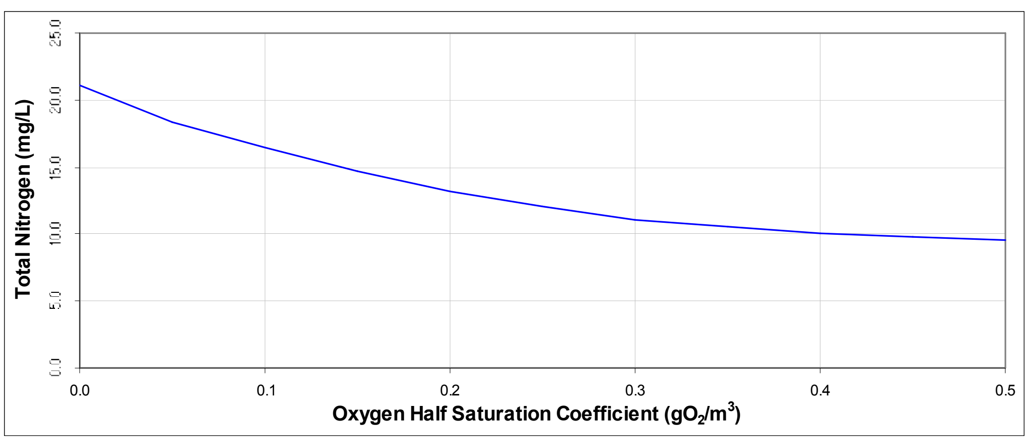

Figure 6.32 Sensitivity Analysis for Oxygen Half Saturation Coefficient

According to Figure 6.32, effluent total nitrogen concentration was found sensitive to the oxygen half saturation coefficient and it was considered in the dynamic parameter estimation.

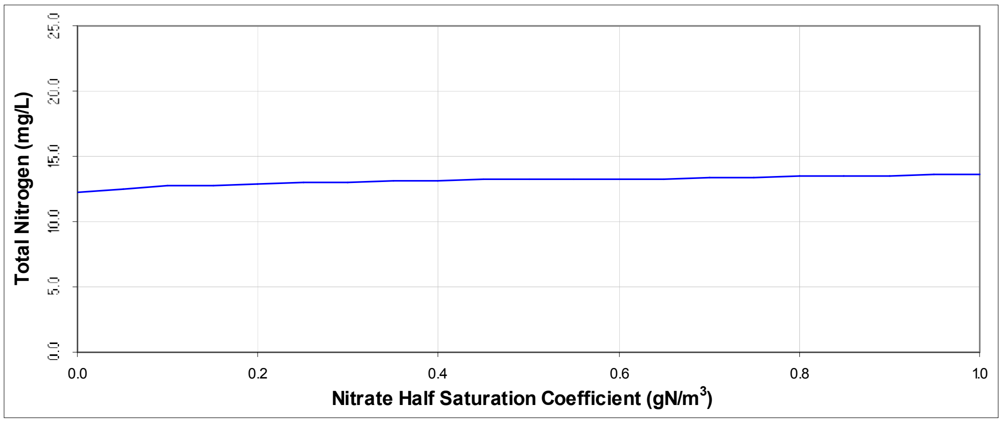

Figure 6.33 Sensitivity Analysis for Nitrate Half Saturation Coefficient

Figure 6.33 shows that effluent total nitrogen concentration is slightly sensitive to nitrate half saturation coefficient. This parameter was taken into consideration in the dynamic parameter estimation.

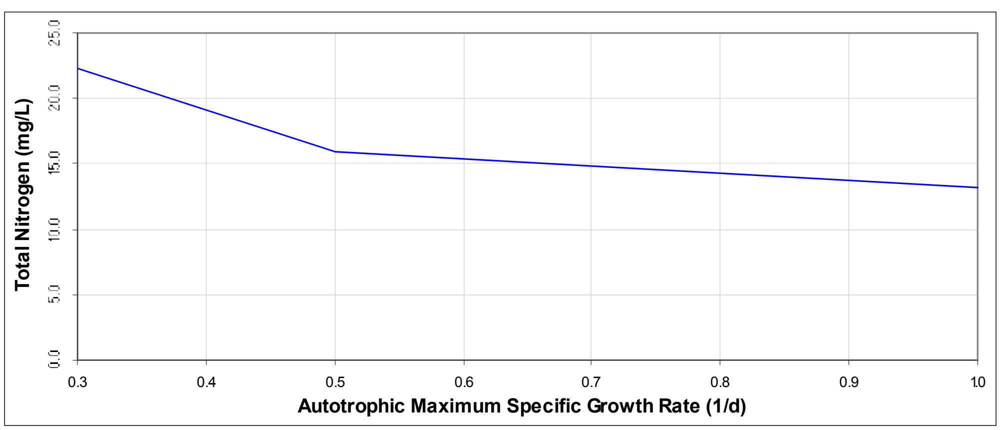

Figure 6.34 Sensitivity Analysis for Autotrophic Maximum Specific Growth Rate

According to Figure 6.34, effluent total nitrogen concentration was found sensitive to autotrophic specific growth rate and was considered in the dynamic parameter estimation.

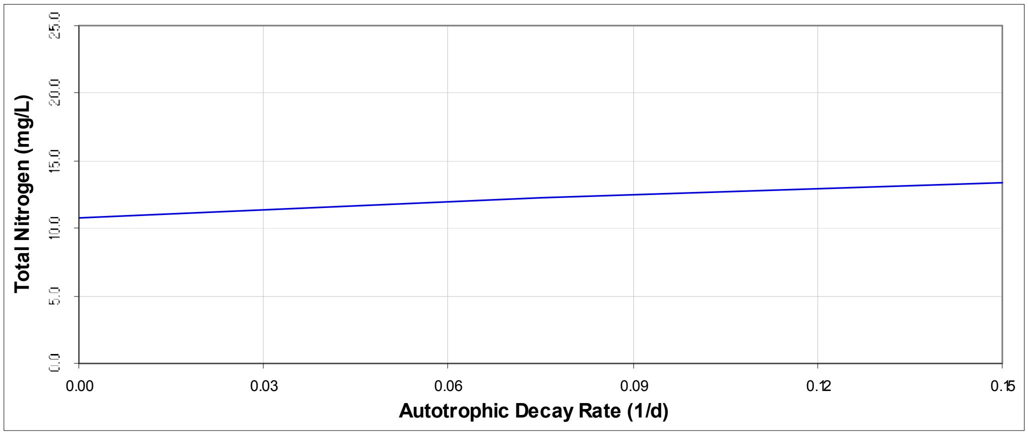

Figure 6.35 Sensitivity Analysis for Autotrophic Decay Rate

According to Figure 6.35, effluent total nitrogen concentration was found slightly sensitive to the autotrophic decay rate; hence this parameter was considered in the dynamic parameter estimation.

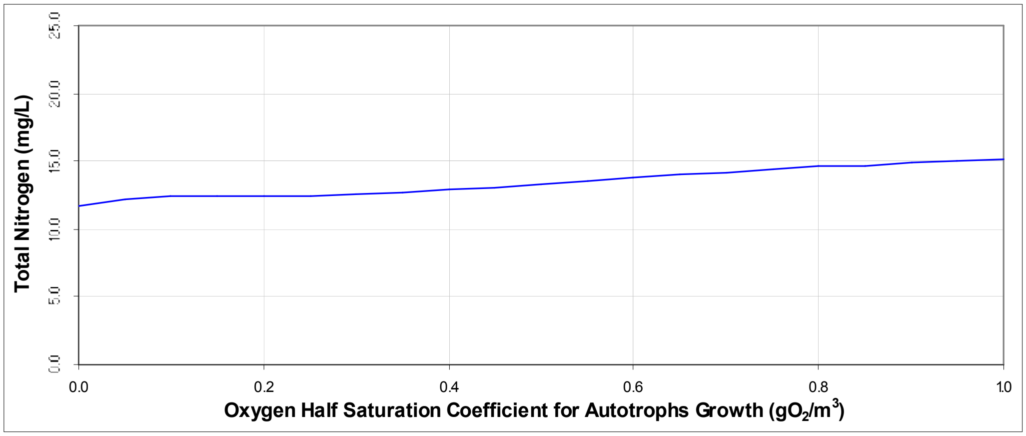

Figure 6.36 Sensitivity Analysis for Oxygen Half Saturation Coefficient for Autotrophic Growth

Figure 6.36 shows that effluent total nitrogen concentration is sensitive to oxygen half saturation coefficient for autotrophic growth. This parameter was also considered in the dynamic parameter estimation.

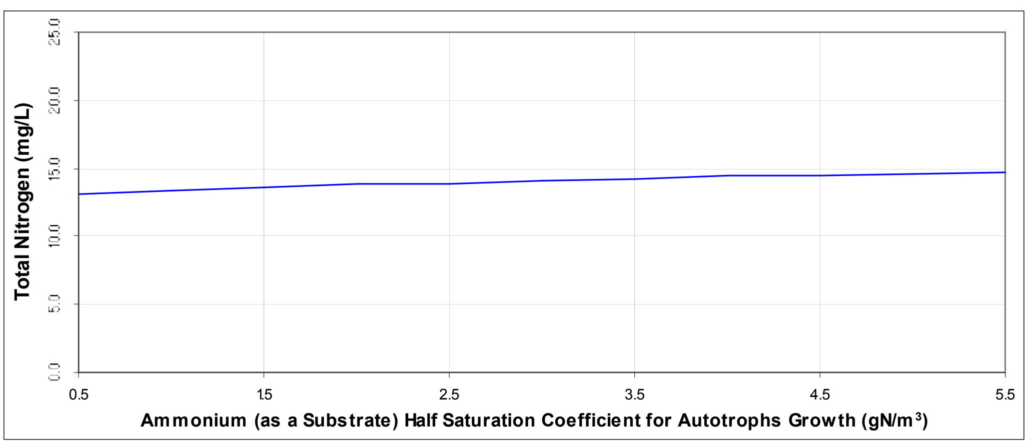

Figure 6.37 Sensitivity Analysis for Ammonium Half Saturation Coefficient for Autotrophic Growth

Figure 6.37 shows that effluent total nitrogen concentration is slightly sensitive to ammonium half saturation coefficient for autotrophic growth. This parameter was therefore considered in the dynamic parameter estimation.

Sensitivity analysis for nitrogen compounds was carried out by using total nitrogen concentration readings in the secondary clarified wastewater. However, later during dynamic parameter estimation for nitrate and ammonium the identified parameters resolved in sensitivity testing with total nitrogen were also used. Therefore, three variables in the model (total nitrogen, nitrate and ammonium) were assigned as the target variables and GPS-X calibrated these using the sensitive parameters.

Table 6.7 shows that the $\bar{x}$ value obtained by using sum of squares objective function was closest to 1, which was 0.86. Therefore, the parameter values obtained by this objective function were used for the simulations.

The results obtained by using the default and modified values are shown in Figure 6.38 and Figure 6.39. The results for all objective functions are presented in Appendix E.

Table 6.7 Dynamic Parameter Estimation Results for the Aerobic Tanks (Total Nitrogen)

	Range	Default	Absolute Difference	Relative Difference	Sum of Squares	Relative Sum of Squares	Maximum Likelihood
Denitrification reduction factor (-)	0.6 – 1.0 [6]	0.6	0.86	0.60	0.88	0.65	0.84
Oxygen half saturation coefficient (gO_2/m^3)	0 – 0.5	0.2	0.28	0.43	0.27	0.39	0.28
Nitrate half saturation coefficient (gN/m^3)	0.2 – 0.8	0.5	0.56	0.68	0.78	0.50	0.48
Autotrophic maximum specific growth rate (1/day)	0.30 – 1.0 [6]	1.0	0.84	0.94	0.86	0.95	0.88
Autotrophic decay rate (1/day)	0.05 – 0.15 [6]	0.15	0.097	0.131	0.083	0.094	0.096
Oxygen half saturation coefficient for autotrophic growth (gO_2/m^3)	0.2 – 0.8	0.5	0.38	0.20	0.50	0.27	0.37
Ammonium (as a substrate) half saturation coefficient for autotrophic growth (gN/m^3)	0.5 – 1.5	1.0	1.20	1.29	1.04	1.40	1.28
$\bar{x}$		1.73	0.80	0.75	0.86	0.60	0.76
σ		0.60	0.35	0.34	0.37	0.30	0.34

$\bar{x} = \frac{\sum(predicted\ total\ N\ /\ measured\ total\ N)}{n}$, σ = *standard deviation*

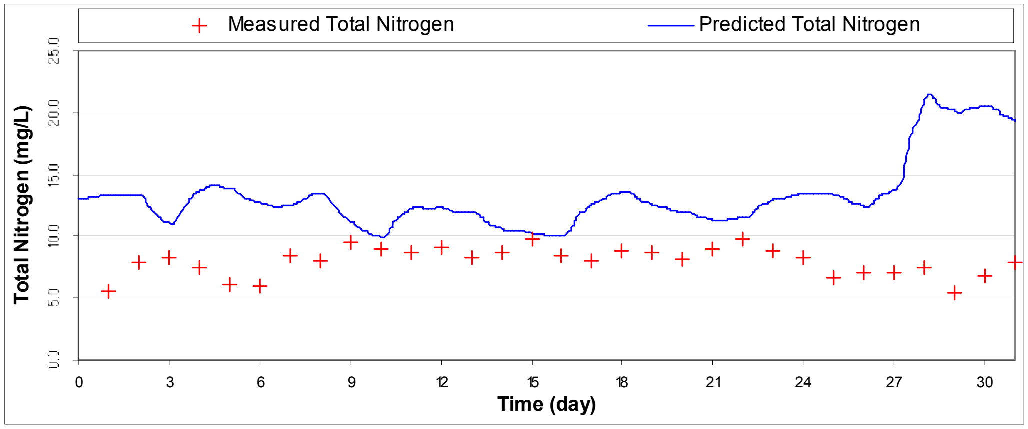

Figure 6.38 Dynamic Run for Aeration Tanks by Using Default Values (Total Nitrogen)

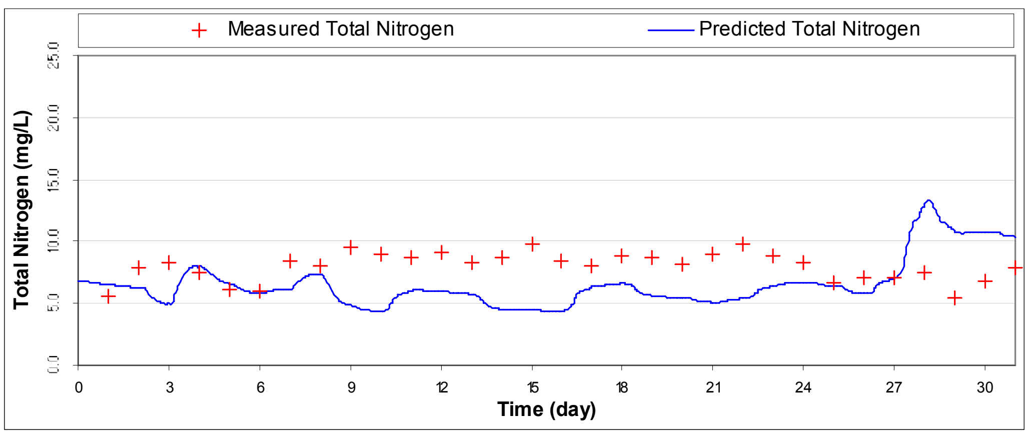

Figure 6.39 Dynamic Run for Aeration Tanks by Using Optimized Values (Total Nitrogen)

According to Figure 6.38, the predicted total nitrogen concentrations were higher than the measured concentrations before calibration. After calibration, as can be seen in Figure 6.39, the predicted total nitrogen concentrations are slightly lower than the measured concentrations. The average of measured and predicted concentrations are 8.00 mg/L and 6.04 mg/L, respectively.

Figure 6.40 and Figure 6.41 show the results for NO_3-N, obtained by using default and optimized values.

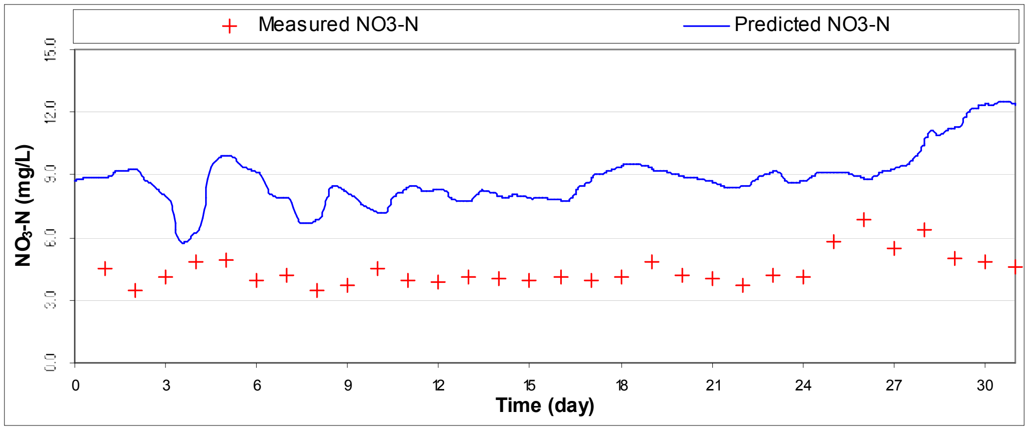

Figure 6.40 Dynamic Run for Aeration Tanks by Using Default Values (NO_3-N)

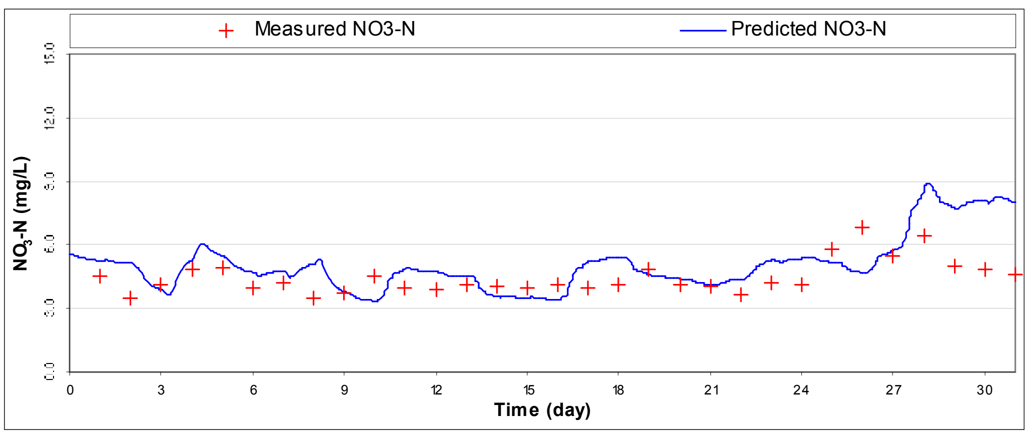

Figure 6.41 Dynamic Run for Aeration Tanks by Using Optimized Values (NO_3-N)

As can be seen in Figure 6.40, the model overestimated the NO_3-N concentration in the final effluent before calibration. Figure 6.41 shows that after calibration a reasonably good fit was obtained for NO_3-N concentrations.

Figure 6.42 and Figure 6.43 show the results for NH_4-N, obtained by using default and optimized values.

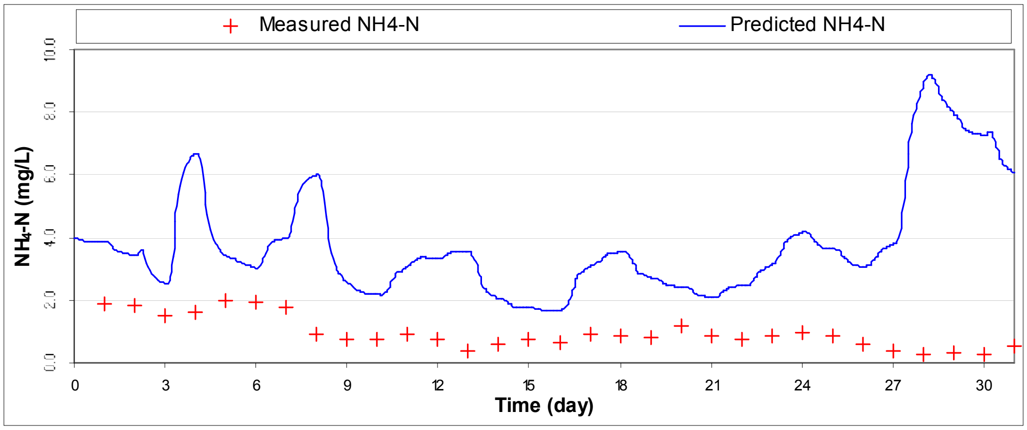

Figure 6.42 Dynamic Run for Aeration Tanks by Using Default Values (NH_4-N)

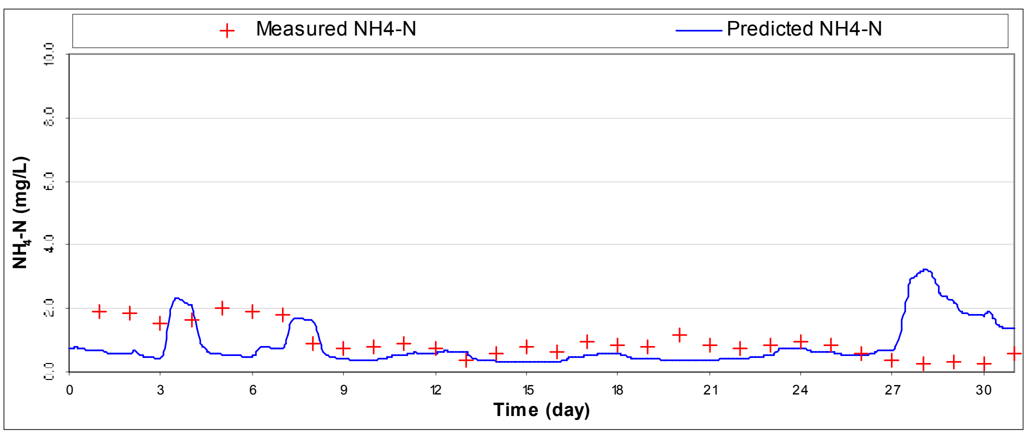

Figure 6.43 Dynamic Run for Aeration Tanks by Using Optimized Values (NH_4-N)

Figure 6.42 shows that before calibration the predicted NH_4-N concentration was much higher than the measured concentrations. After calibration, as can be seen in Figure 6.43, a better fit was obtained. A sudden increase after 27th day was consistent in all the predicted Nitrogen plots.

6.5. Calibration of the Selector Tank

For the calibration of the selector tank, the layout shown in Figure 6.44 was conceived. Activated Sludge Model No.2d was used to model the phosphorous behavior in wastewater and the tank was simulated by using 4 CSTRs to simulate a plug-flow reactor. As can be seen in Figure 6.23, model was built for a single secondary clarifier, therefore, the volume of the selector tank was taken as one fourth of the original total volume. The internal recirculation in the selector tank was taken as 100% and no oxygen was supplied to the tank. Volume of each CSTR in Figure 6.44 was as follows;

$$V_1 = V_2 = V_3 = V_4 = 813 \ m^3$$

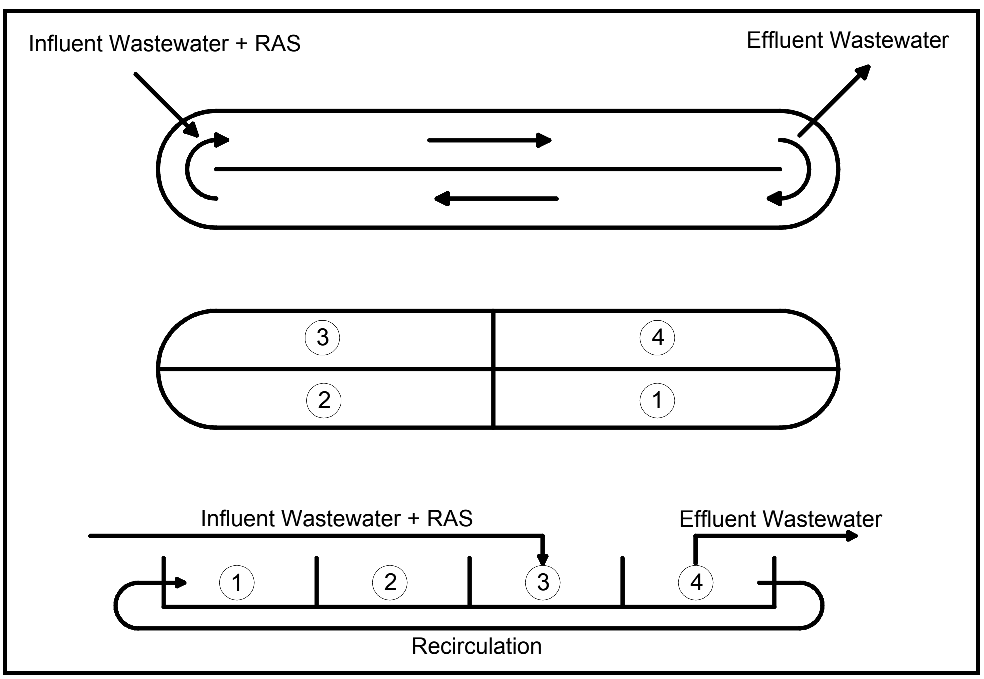

Figure 6.44 Conceptual Internal Layout of the Selector Tank

Default values were used for the kinetic parameters except those for the active autotrophic biomass. The parameter values were taken as zero for the autotrophs since they would be inhibited under anaerobic conditions [6].

6.6. Calibration of the System with Respect to Total Phosphorus

The layout shown in Figure 6.45 was used for the calibration of the system with respect to total phosphorus concentration in the clarified wastewater from the secondary clarifier. As can be seen from the figure, the layout was built for a single primary clarifier; therefore, half of the treatment plant was simulated by this layout.

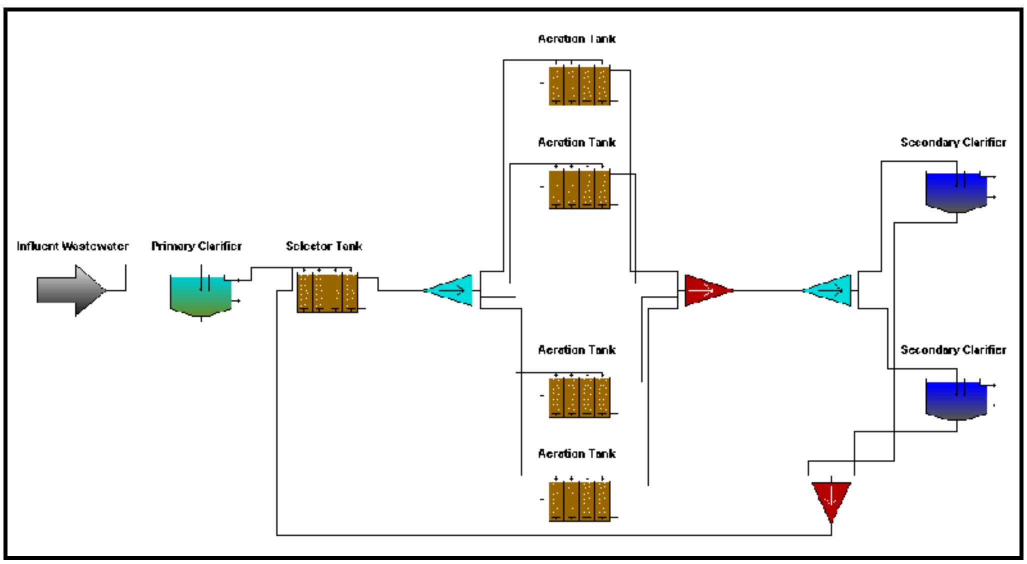

Figure 6.45 Layout of the Treatment Plant

The predicted effluent phosphorus concentration was very high as can be seen in Figure 6.46.

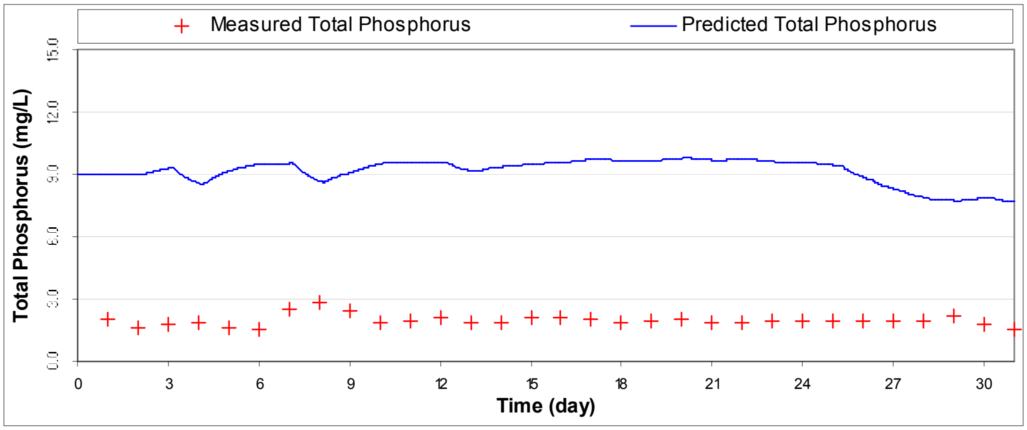

Figure 6.46 Dynamic Run Before Calibration with Respect to Total Phosphorus

The effluent phosphorus concentration was found insensitive to kinetic parameters related to the phosphorous kinetics in the selector and the aeration tanks. The sensitivity of the model to some of the influent wastewater characteristics was also analyzed. The sensitive parameters are presented in Figures 6.47 to 6.49.

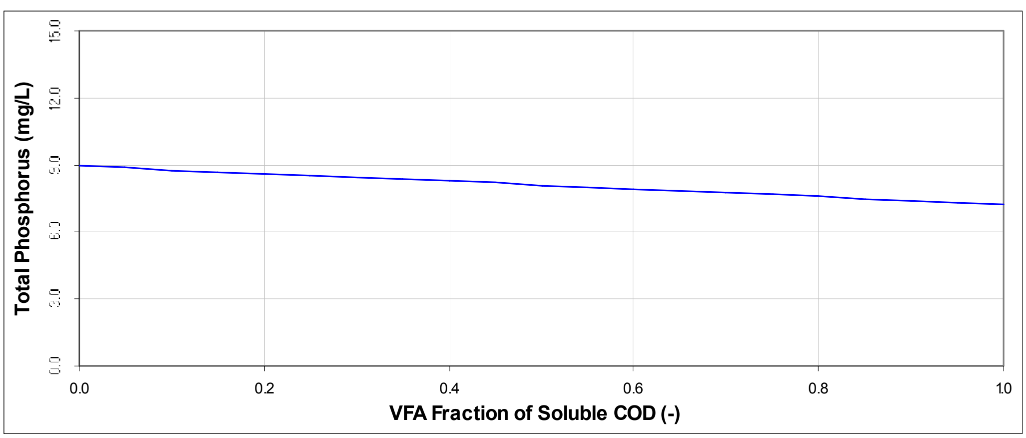

Figure 6.47 Sensitivity Analysis for VFA Fraction of Soluble COD

Volatile acids concentration in raw municipal wastewaters is typically 10-60 gCOD/m^3 [3]. The soluble COD concentration of the influent wastewater was given as 171 gCOD/m^3 by the influent advisor.

According to the advisor VFA fraction of soluble COD was changing between 0.06-0.35. The supernatant from the anaerobic digester, which was not modeled in this study due to lack of data, also contains volatile acids. This stream is given to the inlet but is not considered here. Therefore, it is highly probable that extra VFA imparted to the raw wastewater in this way has also increased VFA fraction to an excess of 0.40 total COD. In turn higher VFA should affect higher phosphorus removal.

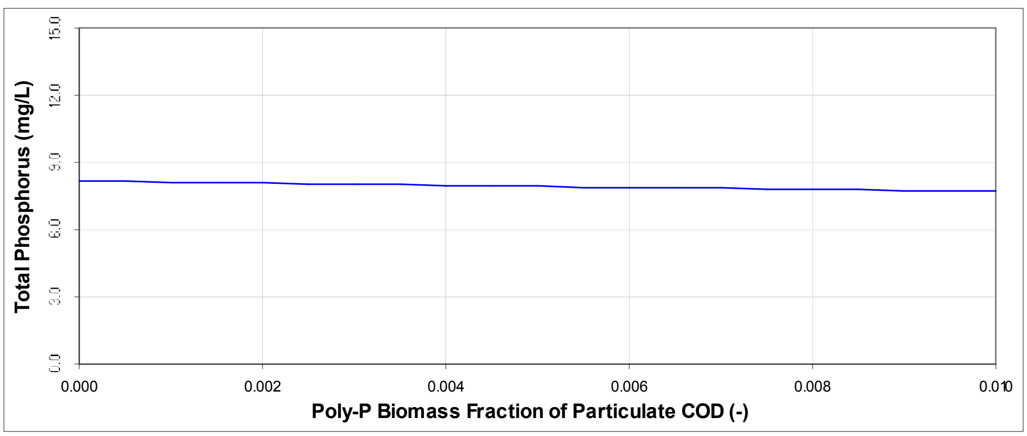

Figure 6.48 Sensitivity Analysis for Poly-P Biomass Fraction of Particulate COD

The typical concentration of phosphorus accumulating organisms in the raw municipal wastewater changes between 0-1 gCOD/m^3 [3]. The particulate COD concentration given by influent advisor was 399 gCOD/m^3. Therefore, poly-P biomass fraction of particulate COD changes between 0-0.003. This parameter was taken as 0.003.

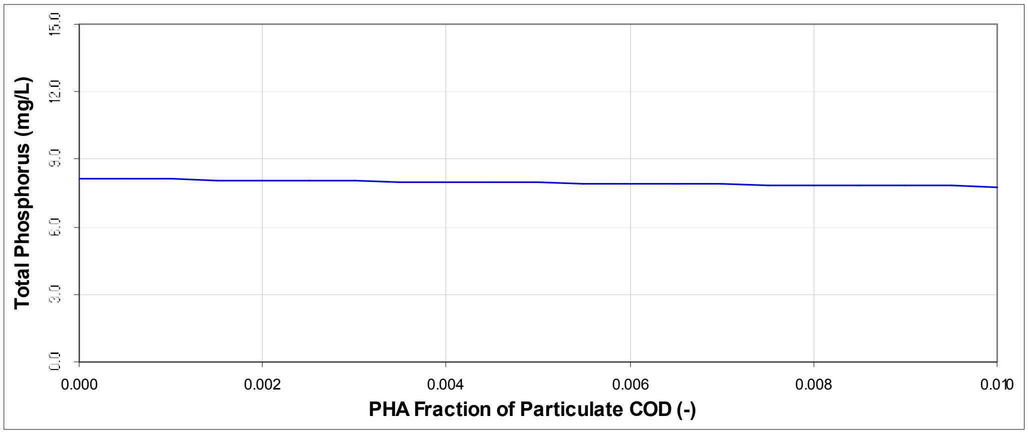

Figure 6.49 Sensitivity Analysis for PHA Fraction of Particulate COD

The typical concentration of stored poly-hydroxy-alkanoate in the raw municipal wastewater changes between 0-1 gCOD/m^3 [3]. Therefore, PHA fraction of particulate COD changes between 0-0.003. This parameter was taken as 0.003.

The results for effluent total phosphorus concentration obtained after calibration is shown in Figure 6.50 and Appendix F.

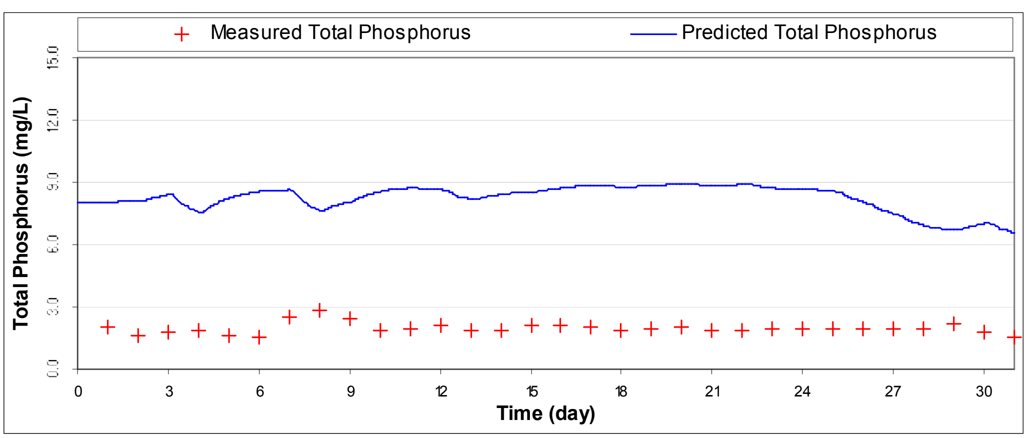

Figure 6.50 Dynamic Run After Calibration with Respect to Total Phosphorus

Comparing Figures 6.46 and 6.50, the predicted total phosphorus slightly decreased after calibration. However, this was still too high compared to the measured total phosphorus. Biological phosphorus removal is directly related to the presence of volatile fatty acids. However, the concentration of volatile fatty acids was not measured in the treatment plant. Also alkalinity of the wastewater was obscure at the time and any chemical precipitation of phosphorus had to be ignored. Therefore, due to lack of information on these parameters a better fit could not be reached for phosphorus.

6.7. Results of the Calibration

The predicted concentrations of some of the variables have changed after calibrating all the units. Therefore, these variables were evaluated once again by using the layout shown in Figure 6.45. The concentrations of effluent COD and TSS were computed as given in Figures 6.51 to 6.57 and the details are given in Appendix G.

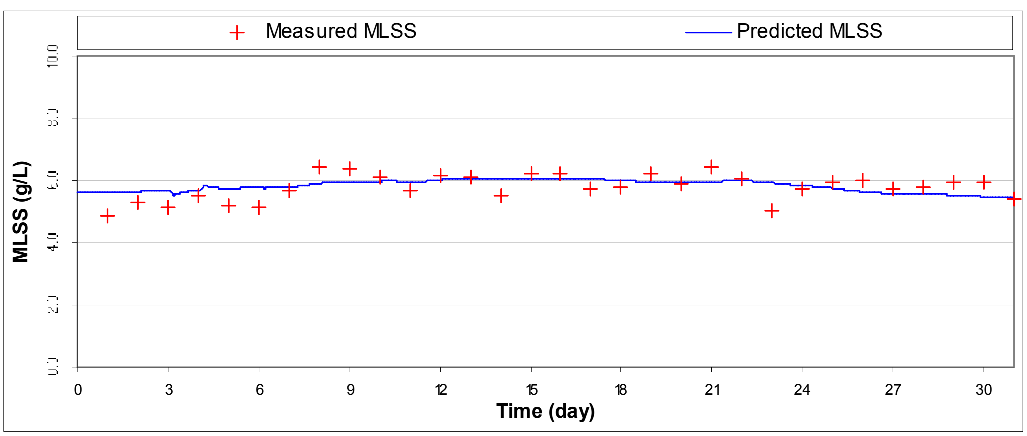

Figure 6.51 Effluent MLSS Concentrations from the Aeration Tanks

Comparing Figures 6.29 and 6.51, the predicted effluent MLSS concentration from the aeration tanks did not change so much after calibrating the whole system.

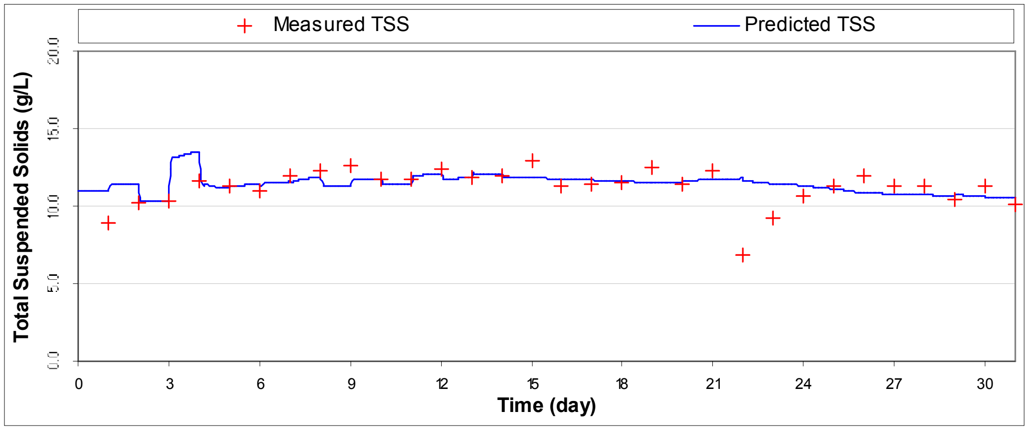

Figure 6.52 Underflow TSS Concentration from the Secondary Clarifiers

In Section 6.3, the underflow TSS concentration from the secondary clarifier was calibrated assuming all the suspended solids settled in the secondary clarifier and the return activated sludge was given by a separate influent object, as can be seen in Figure 6.12. At the end of the calibration of the whole system, the predicted underflow TSS concentration was compared with the real data measured in the plant. The results are presented in Figure 6.52 and the fit is reasonably good.

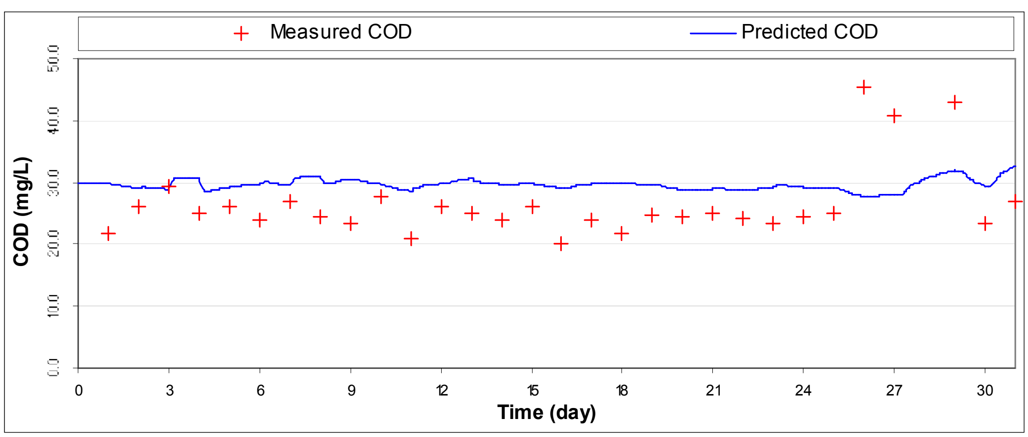

Figure 6.53 COD Concentration in the Final Effluent

As can be seen in Figure 6.53, the predicted COD concentration in the final effluent was slightly higher than the measured COD concentrations. The average of measured and predicted concentrations are 27.24 mg/L and 29.61 mg/L, respectively. $\bar{x}$ value and the standard deviation for COD results are 1.14 and 0.22, respectively.

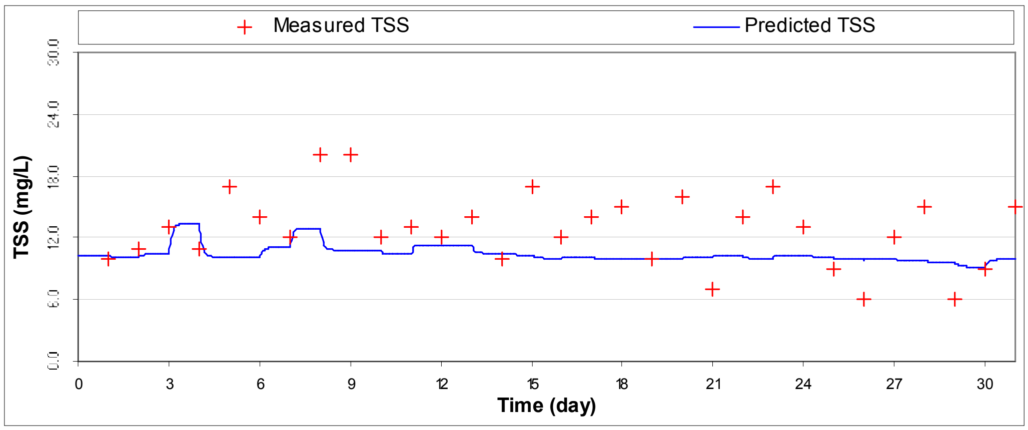

Figure 6.54 TSS Concentrations in the Final Effluent

The results obtained for TSS concentration in the final effluent after calibrating the whole system is shown in Figure 6.54. $\bar{x}$ value and the standard deviation for COD results are 0.88 and 0.28, respectively. The $\bar{x}$ value was lower than 1, which means that the model slightly underestimates the TSS concentrations. As can be seen from this figure the daily abrupt changes in the actual data could not be simulated by the model and the concentrations provided by the model were more stable.

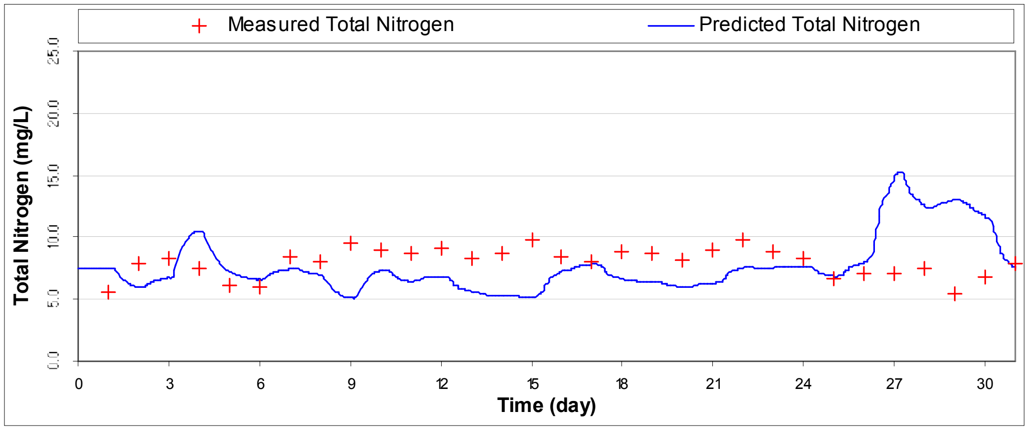

Figure 6.55 Total Nitrogen Concentration in the Final Effluent

Comparing Figures 6.39 and 6.55, the predicted total nitrogen concentrations have slightly increased after final calibration of the whole system. The average of predicted total nitrogen concentration was 7.68 mg/L, whereas average of the measured concentrations was 8.00 mg/L. The $\bar{x}$ value and the standard deviation for total nitrogen results are 1.01 and 0.42, respectively.

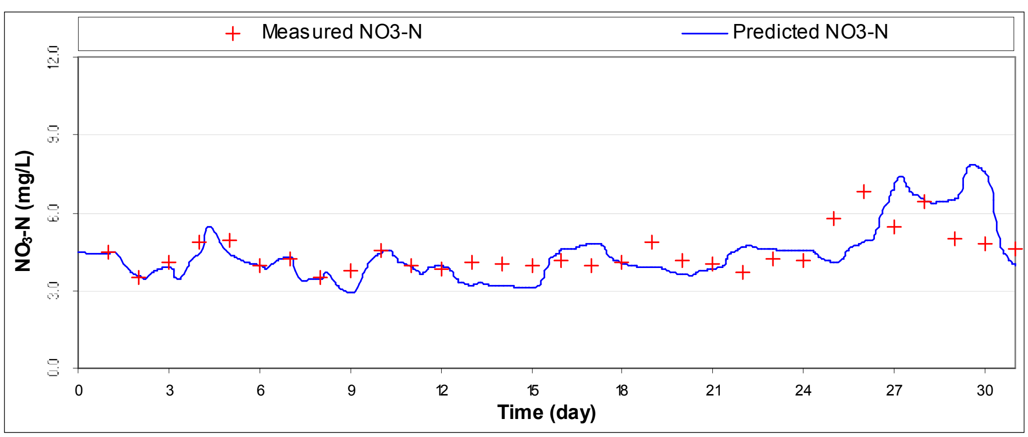

Figure 6.56 The NO_3-N Concentration in the Final Effluent

The results for NO_3-N concentrations obtained at the end of calibration of the whole system are given in Figure 6.56. The average of measured and predicted concentrations were 4.45 mg/L and 4.39 mg/L, respectively. The $\bar{x}$ value and the standard deviation were 0.99 and 0.18, respectively.

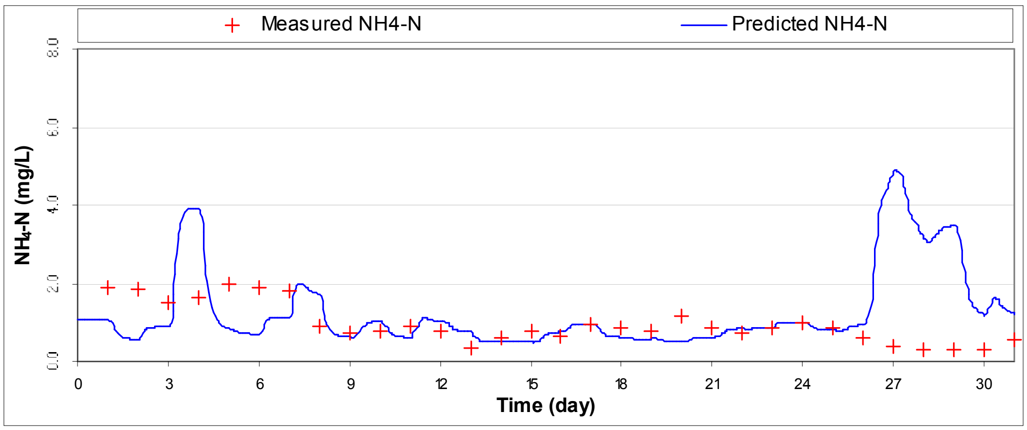

Figure 6.57 The NH_4-N Concentration in the Final Effluent

The result for NH_4-N concentrations obtained at the end of calibration of the whole system is given in Figure 6.57. Perfect fit was almost achieved between 9th and 25th days. However, the sudden increase in predicted values was still present at two occasions. The average of measured and predicted concentrations were 0.95 mg/L and 1.24 mg/L, respectively.

6.8. Validation of the Model

The calibration of the model was undertaken by using the data obtained in March 2004. The validation of the model was done using the data for different seasons of the same year, (May 2004 and July 2004), which are given in Appendix A.

The layout shown in Figure 6.45 was again used for validation.

The values of the sensitive parameters in the aeration tanks were modified with respect to the temperature of the influent wastewater. The Arrhenius relation presented in eq. 6.2 was used for this modification.

$$k_2 = k_1\,\theta^{(T_2 - T_1)} \qquad \text{eq. 6.2}$$

where,

T : temperature,

k_1 : reaction rate constant at temperature T_1,

k_2 : reaction rate constant at temperature T_2,

θ : constant (vary from 1.02 to 1.10) [4].

The average influent wastewater temperatures for March 2004, May 2004 and July 2004 were 16.4 ºC, 18.7 ºC and 22.3 ºC, respectively. The θ value in eq. 6.2 was taken as 1.04.

The calculated values of the sensitive parameters after temperature correction are presented in Table 6.8.

Table 6.8 List of Modified Sensitive Parameters with Respect to Temperature

Sensitive Parameters for Aeration Tanks	March 2004	May 2004	July 2004
Lysis and decay rate constant (1/d)	0.26	0.28	0.33
Hydrolysis rate (1/d)	3.44	3.76	4.34
Slowly biodegradable substrate half saturation coefficient for hydrolysis (g/g)	0.18	0.20	0.23
Denitrification reduction factor (-)	0.88	0.96	1.00*
Oxygen half saturation coefficient (gO_2/m^3)	0.27	0.30	0.34
Nitrate half saturation coefficient (gN/m^3)	0.78	0.85	0.98
Autotrophic maximum specific growth rate (1/day)	0.86	0.94	1.08
Autotrophic decay rate (1/day)	0.083	0.091	0.105
Oxygen half saturation coefficient for autotrophic growth (gO_2/m^3)	0.50	0.55	0.63
Ammonium (as a substrate) half saturation coefficient for autotrophic growth (gN/m^3)	1.04	1.14	1.31

*This parameter was taken as 1.00, since it ranges between 0.60-1.00 [6].

6.8.1. Validation of the Model for May 2004

The validation results for May 2004 are presented in Figures 6.58 to 6.69 together with some of the influent wastewater characteristics to show the effects of shock loads. The detailed results are given in Appendix H. For this month, the average influent flow rate was 152,840 m^3/day. However, on the 16^{th} day of the month influent flow rate increased to 259,200 m^3/day along with COD and TSS concentrations reaching up to 900 mg/L and 680 mg/L, respectively. The effect of the sudden increase can be seen in the validation studies. The measured flow rates for this month are shown in Figure 6.58.

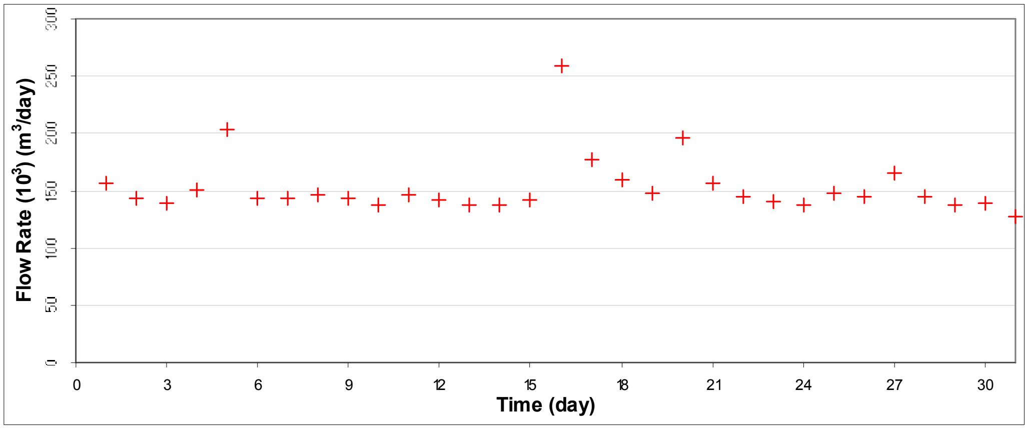

Figure 6.58 Influent Flow Rates for May 2004

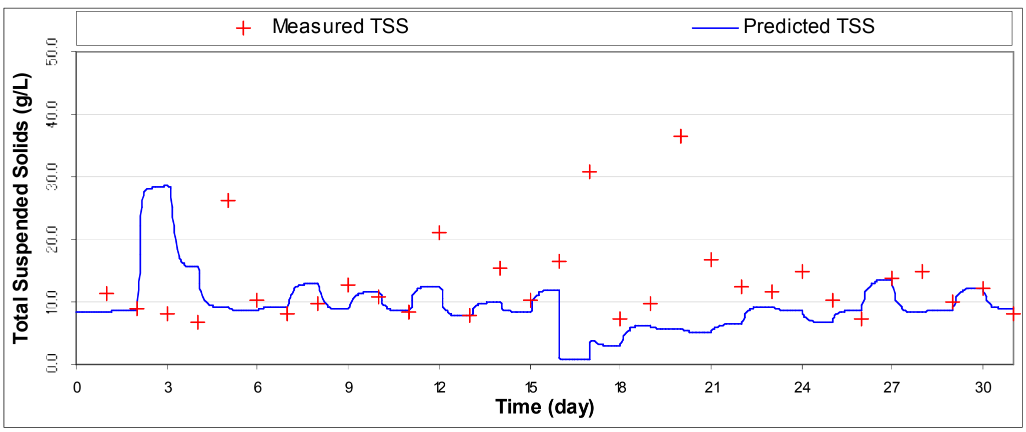

Figure 6.59 Underflow TSS Concentration from the Primary Clarifiers for May 2004 Validation

Figure 6.59 shows that the model was affected from the shock load that occurred on the 16th day. Measured concentrations show that the primary clarifiers were not affected so much from the high loading. The $\bar{x}$ value and the standard deviation for this parameter were 0.89 and 0.64, respectively.

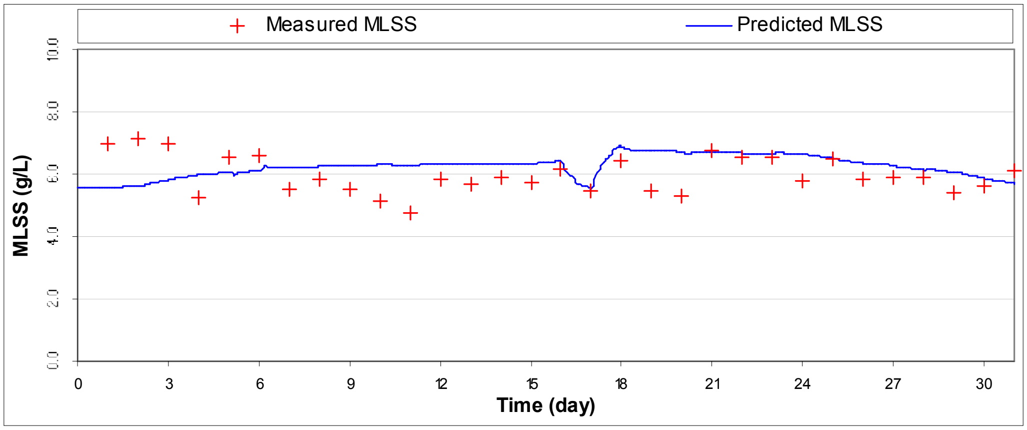

Figure 6.60 Effluent MLSS Concentrations from the Aeration Tanks for May 2004 Validation

Figure 6.60 shows that a reasonably good fit was obtained for effluent MLSS concentrations in the aeration tanks. The $\bar{x}$ value and the standard deviation for this parameter were 1.06 and 0.13, respectively.

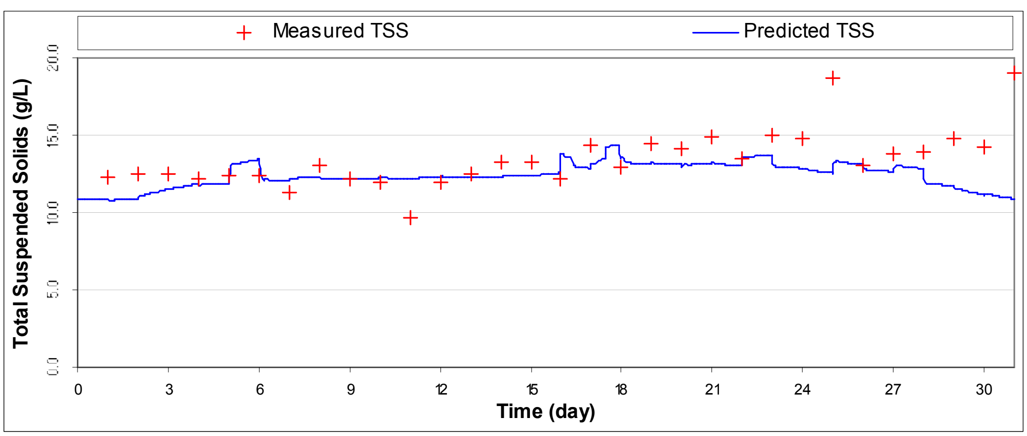

Figure 6.61 Underflow TSS Concentration from the Secondary Clarifiers for May 2004 Validation

Figure 6.61 shows that a good fit was obtained for underflow TSS concentrations from the secondary clarifiers. However, TSS concentration went up to 19 g/L on the 25th and 31st days. These increases were not simulated by the model. The concentrations provided by the model were more stable and changed between 10-15 g/L. The $\bar{x}$ value and the standard deviation for this parameter are 1.06 and 0.13, respectively.

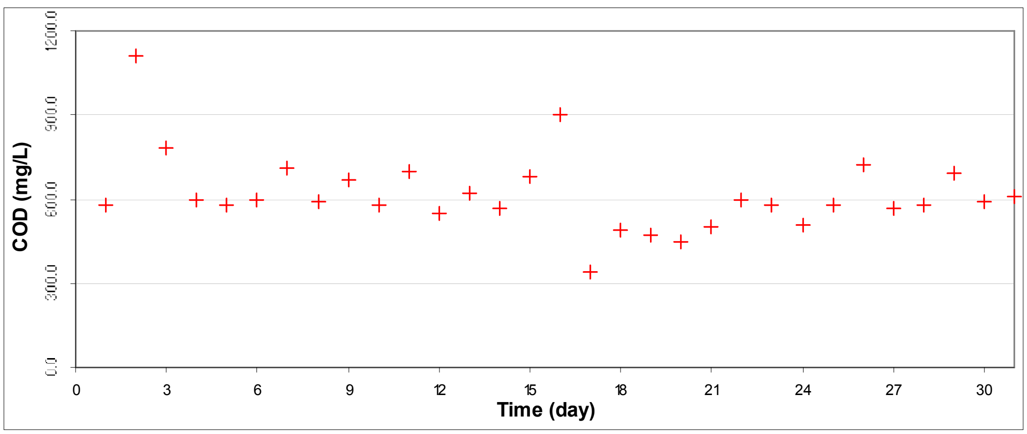

Figure 6.62 COD Concentrations in the Influent Wastewater for May 2004

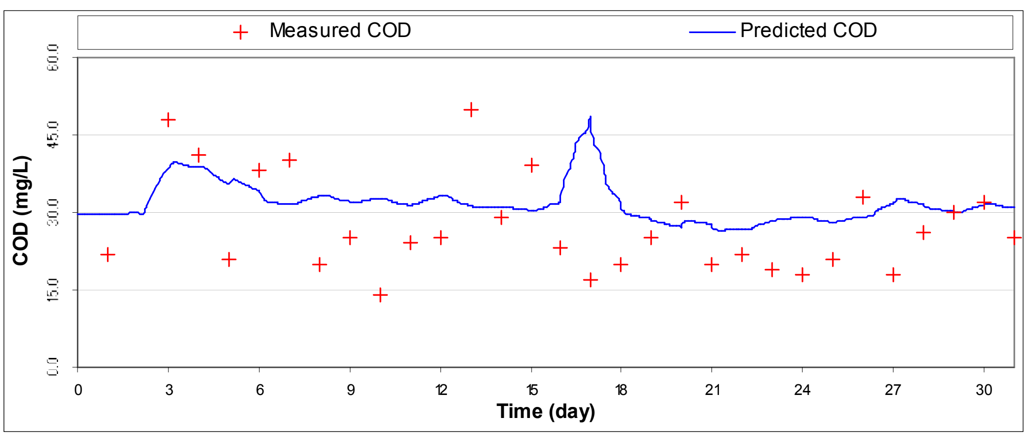

Figure 6.63 COD Concentration in the Final Effluent for May 2004 Validation

The effect of the high loading occurred on the 16th day can be seen in predicted effluent COD concentration shown in Figure 6.63. The COD concentrations in the influent wastewater are also shown in Figure 6.62. The average of measured and predicted concentrations were 27.23 mg/L and 31.72 mg/L, respectively. The model slightly overestimates effluent COD concentration as it was discussed before during simulations with March 2004 data.

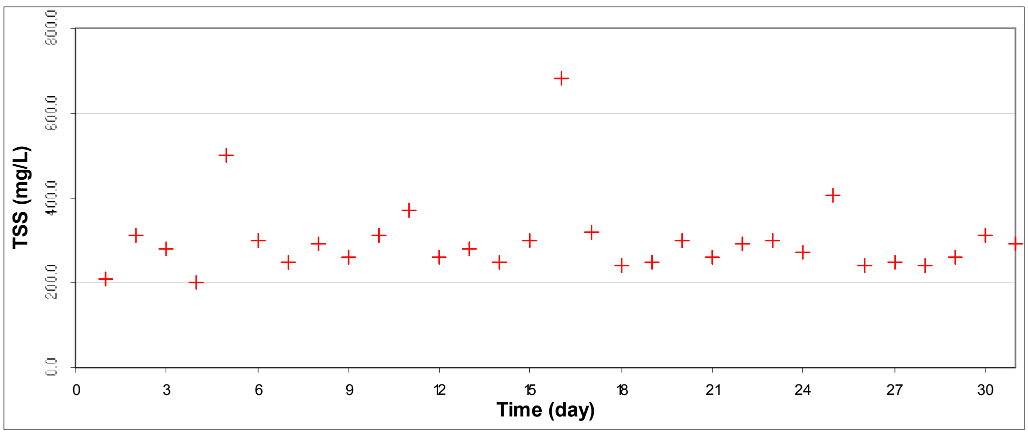

Figure 6.64 TSS Concentrations in the Influent Wastewater for May 2004

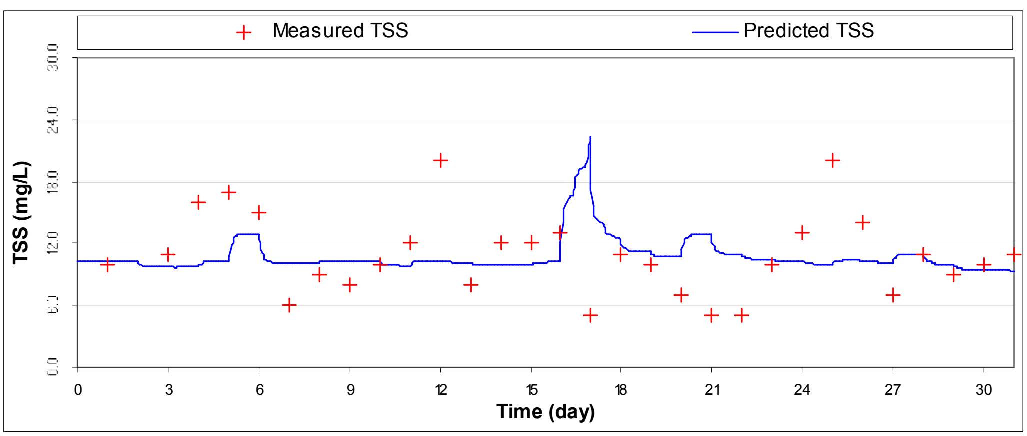

Figure 6.65 TSS Concentration in the Final Effluent for May 2004 Validation

The peak in the predicted effluent TSS that is seen in Figure 6.65 was due to the high concentration of TSS in the influent wastewater on 16th day, which is seen in Figure 6.64. The $\bar{x}$ value and standard deviation for this parameter were 1.16 and 0.65, respectively.

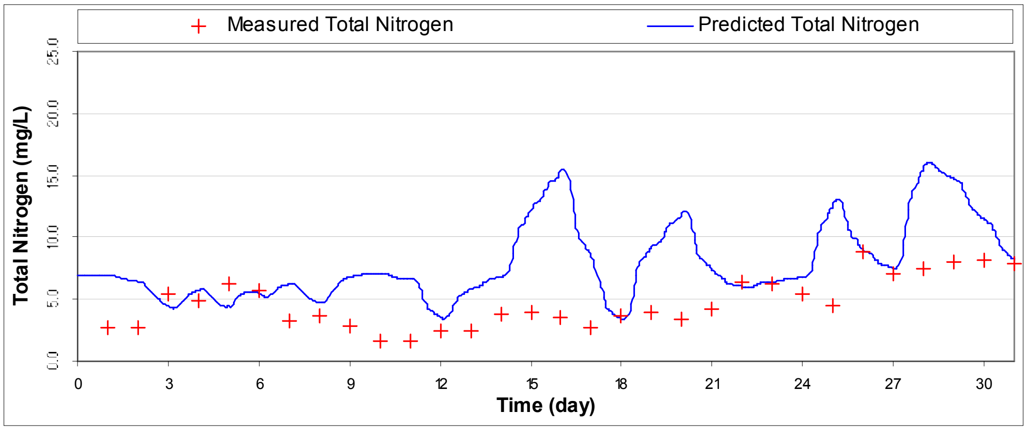

Figure 6.66 Total Nitrogen Concentration in the Final Effluent for May 2004 Validation

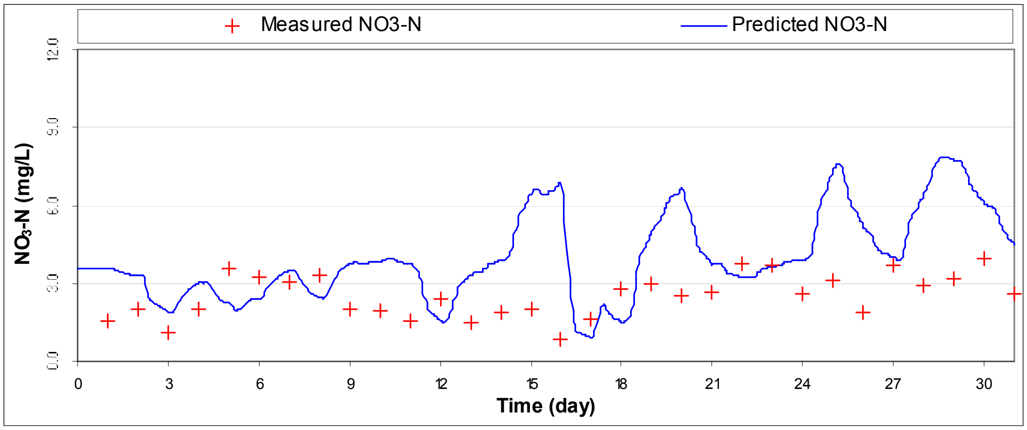

Figure 6.67 NO_3-N Concentration in the Final Effluent for May 2004 Validation

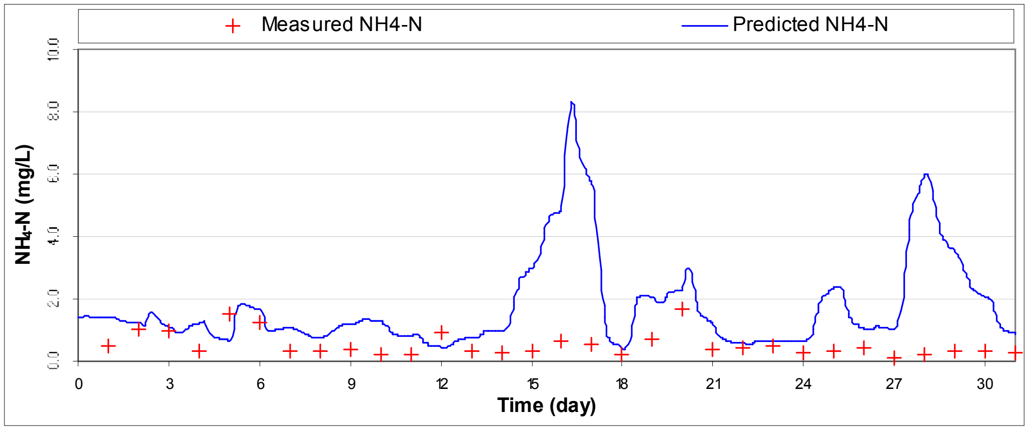

Figure 6.68 NH_4-N Concentration in the Final Effluent for May 2004 Validation

Figures 6.66 to 6.68 show the results related to nitrogen. The nitrogen removal efficiency of the treatment plant was higher in May 2004 due to the higher temperature. In spite of the modification of the sensitive parameters with respect to temperature, the model still slightly overestimated the concentrations related to nitrogen. The predicted concentrations were very variable and some peaks were observed, which were absent in the actual plant data.

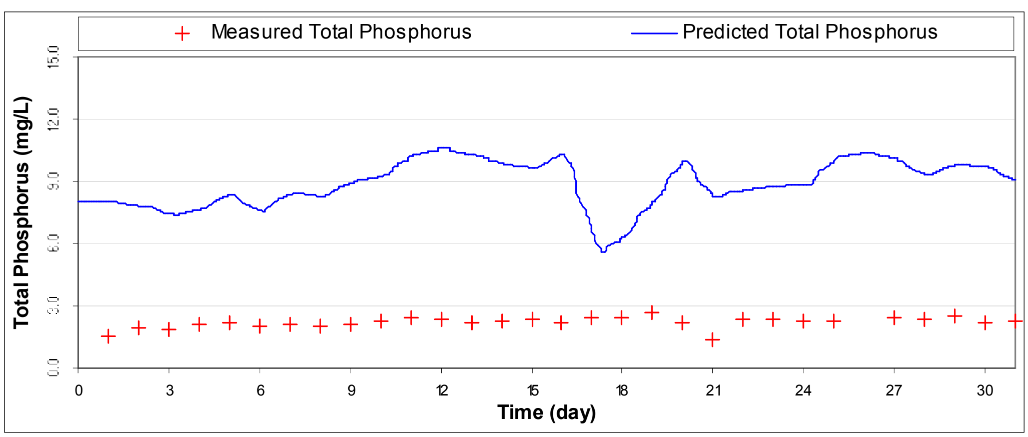

Figure 6.69 Total Phosphorus Concentration in the Final Effluent for May 2004 Validation

As stated before in Section 6.6, the predicted total phosphorus concentrations were too high compared to the measured total phosphorus.

6.8.2. Validation of the Model for July 2004

The validation results for July 2004 are presented in Figures 6.70 to 6.78 and the detailed results are given in Appendix I.

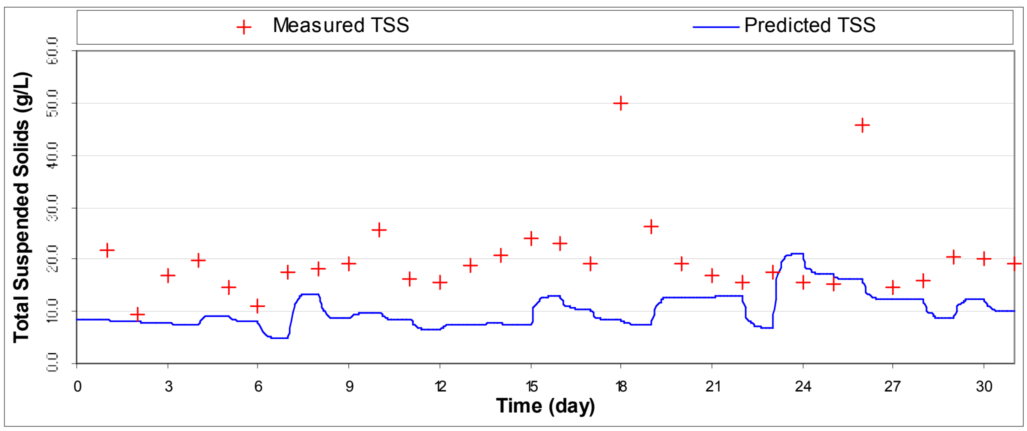

Figure 6.70 Underflow TSS Concentration from the Primary Clarifiers for July 2004 Validation

Figure 6.70 shows that the model underestimated underflow TSS concentration for July 2004. The reason was attributed to the high underflow TSS concentrations observed in this month, as compared to March 2004. The average measured underflow TSS concentrations for March 2004 and July 2004 were 11.27 g/L and 20.11 g/L, respectively. It appears that primary sludge characteristics have substantially changed in July 2004, producing a more compact sludge. This may be the reason for somewhat poorer fit achieved with this data set. Furthermore, the influent flow rate and influent TSS concentration were higher in March 2004.

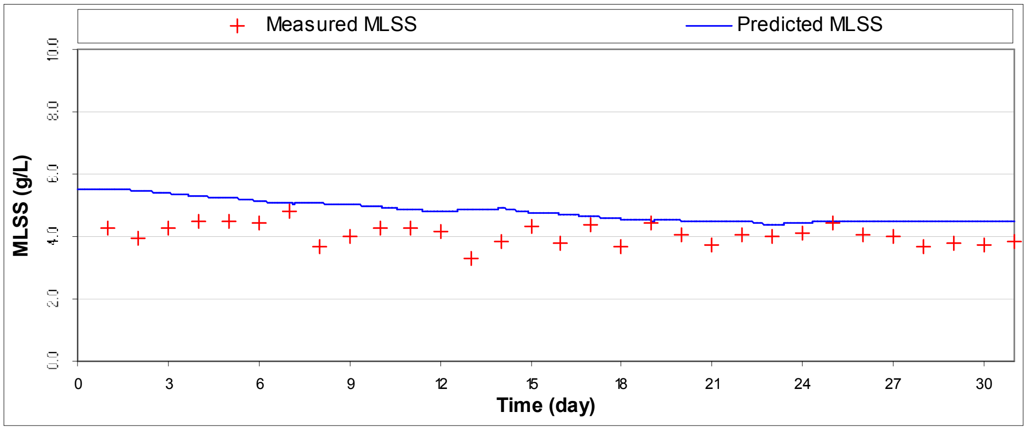

Figure 6.71 Effluent MLSS Concentrations from the Aeration Tanks for July 2004 Validation

Figure 6.71 shows that the model slightly overestimated effluent MLSS concentration from the aerations tanks for July 2004. The $\bar{x}$ value and the standard deviation for this parameter are 1.18 and 0.10, respectively.

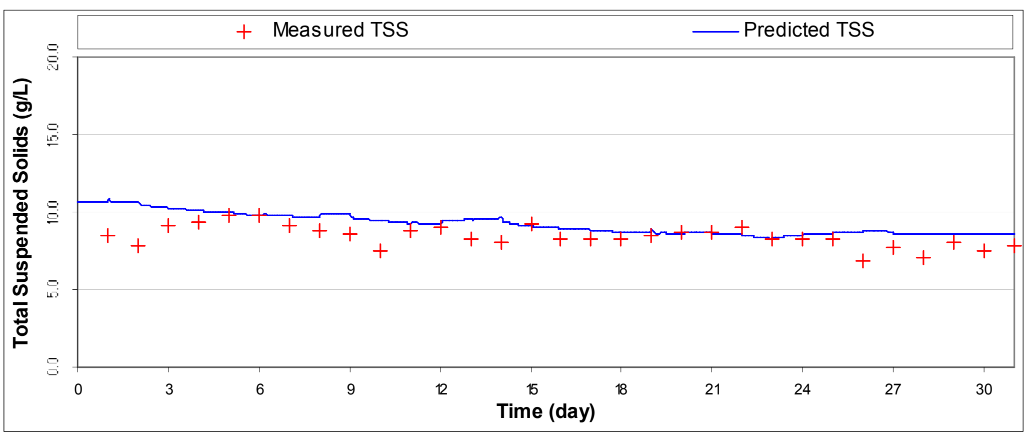

Figure 6.72 Underflow TSS Concentration from the Secondary Clarifiers for July 2004 Validation

Figure 6.72 shows that a good fit was obtained for underflow TSS concentrations from the secondary clarifiers. The $\bar{x}$ value and standard deviation for this parameter were 1.10 and 0.10, respectively.

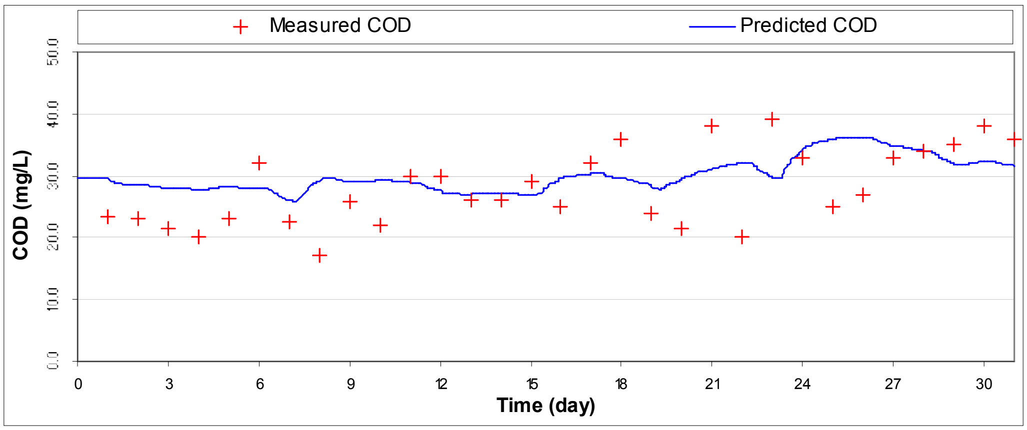

Figure 6.73 COD Concentration in the Final Effluent for July 2004 Validation

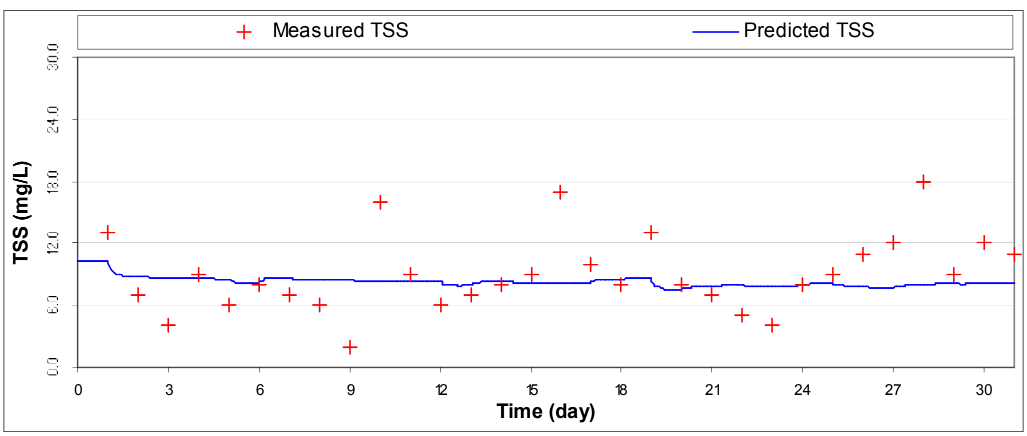

Figure 6.74 TSS Concentration in the Final Effluent for July 2004 Validation

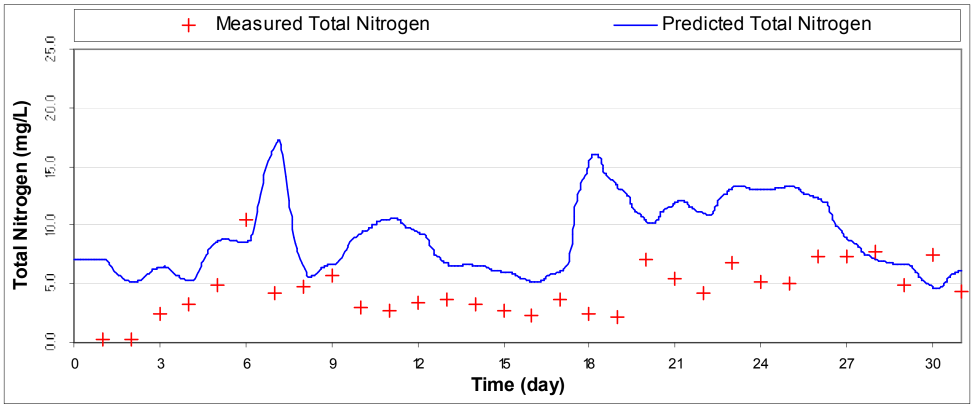

Figure 6.75 Total Nitrogen Concentration in the Final Effluent for July 2004 Validation

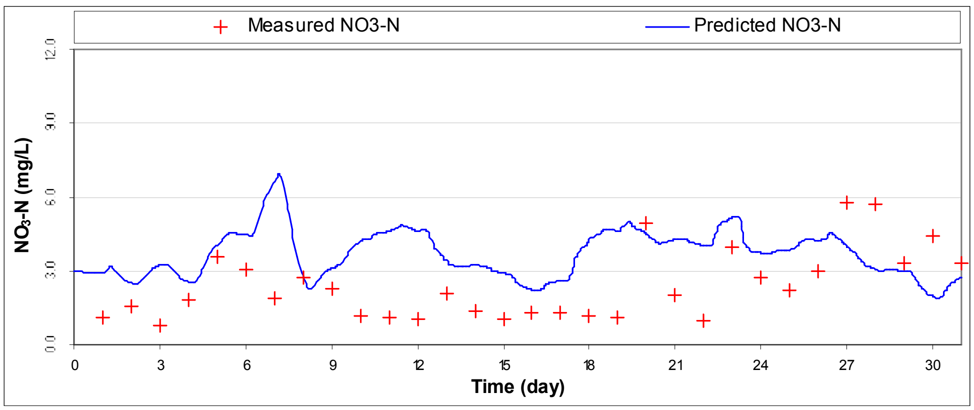

Figure 6.76 NO_3-N Concentration in the Final Effluent for July 2004 Validation

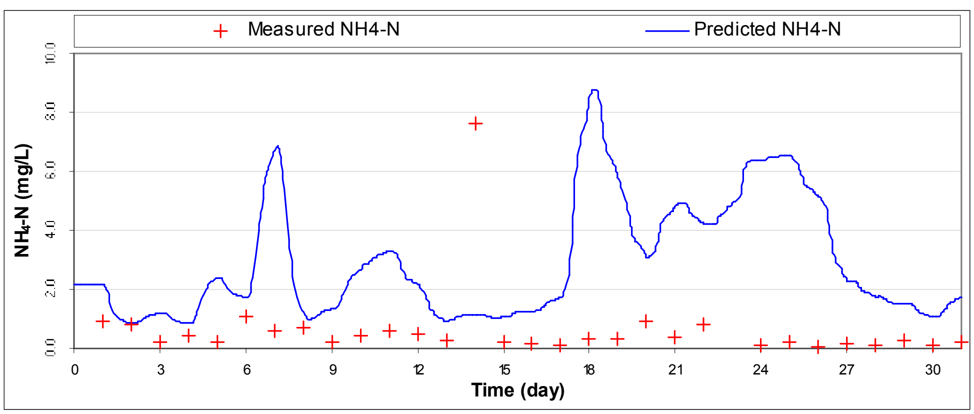

Figure 6.77 NH_4-N Concentration in the Final Effluent for July 2004 Validation

Figures 6.75 to 6.77 show the nitrogen results. Similar to May 2004 validation, the model overestimated these parameters.

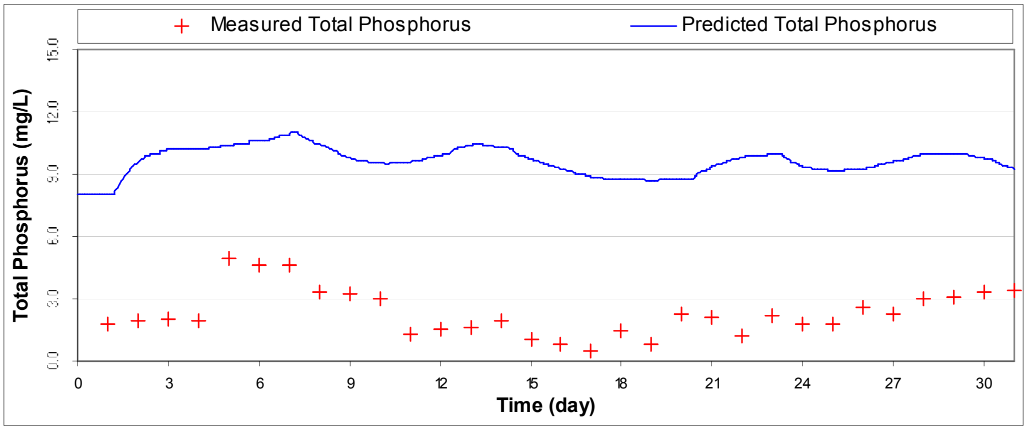

Figure 6.78 Total Phosphorus Concentration in the Final Effluent for July 2004 Validation

As stated before in Section 6.6, the predicted total phosphorus was too high compared to the measured total phosphorus.

CHAPTER 7

CONCLUSION

In this study, Kayseri WWTP was modeled by using the GPS-X simulation program. Activated Sludge Model No 2d (ASM2d), which is also capable of simulating nitrogen and phosphorus removal, was used for the simulation. The calibration of the model was carried out by using data obtained in March 2004 and validation of the model was done by using data obtained in May 2004 and July 2004. The reason for selecting different months was to test the model in different climatic periods. For instance the treatment efficiency for nitrogen was predicted usually higher in summer.

The following conclusions were reached at the end of the study:

- The calibration of the model with March 2004 data provided good fits except for the total phosphorus. The problem with total phosphorus was probably the lack of information about the volatile fatty acids concentration in the influent wastewater.

- During calibration, rather good fits were obtained for underflow total suspended solids from the primary clarifier, effluent MLSS concentration from the aeration tanks and the underflow total suspended solids from the secondary clarifier.

- Reasonably good fits were obtained for components related to nitrogen during calibration. However, some unexpected peaks were also seen in the results provided by GPS-X.

- The concentrations of COD and total suspended solids provided by the simulation were rather stable. Their daily fluctuations could not be accurately simulated by the program; yet the fits were acceptable. The poor fits during fluctuations may well be related with the analysis or sampling accuracy attained in the plant site.

- The obtained fits for the validation runs for underflow total suspended solids concentration from the primary clarifier, effluent MLSS concentration from the aeration tanks, underflow total suspended solids from the secondary clarifier, COD and total suspended solids in the final effluent were rather good.

- The validation results for nitrogen components show that the program somewhat overestimates these for summer months (*i.e.* July 2004) in spite of the modification of the sensitive parameters with respect to the temperature.

- The R^2 obtained from regression of predicted versus measured data for testing goodness of fit yielded poor results. This was most probably due to system variability obscuring the individual parameter effect *i.e*. a bias or offset in the responses was present in most of the cases deviating predicted/measured values considerably away from the ideal line of R^2=1.0. Whereas ratio between predicted and measured data should ideally be 1.0; regardless of the bias. Therefore average of ratios between predicted/measured was used to assess goodness of fit. Accordingly an average figure close to 1.0 was taken index of good fit. The standard deviation of the predicted/measured data also gave an estimate of its dispersion tendency.

Recommendations:

- The future work should involve calibration of phosphorus with more adequate and accurate data. For this purpose, the volatile fatty acids concentration in the influent wastewater should be determined by taking samples from the treatment plant.

- The calibrated model can be used to see the effects of configuration changes on the plant performance without actually making changes on the treatment plant.

- For more accurate simulation, calibration of the model may be performed by using the summer data while using winter data for validation.

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APPENDIX A

Table A.1 Data for March 2004 [16]

Time (days)	Influent Wastewater									
	Flow Rate (m^3/day)	Temperature (ºC)	NH_4-N (mg/L)	NO_3-N (mg/L)	Total N (mg/L)	BOD_5 (mg/L)	Suspended Solids (mg/L)	COD (mg/L)	PO_4-P (mg/L)	Total P (mg/L)
1	152,371	16.0	32.0	0.50	51.0	420	454	540	6.10	8.20
2	160,212	15.8	34.5	0.56	52.3	410	412	532	6.80	9.50
3	219,514	16.4	36.8	0.54	54.8	380	309	526	6.30	8.90
4	151,474	17.0	36.2	0.49	59.1	390	252	591	6.90	9.20
5	151,042	17.1	35.3	0.51	57.2	330	310	575	6.70	8.60
6	172,155	15.8	34.7	0.58	56.3	460	976	523	6.90	9.10
7	209,379	13.9	32.2	0.49	54.2	300	577	556	6.01	8.80
8	164,550	14.0	31.9	0.55	57.8	330	274	598	6.65	9.30
9	161,598	15.0	36.8	0.48	61.4	350	229	542	6.87	8.70
10	154,543	15.5	33.3	0.54	54.6	340	278	513	6.32	9.45
11	173,760	15.9	34.5	0.49	58.5	430	378	562	6.88	8.42
12	173,435	15.0	32.4	0.50	57.9	280	245	589	6.08	9.55
13	155,581	16.2	31.9	0.47	59.6	410	202	554	6.40	8.70
14	151,828	16.2	32.5	0.59	56.9	270	211	579	6.34	8.91
15	145,227	15.8	37.8	0.49	57.2	400	208	545	6.29	8.58
16	147,570	16.2	39.5	0.53	59.2	320	175	593	6.70	8.98
17	145,332	16.6	35.8	0.47	58.6	360	285	585	6.32	9.14
18	145,873	16.8	34.7	0.51	55.7	230	315	557	6.50	8.94
19	146,786	16.8	32.8	0.55	54.9	310	228	529	6.74	8.65
20	148,396	16.8	34.5	0.52	56.7	210	258	557	6.51	8.93
21	148,906	16.8	37.4	0.53	58.1	400	242	542	6.78	8.47
22	146,616	16.5	38.1	0.48	55.2	220	295	586	6.45	8.87
23	155,859	16.9	36.5	0.45	57.4	430	273	551	6.81	9.63
24	152,693	17.2	34.8	0.51	56.7	450	296	557	6.53	8.93
25	149,869	17.5	36.0	0.50	47.4	390	320	488	5.21	6.18
26	151,835	17.3	52.8	0.47	73.3	390	258	545	5.04	6.07
27	148,209	17.5	48.1	0.53	51.5	310	276	686	4.92	5.43
28	146,819	17.7	50.9	0.45	53.6	370	315	680	5.08	5.79
29	135,409	17.4	41.9	0.51	54.1	330	215	490	4.80	5.72
30	154,035	17.1	38.9	0.49	54.1	360	320	745	5.15	8.94
31	164,414	17.2	36.0	0.45	49.0	410	286	649	5.11	8.28
Maximum	219,514	17.7	52.8	0.59	73.3	460	976	745	6.9	9.6
Average	157,590	16.4	36.8	0.51	56.3	355	312	570	6.2	8.4
Minimum	135,409	13.9	31.9	0.45	47.4	210	175	488	4.8	5.4

Table A.1 Data for March 2004 (Continued) [16]

Time (days)	Primary Sludge		Aeration Tanks (Outlet)	Return Activated Sludge		Excess Sludge
	Flow Rate (m^3/day)	Solids Content (g/L)	MLSS (mg/L)	Flow Rate (m^3/day)	MLSS (mg/L)	Flow Rate (m^3/day)
1	734.3	13.71	4,880	141,959	8,859	2,468
2	667.7	10.98	5,301	189,561	10,182	2,340
3	1,728.0	6.38	5,148	154,299	10,321	2,172
4	743.9	8.84	5,487	151,679	11,626	3,237
5	697.3	6.10	5,165	149,452	11,333	2,419
6	775.2	17.19	5,151	167,974	10,939	2,146
7	839.7	43.91	5,649	201,721	11,923	2,450
8	923.2	12.17	6,410	176,301	12,246	2,480
9	776.1	9.20	6,397	162,267	12,564	2,493
10	831.3	12.77	6,102	164,953	11,718	2,529
11	725.0	9.34	5,689	164,679	11,763	2,076
12	705.8	11.09	6,138	178,016	12,349	2,477
13	685.8	5.11	6,106	150,388	11,847	2,556
14	713.9	5.42	5,490	152,054	11,925	2,562
15	673.9	5.79	6,208	148,036	12,939	2,803
16	704.3	5.33	6,228	150,694	11,352	2,635
17	578.4	6.45	5,724	149,731	11,400	3,153
18	565.3	6.51	5,798	149,003	11,523	3,314
19	599.7	8.87	6,198	149,916	12,488	2,569
20	562.0	10.87	5,885	149,583	11,400	1,973
21	596.9	22.49	6,440	150,594	12,313	1,744
22	634.6	9.20	6,055	148,562	6,845	4,017
23	608.6	9.26	5,012	156,717	9,199	4,107
24	617.4	6.95	5,745	153,749	10,616	4,267
25	613.0	8.49	5,927	151,147	11,254	4,362
26	620.6	9.83	6,009	152,540	11,948	3,929
27	1,417.1	14.59	5,728	149,658	11,264	3,759
28	1,031.7	17.90	5,780	147,851	11,264	4,339
29	550.0	7.44	5,968	136,225	10,415	3,092
30	598.3	8.72	5,963	154,585	11,325	4,993
31	874.0	18.42	5,430	165,618	10,092	4,971
Maximum	1,728.0	43.9	6,440	201,721	12,939	4,993
Average	754.6	11.3	5,781	157,081	11,201	3,046
Minimum	550.0	5.1	4,880	136,225	6,845	1,744

Table A.1 Data for March 2004 (Continued) [16]

Time (days)	Final Effluent							
	NH_4-N (mg/L)	NO_3-N (mg/L)	Total N (mg/L)	BOD_5 (mg/L)	Suspended Solids (mg/L)	COD (mg/L)	PO_4-P (mg/L)	Total P (mg/L)
1	1.90	4.50	5.63	14	10	21.8	1.89	1.99
2	1.85	3.50	7.89	15	11	26.0	1.52	1.65
3	1.52	4.11	8.25	20	13	29.4	1.64	1.78
4	1.63	4.87	7.45	14	11	25.0	1.45	1.88
5	1.99	4.93	6.11	14	17	26.0	1.23	1.62
6	1.91	3.98	5.98	14	14	24.0	1.21	1.56
7	1.80	4.20	8.42	13	12	27.0	1.61	2.54
8	0.89	3.48	8.01	11	20	24.5	1.75	2.86
9	0.75	3.74	9.56	18	20	23.4	1.52	2.44
10	0.77	4.54	9.03	13	12	27.7	1.68	1.89
11	0.89	3.98	8.63	12	13	21.0	0.86	1.93
12	0.76	3.85	9.06	13	12	26.0	1.45	2.08
13	0.35	4.10	8.35	9	14	25.0	1.28	1.87
14	0.60	4.02	8.64	10	10	24.0	1.06	1.83
15	0.77	3.97	9.85	13	17	26.0	1.86	2.10
16	0.65	4.12	8.45	13	12	20.0	1.26	2.09
17	0.94	3.96	8.08	14	14	24.0	1.89	2.00
18	0.86	4.10	8.84	11	15	21.7	1.44	1.87
19	0.78	4.85	8.71	10	10	24.7	1.56	1.94
20	1.16	4.16	8.15	10	16	24.6	1.48	1.99
21	0.84	4.01	9.02	11	7	25.0	1.64	1.85
22	0.75	3.68	9.85	4	14	24.3	1.57	1.89
23	0.86	4.20	8.78	20	17	23.5	1.45	1.96
24	0.97	4.12	8.29	6	13	24.5	1.49	1.98
25	0.87	5.77	6.72	16	9	25.0	1.75	1.95
26	0.59	6.82	7.12	13	6	45.4	1.84	1.98
27	0.38	5.48	7.04	12	12	40.7	1.87	1.96
28	0.29	6.40	7.54	7	15	51.2	1.71	1.93
29	0.31	5.02	5.47	10	6	42.9	1.82	2.17
30	0.29	4.83	6.78	16	9	23.5	1.40	1.80
31	0.56	4.63	7.89	10	15	26.8	1.31	1.51
Maximum	1.99	6.82	9.85	20	20	51.2	1.89	2.86
Average	0.95	4.45	7.99	12	13	27.2	1.53	1.96
Minimum	0.29	3.48	5.47	4	6	20.0	0.86	1.51

Table A.2 Data for May 2004 [16]

Time (days)	Influent Wastewater									
	Flow Rate (m^3/day)	Temperature (ºC)	NH_4-N (mg/L)	NO_3-N (mg/L)	Total N (mg/L)	BOD_5 (mg/L)	Suspended Solids (mg/L)	COD (mg/L)	PO_4-P (mg/L)	Total P (mg/L)
1	155,972	17.7	36.0	0.84	50.0	400	210	580	5.7	8.6
2	143,283	18.4	41.0	1.00	50.0	420	310	1,110	6.9	7.9
3	138,828	18.3	42.0	1.40	56.0	410	280	780	6.0	11.0
4	150,363	18.4	32.0	1.34	48.0	310	200	600	6.6	9.7
5	203,873	18.0	31.0	1.56	45.0	320	500	580	5.9	7.9
6	143,436	18.6	39.0	1.44	54.0	270	300	600	6.4	8.6
7	143,900	18.8	36.0	0.60	58.0	290	250	710	5.7	8.0
8	146,418	18.9	40.0	0.80	47.0	380	290	590	6.9	9.0
9	143,843	19.2	42.0	0.99	50.0	380	260	670	7.0	8.9
10	137,118	19.1	39.0	1.50	50.0	390	310	580	8.3	11.0
11	146,379	19.2	31.0	1.30	50.0	320	370	700	8.9	10.0
12	142,537	19.5	37.0	0.60	50.0	350	260	550	6.9	8.6
13	138,103	19.2	41.0	1.50	49.0	280	280	620	6.5	8.6
14	137,136	19.2	54.0	0.50	58.0	400	250	570	6.4	10.0
15	141,487	19.3	60.0	0.99	59.0	340	300	680	8.7	12.0
16	259,200	18.7	35.0	1.80	46.0	400	680	900	5.9	9.0
17	177,582	17.1	21.0	0.70	34.0	260	320	340	4.1	6.0
18	159,273	17.8	43.0	0.70	49.0	240	240	490	6.3	9.0
19	147,901	18.6	48.0	1.90	53.0	90	250	470	8.3	9.0
20	195,819	16.4	32.0	1.90	35.0	330	300	450	4.7	6.0
21	156,059	17.4	34.0	0.60	46.0	240	260	500	5.9	10.0
22	144,279	18.6	39.0	1.44	44.0	330	290	600	6.2	8.0
23	140,358	18.9	40.0	1.70	48.0	320	300	580	5.9	8.8
24	137,084	18.9	54.0	3.00	58.0	180	270	510	8.3	10.0
25	148,280	19.2	41.0	0.60	46.0	350	406	581	8.3	10.0
26	144,763	19.4	43.0	0.80	54.0	360	240	725	8.0	10.0
27	165,970	19.6	56.0	1.95	51.0	350	250	570	6.9	9.0
28	145,434	19.5	53.0	2.20	58.0	320	240	580	8.0	10.0
29	137,362	19.4	50.0	1.90	50.0	400	260	690	7.5	10.0
30	138,374	19.6	40.0	1.80	50.0	400	310	590	5.9	9.0
31	127,615	19.1	49.0	1.90	48.0	390	290	610	6.5	9.0
Maximum	259,200	19.6	60.0	3.00	59.0	420	680	1,110	8.9	12.0
Average	152,840	18.7	41.3	1.33	49.8	330	299	616	6.8	9.1
Minimum	127,615	16.4	21.0	0.50	34.0	90	200	340	4.1	6.0

Table A.2 Data for May 2004 (Continued) [16]

Time (days)	Primary Sludge		Aeration Tanks (Outlet)	Return Activated Sludge		Excess Sludge
	Flow Rate (m^3/day)	Solids Content (g/L)	MLSS (mg/L)	Flow Rate (m^3/day)	MLSS (mg/L)	Flow Rate (m^3/day)
1	588.0	11.4	6,950	159,200	12,245	2,480
2	599.9	8.8	7,125	141,132	12,547	2,234
3	601.3	8.2	6,989	139,706	12,450	595
4	585.8	6.8	5,256	151,633	12,168	1,015
5	578.4	26.3	6,523	165,961	12,365	1,800
6	607.6	10.3	6,584	146,094	12,368	2,085
7	592.4	8.2	5,497	142,547	11,308	2,143
8	619.3	9.8	5,817	149,075	13,087	2,084
9	618.8	12.6	5,488	146,585	12,184	2,147
10	616.9	10.9	5,129	139,937	11,931	2,155
11	580.2	8.3	4,772	148,838	9,633	2,163
12	596.4	21.0	5,844	145,382	11,937	2,142
13	557.0	7.9	5,680	140,869	12,551	2,192
14	620.4	15.3	5,871	139,494	13,305	1,776
15	586.0	10.2	5,721	143,627	13,249	1,510
16	580.3	16.6	6,148	167,986	12,152	2,269
17	599.9	30.7	5,445	180,589	14,380	3,156
18	1,728.0	7.2	6,430	161,889	12,897	2,011
19	481.9	9.8	5,445	150,555	14,416	2,048
20	479.3	36.4	5,321	198,868	14,089	2,340
21	632.7	16.8	6,754	159,104	14,907	2,328
22	1,728.0	12.3	6,559	132,571	13,530	2,032
23	577.1	11.7	6,559	143,716	14,989	2,687
24	617.3	14.9	5,792	140,471	14,776	3,417
25	617.9	10.3	6,513	130,137	18,726	4,196
26	589.5	7.4	5,828	134,269	13,062	4,322
27	1,728.0	13.9	5,876	143,850	13,825	4,529
28	773.8	14.8	5,870	146,809	13,860	4,509
29	796.0	10.1	5,401	138,582	14,782	6,326
30	773.7	12.1	5,610	139,556	14,200	5,373
31	744.3	8.2	6,120	130,885	19,058	3,504
Maximum	1,728.0	36.4	7,125	198,868	19,058	6,326
Average	722.4	13.2	5,965	148,384	13,451	2,696
Minimum	479.3	6.8	4,772	130,137	9,633	595

Table A.2 Data for May 2004 (Continued) [16]

Time (days)	Final Effluent							
	NH_4-N (mg/L)	NO_3-N (mg/L)	Total N (mg/L)	BOD_5 (mg/L)	Suspended Solids (mg/L)	COD (mg/L)	PO_4-P (mg/L)	Total P (mg/L)
1	0.50	1.53	2.70	7	10	22.0	1.35	1.51
2	1.05	1.99	2.65				1.60	1.95
3	1.00	1.09	5.50	12	11	48.0	1.87	1.90
4	0.32	1.98	4.89	10	16	41.0	1.98	2.10
5	1.52	3.58	6.27	20	17	21.0	2.10	2.20
6	1.27	3.27	5.76	11	15	38.0	1.76	2.00
7	0.33	3.02	3.20	6	6	40.0	1.70	2.10
8	0.33	3.28	3.73	8	9	20.0	1.82	2.06
9	0.40	2.01	2.91	7	8	25.0	1.96	2.08
10	0.23	1.96	1.61	7	10	14.0	1.92	2.30
11	0.24	1.57	1.63	20	12	24.0	1.84	2.42
12	0.90	2.38	2.38	7	20	25.0	1.72	2.36
13	0.30	1.50	2.41	9	8	50.0	1.65	2.20
14	0.27	1.86	3.80	6	12	29.0	1.82	2.26
15	0.31	2.02	3.90	10	12	39.0	1.86	2.38
16	0.63	0.82	3.58	10	13	23.0	1.81	2.18
17	0.54	1.63	2.73	7	5	17.0	1.85	2.40
18	0.20	2.79	3.63	10	11	20.0	2.01	2.40
19	0.71	2.99	3.98	20	10	25.0	2.21	2.68
20	1.68	2.50	3.44	10	7	32.0	2.08	2.18
21	0.37	2.68	4.15	10	5	20.0	1.31	1.40
22	0.45	3.73	6.36	7	5	22.0	2.12	2.34
23	0.50	3.69	6.28	8	10	19.0	2.18	2.34
24	0.29	2.60	5.50	9	13	18.0	2.20	2.30
25	0.31	3.14	4.55	15	20	21.0	2.25	2.29
26	0.44	1.85	8.80	8	14	33.0	2.00	
27	0.13	3.70	7.10	7	7	18.0	2.10	2.41
28	0.21	2.90	7.50	9	11	26.0	2.25	2.35
29	0.32	3.21	7.99	8	9	30.0	2.15	2.48
30	0.35	3.95	8.10	5	10	32.0	1.98	2.19
31	0.29	2.60	7.89	6	11	25.0	2.20	2.30
Maximum	1.68	3.95	8.80	20	20	50.0	2.25	2.68
Average	0.53	2.51	4.67	10	11	27.2	1.92	2.13
Minimum	0.13	0.82	1.61	5	5	14.0	1.31	1.40

Table A.3 Data for July 2004 [16]

Time (days)	Influent Wastewater									
	Flow Rate (m^3/day)	Temperature (°C)	NH_4-N (mg/L)	NO_3-N (mg/L)	Total N (mg/L)	BOD_5 (mg/L)	Suspended Solids (mg/L)	COD (mg/L)	PO_4-P (mg/L)	Total P (mg/L)
1	127,710	21.4	34.3	1.4	52.6	420	274	564	9.1	11.2
2	126,294	21.4	38.4	1.3	49.3	440	238	546	7.9	10.5
3	127,810	21.6	33.6	2.7	49.9	420	280	542	7.5	9.8
4	125,683	21.6	45.6	2.0	52.1	320	256	598	8.4	10.7
5	117,275	21.3	43.4	1.2	50.7	430	274	558	7.9	9.6
6	129,709	21.8	58.6	2.0	62.0	230	318	430	8.5	10.0
7	127,975	21.9	33.1	1.1	54.1	420	296	720	8.3	10.1
8	128,791	22.1	38.0	1.3	48.3	300	286	580	7.0	7.8
9	125,122	22.3	46.2	2.0	48.4	370	296	611	7.4	9.1
10	128,491	22.4	46.2	2.4	59.5	330	236	572	7.7	10.2
11	126,415	22.4	40.8	1.4	54.3	320	276	503	8.0	10.5
12	115,277	21.8	35.8	1.5	57.6	370	240	538	8.8	11.7
13	123,528	22.0	36.7	1.3	52.7	430	292	543	8.1	10.2
14	126,083	22.6	34.4	0.8	46.6	400	294	533	6.8	8.6
15	125,844	22.8	35.8	1.7	58.6	370	328	708	7.7	8.1
16	128,160	22.9	37.1	1.6	44.0	380	288	638	7.1	8.8
17	136,149	22.3	57.0	1.4	59.0	420	238	568	7.2	9.4
18	138,565	22.1	45.0	1.2	48.0	300	290	537	6.9	8.7
19	112,207	21.6	47.0	1.7	50.0	440	286	700	6.8	9.8
20	121,390	22.1	52.0	0.7	58.0	390	328	698	9.0	12.0
21	124,239	22.3	48.0	1.2	50.0	330	272	712	9.1	9.5
22	124,452	22.6	50.0	0.8	53.0	390	270	518	7.8	8.9
23	124,684	22.5	56.0	0.9	58.0	400	248	908	8.0	9.3
24	128,838	22.4	55.0	1.0	57.2	350	260	818	8.1	9.6
25	122,733	22.7	53.0	1.2	56.0	360	310	790	7.9	9.1
26	118,242	22.2	43.0	1.6	55.0	350	274	686	7.9	9.6
27	123,754	22.2	39.8	1.7	59.8	430	288	690	8.7	12.2
28	127,091	23.0	37.0	0.4	77.0	320	372	580	7.8	10.1
29	127,243	23.1	33.5	1.4	52.6	380	298	693	7.9	9.8
30	127,828	23.2	38.0	2.3	57.0	340	206	624	6.6	8.7
31	127,903	23.4	52.2	1.6	79.3	380	338	681	8.6	14.6
Maximum	138,565	23.4	58.6	2.71	79.3	440	372	908	9.1	14.6
Average	125,661	22.3	43.4	1.44	55.2	372	282	625	7.9	9.9
Minimum	112,207	21.3	33.1	0.41	44.0	230	206	430	6.6	7.8

Table A.3 Data for July 2004 (Continued) [16]

Time (days)	Primary Sludge		Aeration Tanks (Outlet)	Return Activated Sludge		Excess Sludge
	Flow Rate (m^3/day)	Solids Content (g/L)	MLSS (mg/L)	Flow Rate (m^3/day)	MLSS (mg/L)	Flow Rate (m^3/day)
1	764.1	21.8	4,279	131,148	8,453	2,549
2	757.2	9.3	3,942	131,111	7,822	3,738
3	729.4	17.0	4,266	132,652	9,165	3,732
4	782.6	19.7	4,477	130,561	9,390	3,744
5	785.9	14.7	4,480	122,115	9,780	3,719
6	702.4	11.0	4,418	132,869	9,753	3,145
7	770.3	17.4	4,809	131,123	9,154	3,616
8	781.6	18.3	3,702	126,945	8,813	3,262
9	1,728.0	19.1	3,980	127,415	8,583	4,312
10	772.5	25.7	4,254	130,852	7,506	4,584
11	774.7	16.3	4,285	129,322	8,833	3,598
12	689.7	15.5	4,156	115,790	8,997	1,274
13	768.5	18.8	3,294	124,570	8,302	1,257
14	767.8	20.6	3,844	128,319	8,066	4,819
15	763.6	24.2	4,317	128,757	9,207	5,090
16	778.5	23.1	3,808	130,927	8,286	4,836
17	705.4	19.0	4,380	138,604	8,298	4,929
18	706.4	50.0	3,700	140,815	8,290	4,390
19	752.8	26.2	4,423	115,174	8,455	3,641
20	802.2	19.3	4,054	122,671	8,689	3,600
21	837.8	16.9	3,712	126,258	8,669	4,136
22	847.6	15.6	4,031	127,866	8,970	4,987
23	908.4	17.5	4,010	126,767	8,231	3,736
24	875.2	15.5	4,120	131,007	8,235	3,555
25	757.2	15.3	4,410	123,230	8,250	3,650
26	889.5	45.8	4,080	115,788	6,814	3,724
27	1,048.8	14.6	3,980	126,087	7,719	3,221
28	969.5	16.0	3,686	130,136	7,062	3,011
29	989.7	20.4	3,798	131,586	8,006	3,375
30	831.4	20.0	3,736	131,826	7,461	3,233
31	936.3	19.1	3,837	131,602	7,786	3,230
Maximum	1,728.0	50.0	4,809	140,815	9,780	5,090
Average	837.9	20.1	4,073	128,190	8,421	3,667
Minimum	689.7	9.3	3,294	115,174	6,814	1,257

Table A.3 Data for July 2004 (Continued) [16]

Time (days)	Final Effluent							
	NH_4-N (mg/L)	NO_3-N (mg/L)	Total N (mg/L)	BOD_5 (mg/L)	Suspended Solids (mg/L)	COD (mg/L)	PO_4-P (mg/L)	Total P (mg/L)
1	0.92	1.11	0.27	10	13	23.4	1.59	1.78
2	0.82	1.54	0.32	9	7	23.1	1.76	1.92
3	0.21	0.75	2.44	6	4	21.4	1.86	1.99
4	0.44	1.82	3.20	6	9	20.1	1.84	1.91
5	0.22	3.57	4.92	5	6	23.2	4.89	4.95
6	1.06	3.03	10.50	8	8	32.0	4.49	4.60
7	0.58	1.89	4.17	12	7	22.6	4.34	4.61
8	0.69	2.71	4.80	7	6	17.0	3.11	3.30
9	0.22	2.25	5.75	4	2	25.7	3.13	3.23
10	0.42	1.18	3.00	6	16	22.0	2.12	2.99
11	0.59	1.10	2.72	11	9	30.0	1.15	1.33
12	0.47	1.01	3.46	8	6	30.0	1.44	1.58
13	0.25	2.10	3.73	5	7	26.0	1.77	1.60
14	7.60	1.37	3.29	3	8	26.0	1.57	1.95
15	0.20	1.05	2.73	4	9	29.0	1.03	1.06
16	0.15	1.30	2.25	7	17	25.0	0.66	0.80
17	0.12	1.27	3.70	6	10	32.0	0.30	0.48
18	0.30	1.18	2.48	5	8	36.0	1.00	1.48
19	0.30	1.10	2.20	5	13	24.0	0.72	0.80
20	0.90	4.96	7.00	13	8	21.5	2.16	2.30
21	0.40	2.00	5.40	6	7	38.0	1.70	2.10
22	0.80	1.00	4.20	3	5	20.0	0.90	1.20
23	0.02	3.98	6.80	7	4	39.0	1.90	2.20
24	0.10	2.70	5.10	7	8	33.0	1.32	1.78
25	0.20	2.20	5.01	5	9	25.0	1.48	1.82
26	0.03	3.00	7.40	7	11	27.0	2.30	2.60
27	0.17	5.75	7.38	13	12	33.0	2.05	2.31
28	0.12	5.70	7.80	7	18	34.0	2.10	2.98
29	0.26	3.34	4.93	6	9	35.0	2.80	3.11
30	0.10	4.40	7.50	8	12	38.0	2.80	3.30
31	0.23	3.34	4.33	7	11	36.0	3.06	3.44
Maximum	7.60	5.75	10.50	13	18	39.0	4.89	4.95
Average	0.61	2.38	4.48	7	9	28.0	2.04	2.31
Minimum	0.02	0.75	0.27	3	2	17.0	0.30	0.48

APPENDIX B

Table B.1 Results of the Dynamic Runs for Primary Clarifiers

Time (days)	Measured TSS (g/L)	Default		Absolute Difference		Relative Difference		Sum of Squares		Relative Sum of Squares		Maximum Likelihood	
		Predicted TSS (g/L)	x	Predicted TSS (g/L)	x	Predicted TSS (g/L)	x	Predicted TSS (g/L)	x	Predicted TSS (g/L)	x	Predicted TSS (g/L)	x
1	13.71	28.30	2.06	8.62	0.63	6.71	0.49	8.21	0.60	7.05	0.51	8.24	0.60
2	10.98	27.93	2.54	8.06	0.73	7.56	0.69	9.47	0.86	6.62	0.60	9.49	0.86
3	6.38	27.89	4.37	8.40	1.32	6.63	1.04	7.83	1.23	6.90	1.08	7.86	1.23
4	8.84	2.93	0.33	3.51	0.40	0.77	0.09	1.33	0.15	0.35	0.04	1.35	0.15
5	6.10	22.67	3.72	8.73	1.43	7.50	1.23	10.92	1.79	6.70	1.10	10.92	1.79
6	17.19	25.83	1.50	9.49	0.55	6.90	0.40	9.87	0.57	7.75	0.45	9.89	0.58
7	43.91	19.25	0.44	7.33	0.17	4.97	0.11	6.66	0.15	5.71	0.13	6.70	0.15
8	12.17	5.24	0.43	7.28	0.60	1.24	0.10	2.07	0.17	0.41	0.03	2.10	0.17
9	9.20	21.64	2.35	7.72	0.84	6.00	0.65	8.17	0.89	5.75	0.63	8.22	0.89
10	12.77	23.69	1.85	7.66	0.60	6.49	0.51	8.66	0.68	6.30	0.49	8.69	0.68
11	9.34	23.22	2.48	6.50	0.70	7.36	0.79	10.30	1.10	5.36	0.57	10.30	1.10
12	11.09	17.31	1.56	8.41	0.76	4.96	0.45	6.82	0.61	5.37	0.48	6.86	0.62
13	5.11	17.48	3.42	9.63	1.88	5.21	1.02	6.83	1.34	6.38	1.25	6.87	1.34
14	5.42	27.83	5.13	9.07	1.67	7.22	1.33	9.57	1.76	7.44	1.37	9.60	1.77
15	5.79	28.87	4.99	9.32	1.61	7.24	1.25	9.67	1.67	7.61	1.31	9.69	1.67
16	5.33	29.42	5.52	8.92	1.67	7.55	1.42	12.25	2.30	7.32	1.37	12.16	2.28
17	6.45	30.01	4.65	9.90	1.53	7.08	1.10	11.16	1.73	8.06	1.25	11.16	1.73
18	6.51	32.92	5.05	11.64	1.79	7.37	1.13	12.19	1.87	9.48	1.46	12.10	1.86
19	8.87	34.55	3.90	11.01	1.24	7.27	0.82	11.88	1.34	9.01	1.02	11.87	1.34
20	10.87	33.51	3.08	9.48	0.87	7.16	0.66	11.37	1.05	7.78	0.72	11.37	1.05
21	22.49	33.65	1.50	10.78	0.48	6.93	0.31	10.69	0.48	8.79	0.39	10.78	0.48
22	9.20	33.78	3.67	9.94	1.08	6.89	0.75	10.65	1.16	8.14	0.88	10.65	1.16
23	9.26	33.71	3.64	10.69	1.15	7.13	0.77	11.35	1.23	8.70	0.94	11.35	1.23
24	6.95	33.78	4.86	10.05	1.45	6.27	0.90	8.60	1.24	8.23	1.18	8.63	1.24
25	8.49	33.36	3.93	9.98	1.18	6.88	0.81	9.39	1.11	8.16	0.96	9.43	1.11
26	9.83	31.43	3.20	8.02	0.82	7.83	0.80	10.30	1.05	6.62	0.67	10.32	1.05
27	14.59	30.28	2.08	9.23	0.63	7.70	0.53	9.68	0.66	7.54	0.52	9.70	0.66
28	17.90	24.68	1.38	6.89	0.38	7.24	0.40	11.13	0.62	5.58	0.31	11.13	0.62
29	7.44	25.30	3.40	9.05	1.22	7.31	0.98	11.99	1.61	7.33	0.99	12.00	1.61
30	8.72	28.46	3.26	9.01	1.03	8.92	1.02	24.51	2.81	7.44	0.85	24.70	2.83
31	18.42	32.74	1.78	17.18	0.93	6.30	0.34	9.04	0.49	13.69	0.74	9.07	0.49
Average	11.27	26.50	2.97	9.08	1.01	6.54	0.74	9.76	1.11	7.02	0.78	9.78	1.11
σ			1.48		0.46		0.37		0.63		0.40		0.63

x = Predicted TSS / Measured TSS, σ = standard deviation

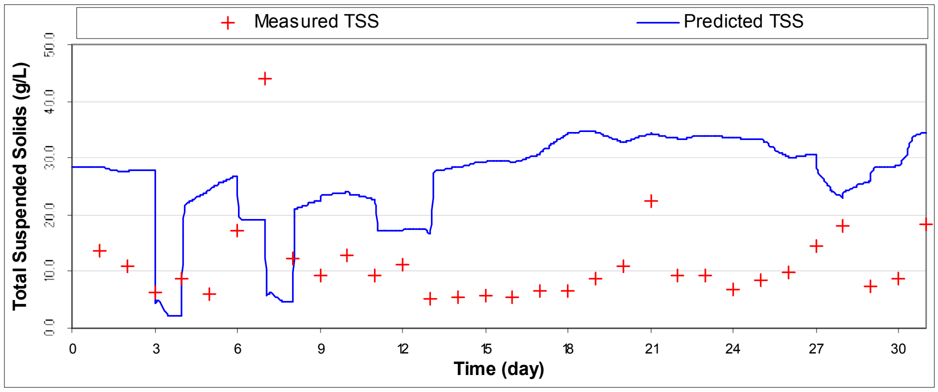

Figure B.1 Dynamic Run for Primary Clarifiers by Using Default Values

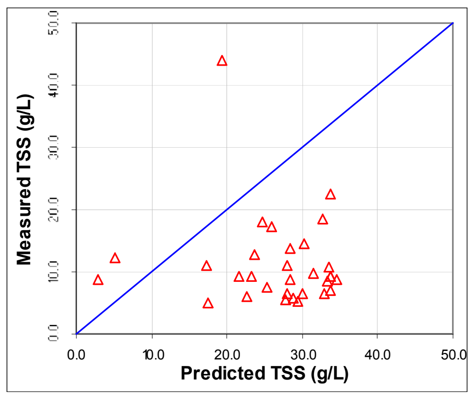

Figure B.2 Predicted TSS versus Measured TSS for Default Values

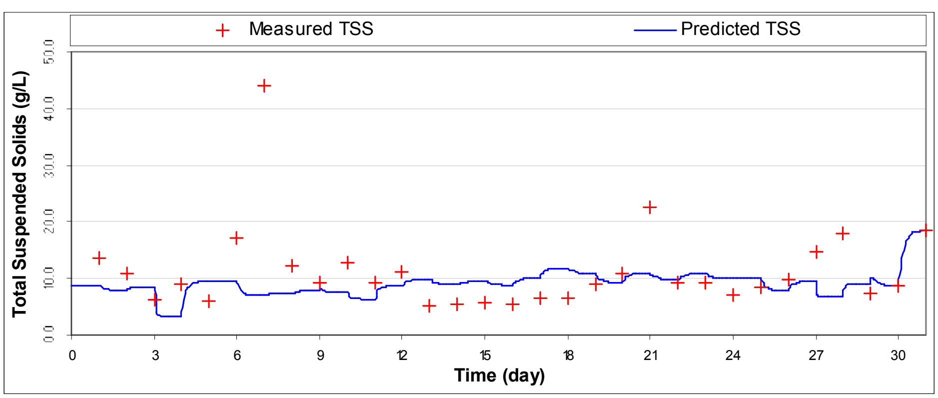

Figure B.3 Dynamic Run for Primary Clarifiers by Using Absolute Difference Results

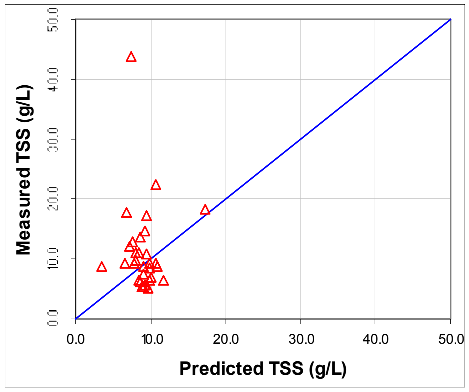

Figure B.4 Predicted TSS versus Measured TSS for Absolute Difference Results

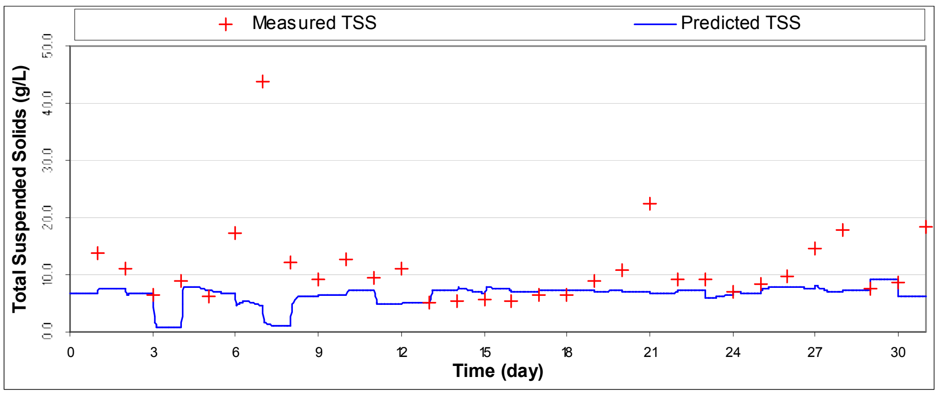

Figure B.5 Dynamic Run for Primary Clarifiers by Using Relative Difference Results

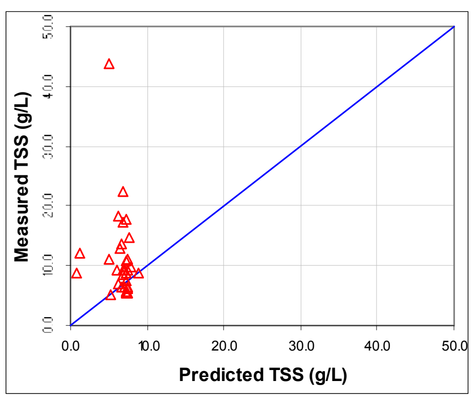

Figure B.6 Predicted TSS versus Measured TSS for Relative Difference Results

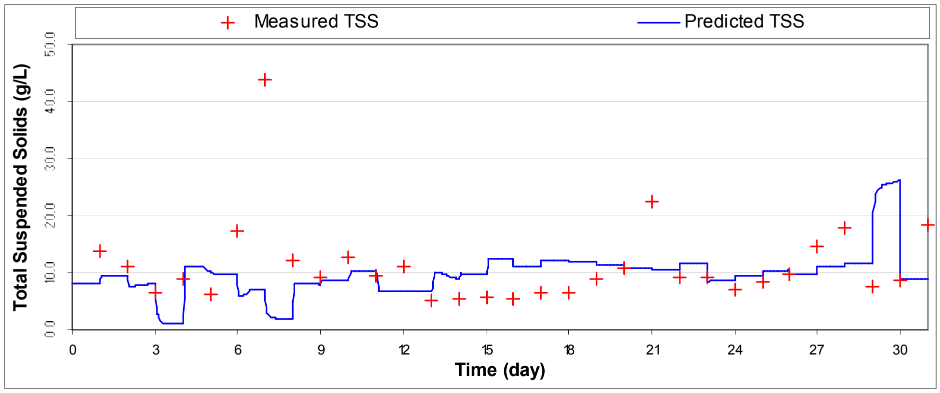

Figure B.7 **Dynamic Run for Primary Clarifiers by Using Sum of Squares Results**

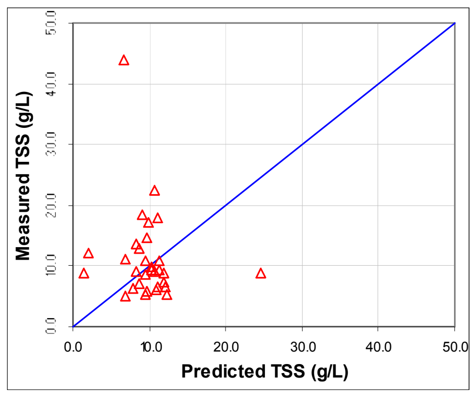

Figure B.8 **Predicted TSS versus Measured TSS for Sum of Squares Results**

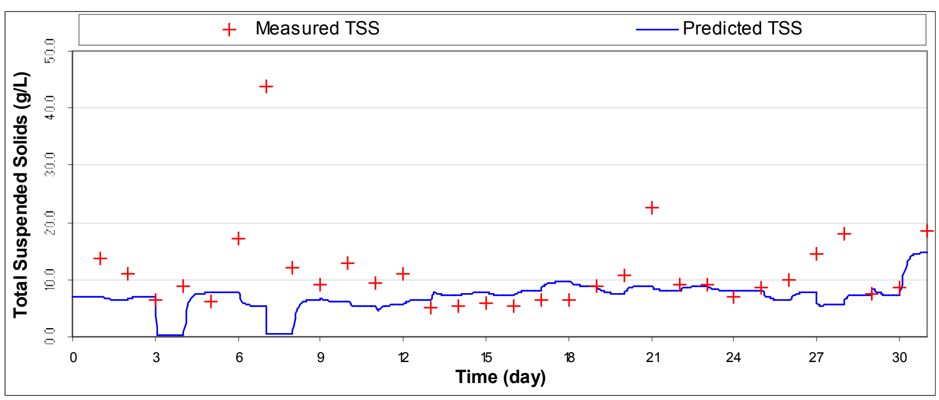

Figure B.9 **Dynamic Run for Primary Clarifiers by Using Relative Sum of Squares Results**

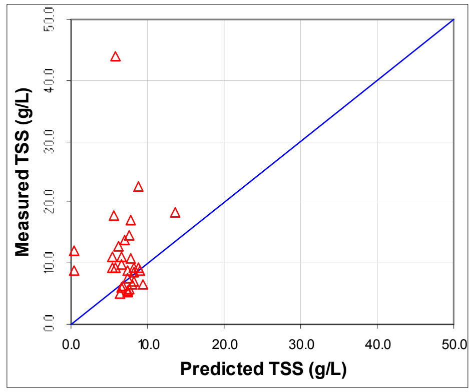

Figure B.10 Predicted TSS versus Measured TSS for Relative Sum of Squares Results

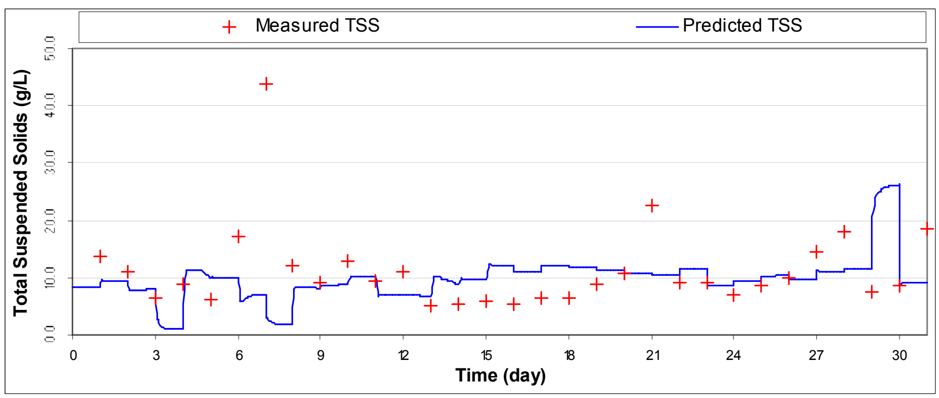

Figure B.11 Dynamic Run for Primary Clarifiers by Using Maximum Likelihood Results

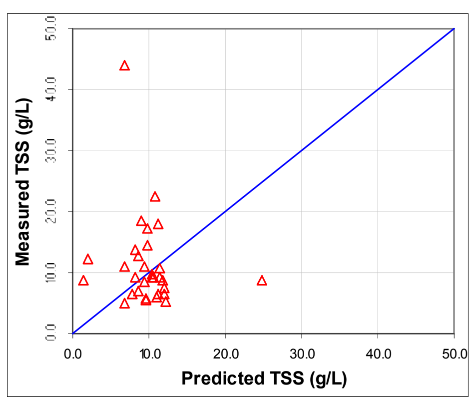

Figure B.12 Predicted TSS versus Measured TSS for Maximum Likelihood Results

APPENDIX C

Table C.1 Results of the Dynamic Runs for Secondary Clarifiers

Time (days)	Target TSS (g/L)	Default		Absolute Difference		Relative Difference		Sum of Squares		Relative Sum of Squares		Maximum Likelihood	
		Predicted TSS (g/L)	x	Predicted TSS (g/L)	x	Predicted TSS (g/L)	x	Predicted TSS (g/L)	x	Predicted TSS (g/L)	x	Predicted TSS (g/L)	x
1	14.49	9.32	0.64	14.00	0.97	14.00	0.97	14.00	0.97	14.00	0.97	14.00	0.97
2	11.24	8.91	0.79	12.68	1.13	12.68	1.13	12.68	1.13	12.68	1.13	12.68	1.13
3	15.67	8.80	0.56	11.93	0.76	11.93	0.76	11.93	0.76	11.93	0.76	11.93	0.76
4	11.71	8.54	0.73	14.10	1.20	14.09	1.20	14.05	1.20	14.06	1.20	14.05	1.20
5	13.23	9.11	0.69	13.21	1.00	13.21	1.00	13.24	1.00	13.23	1.00	13.24	1.00
6	14.21	9.38	0.66	14.05	0.99	14.05	0.99	14.05	0.99	14.05	0.99	14.05	0.99
7	14.08	9.15	0.65	13.97	0.99	13.97	0.99	13.97	0.99	13.97	0.99	13.97	0.99
8	13.94	9.11	0.65	13.97	1.00	13.96	1.00	13.91	1.00	13.92	1.00	13.91	1.00
9	15.35	9.63	0.63	14.36	0.94	14.36	0.94	14.32	0.93	14.35	0.93	14.32	0.93
10	15.21	9.82	0.65	14.70	0.97	14.70	0.97	14.60	0.96	14.67	0.96	14.60	0.96
11	15.83	9.71	0.61	14.62	0.92	14.62	0.92	14.54	0.92	14.57	0.92	14.54	0.92
12	14.53	9.45	0.65	14.32	0.99	14.32	0.99	14.28	0.98	14.29	0.98	14.27	0.98
13	15.49	9.56	0.62	14.26	0.92	14.25	0.92	14.21	0.92	14.22	0.92	14.20	0.92
14	14.91	9.66	0.65	14.74	0.99	14.74	0.99	14.71	0.99	14.73	0.99	14.70	0.99
15	14.64	9.62	0.66	14.70	1.00	14.70	1.00	14.68	1.00	14.69	1.00	14.68	1.00
16	15.48	9.92	0.64	15.02	0.97	15.02	0.97	14.97	0.97	14.99	0.97	14.97	0.97
17	14.64	9.68	0.66	14.79	1.01	14.78	1.01	14.75	1.01	14.76	1.01	14.75	1.01
18	14.28	9.55	0.67	14.70	1.03	14.70	1.03	14.70	1.03	14.70	1.03	14.70	1.03
19	14.34	9.55	0.67	14.70	1.02	14.70	1.02	14.70	1.02	14.70	1.02	14.70	1.02
20	15.23	9.77	0.64	14.87	0.98	14.87	0.98	14.85	0.97	14.86	0.98	14.84	0.97
21	14.70	9.61	0.65	14.75	1.00	14.74	1.00	14.73	1.00	14.73	1.00	14.73	1.00
22	14.82	9.71	0.66	14.81	1.00	14.81	1.00	14.78	1.00	14.78	1.00	14.78	1.00
23	11.07	8.63	0.78	13.96	1.26	13.94	1.26	13.90	1.26	13.91	1.26	13.90	1.26
24	10.90	8.47	0.78	11.92	1.09	11.94	1.10	12.16	1.12	12.07	1.11	12.17	1.12
25	12.37	8.92	0.72	12.31	0.99	12.31	0.99	12.31	0.99	12.31	0.99	12.31	0.99
26	13.49	9.26	0.69	13.39	0.99	13.39	0.99	13.39	0.99	13.39	0.99	13.39	0.99
27	14.27	9.51	0.67	14.28	1.00	14.28	1.00	14.28	1.00	14.28	1.00	14.28	1.00
28	14.10	9.50	0.67	14.14	1.00	14.14	1.00	14.14	1.00	14.14	1.00	14.14	1.00
29	14.08	9.47	0.67	13.96	0.99	13.96	0.99	13.96	0.99	13.96	0.99	13.96	0.99
30	13.29	9.38	0.71	13.43	1.01	13.43	1.01	13.43	1.01	13.43	1.01	13.43	1.01
31	13.59	9.28	0.68	13.55	1.00	13.55	1.00	13.55	1.00	13.55	1.00	13.55	1.00
Average	14.04	9.35	0.67	14.00	1.00	14.00	1.00	13.99	1.00	14.00	1.00	13.99	1.00
σ			0.05		0.08		0.08		0.09		0.09		0.09

x = Predicted TSS / Target TSS, σ = standard deviation

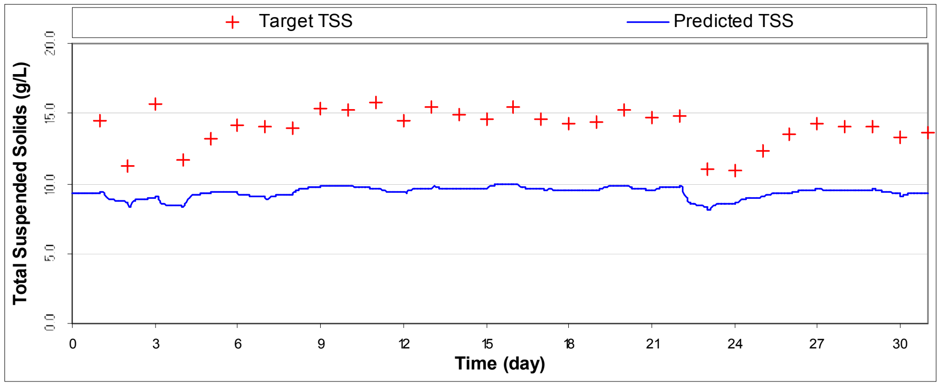

Figure C.1 Dynamic Run for Secondary Clarifiers by Using Default Values

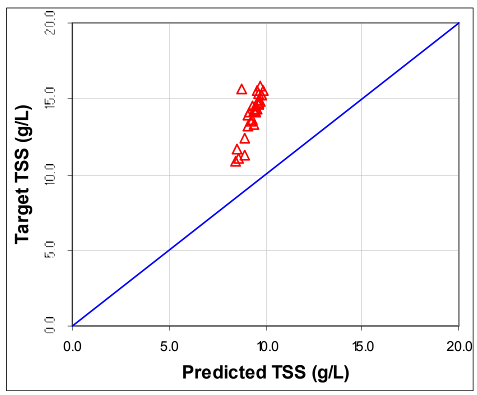

Figure C.2 Predicted TSS versus Measured TSS for Default Values

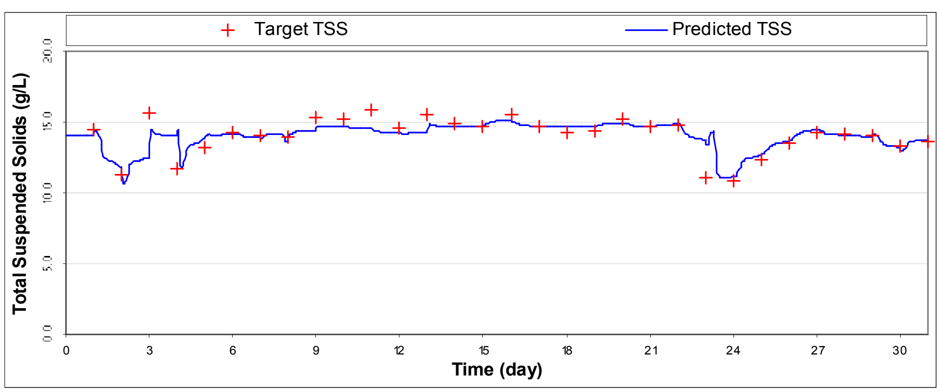

Figure C.3 Dynamic Run for Secondary Clarifiers by Using Absolute Difference Results

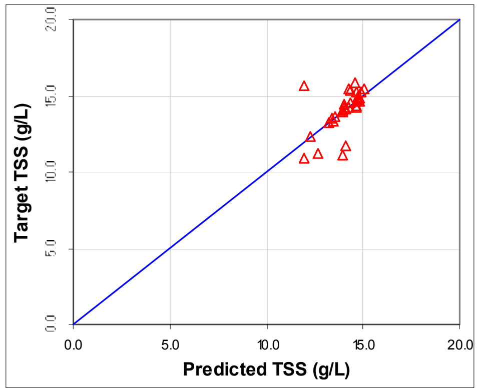

Figure C.4 Predicted TSS versus Measured TSS for Absolute Difference Results

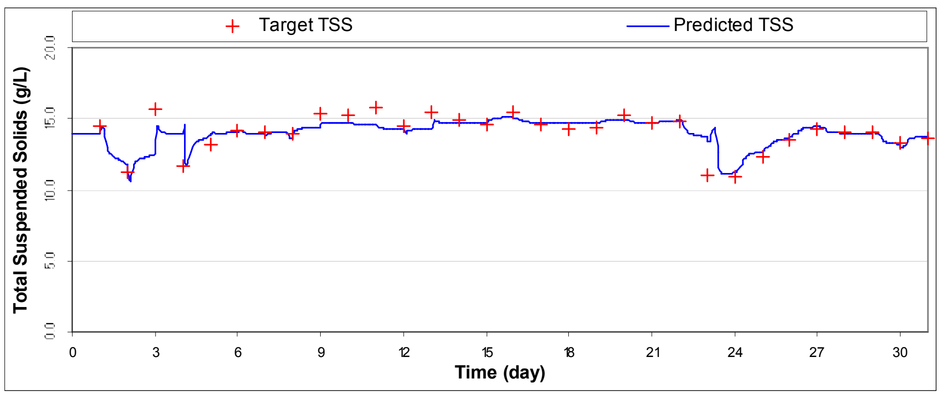

Figure C.5 Dynamic Run for Secondary Clarifiers by Using Relative Difference Results

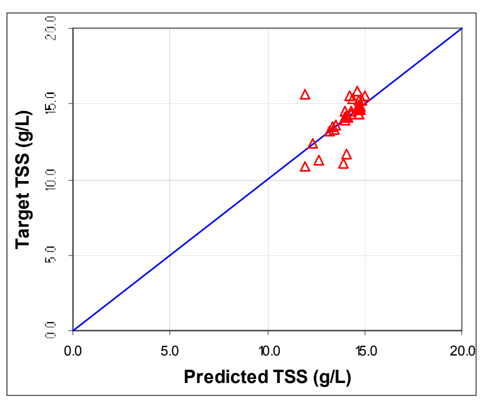

Figure C.6 Predicted TSS versus Measured TSS for Relative Difference Results

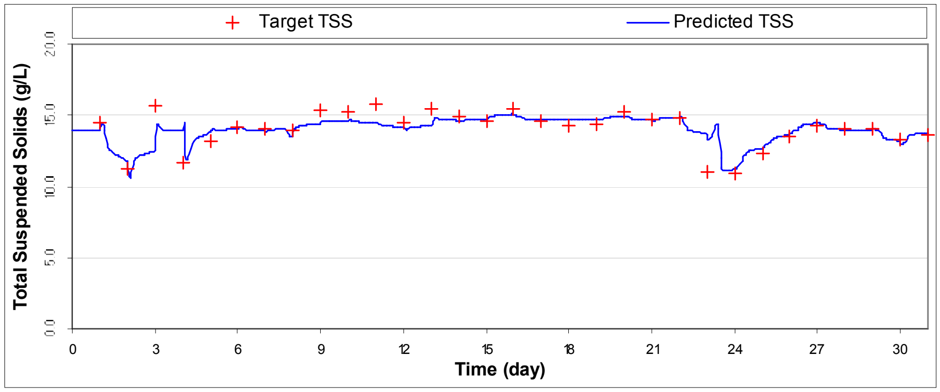

Figure C.7 Dynamic Run for Secondary Clarifiers by Using Sum of Squares Results

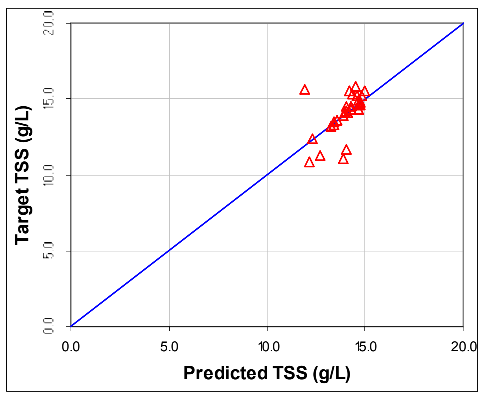

Figure C.8 Predicted TSS versus Measured TSS for Sum of Squares Results

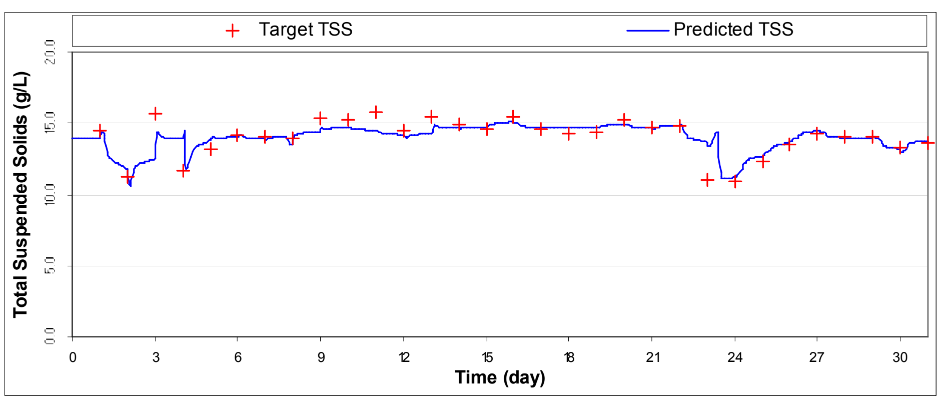

Figure C.9 Dynamic Run for Secondary Clarifiers by Using Relative Sum of Squares Results

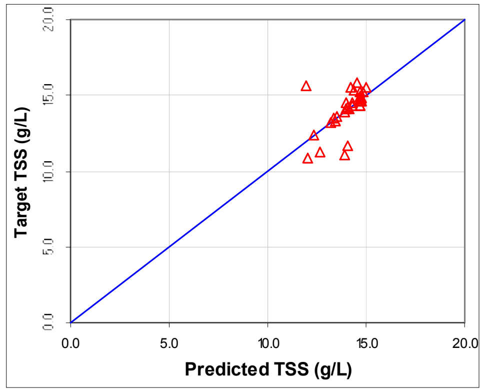

Figure C.10 Predicted TSS versus Measured TSS for Relative Sum of Squares Results

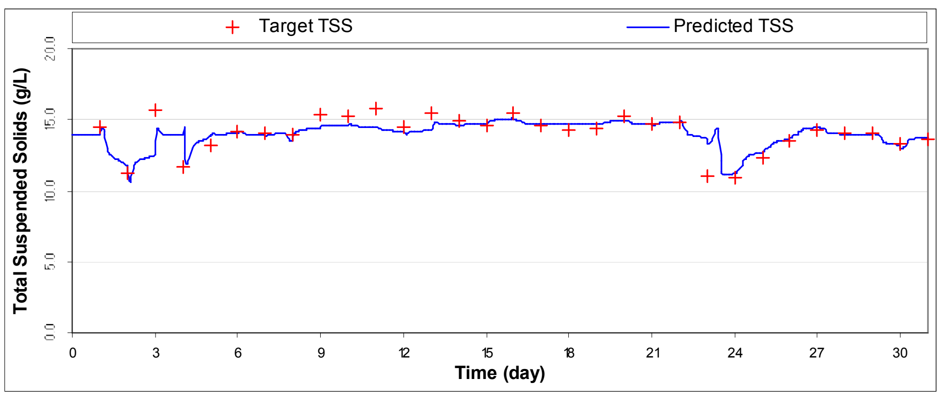

Figure C.11 Dynamic Run for Secondary Clarifiers by Using Maximum Likelihood Results

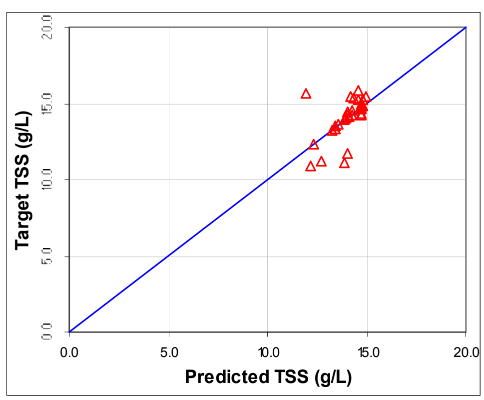

Figure C.12 Predicted TSS versus Measured TSS for Maximum Likelihood Results

APPENDIX D

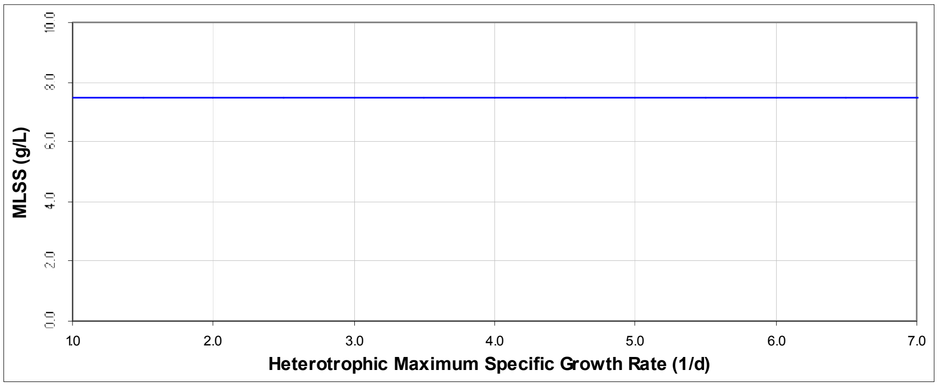

Figure D.1 Sensitivity Analysis for Heterotrophic Maximum Specific Growth Rate

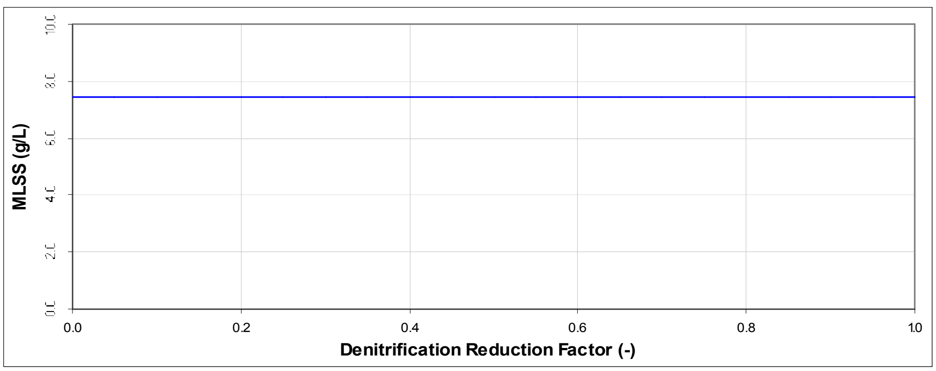

Figure D.2 Sensitivity Analysis for Denitrification Reduction Factor

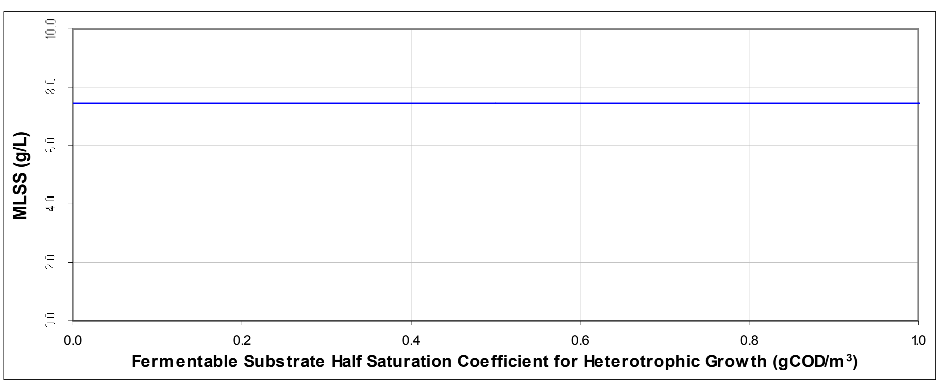

Figure D.3 Sensitivity Analysis for Fermentable Substrate Half Saturation Coefficient for Heterotrophic Growth

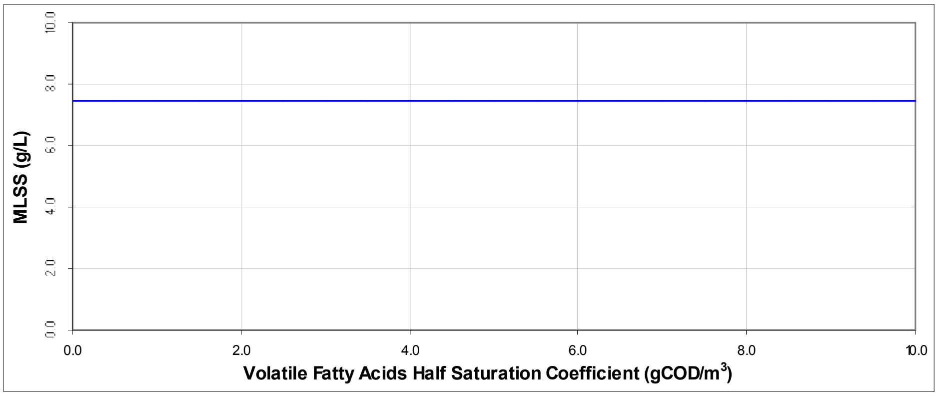

Figure D.4 Sensitivity Analysis for Volatile Fatty Acids Half Saturation Coefficient

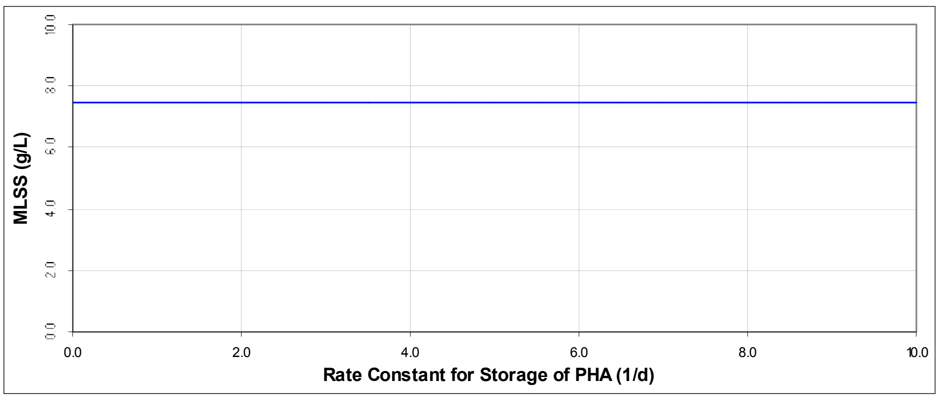

Figure D.5 Sensitivity Analysis for Rate Constant for Storage of PHA

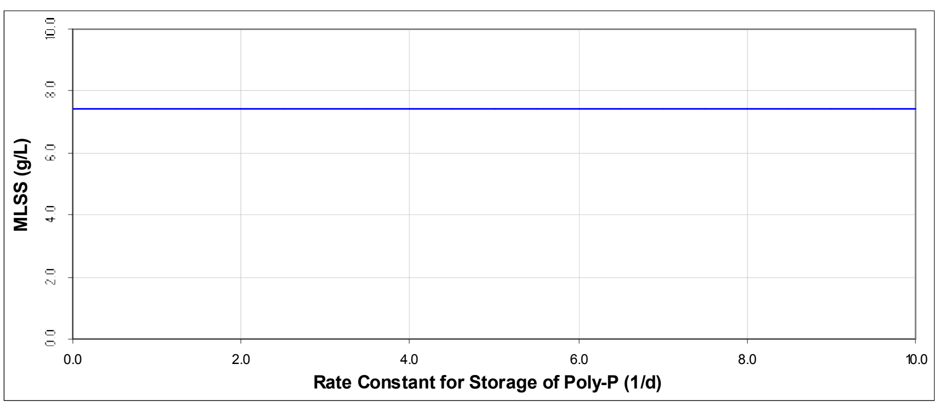

Figure D.6 Sensitivity Analysis for Rate Constant for Storage of Poly-P

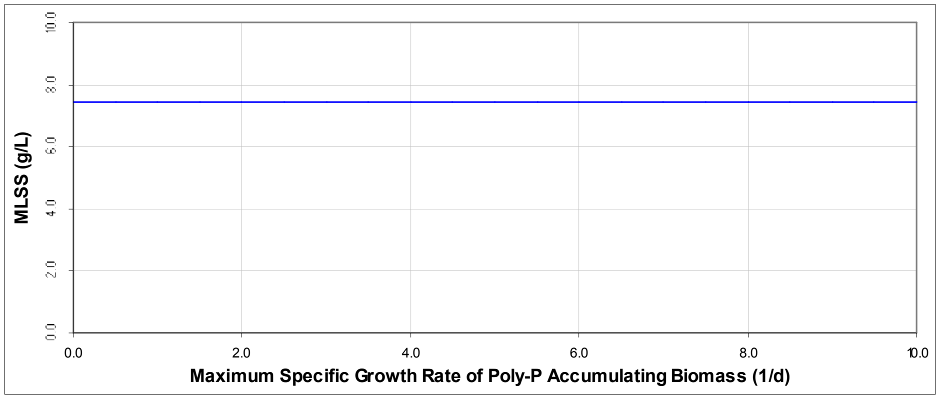

Figure D.7 Sensitivity Analysis for Maximum Specific Growth Rate of Poly-P Accumulating Biomass

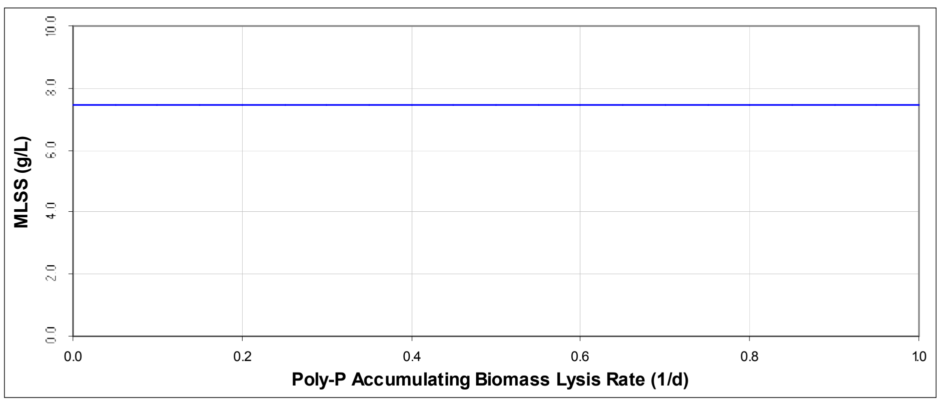

Figure D.8 Sensitivity Analysis for Poly-P Accumulating Biomass Lysis Rate

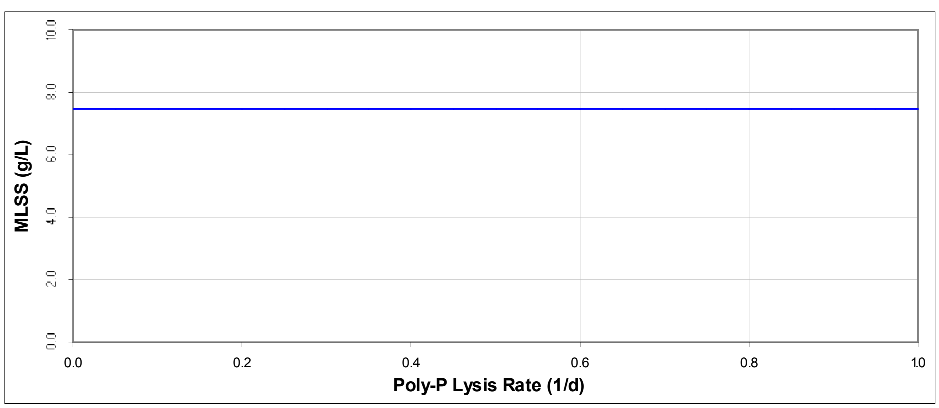

Figure D.9 Sensitivity Analysis for Poly-P Lysis Rate

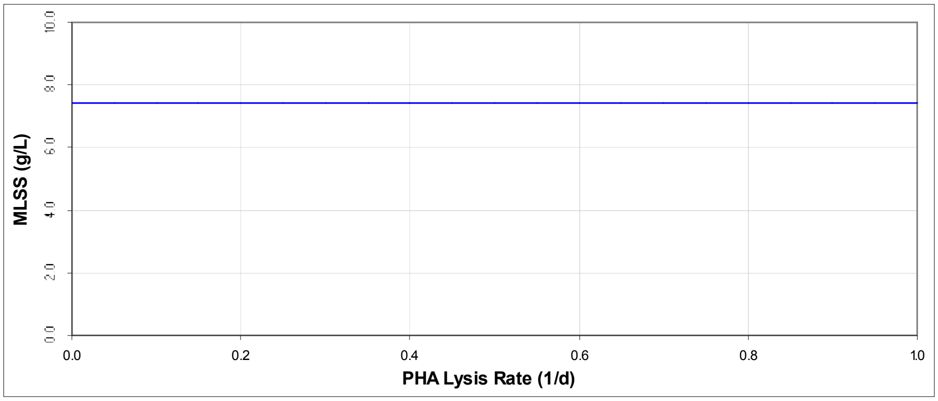

Figure D.10 Sensitivity Analysis for PHA Lysis Rate

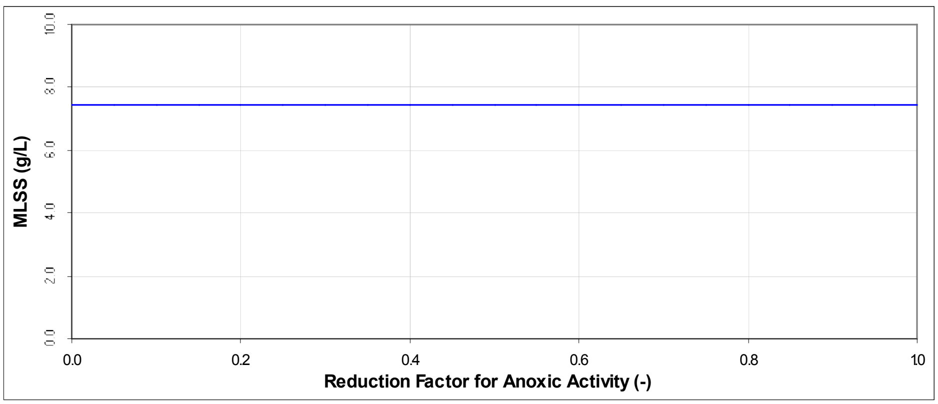

Figure D.11 Sensitivity Analysis for Reduction Factor for Anoxic Activity

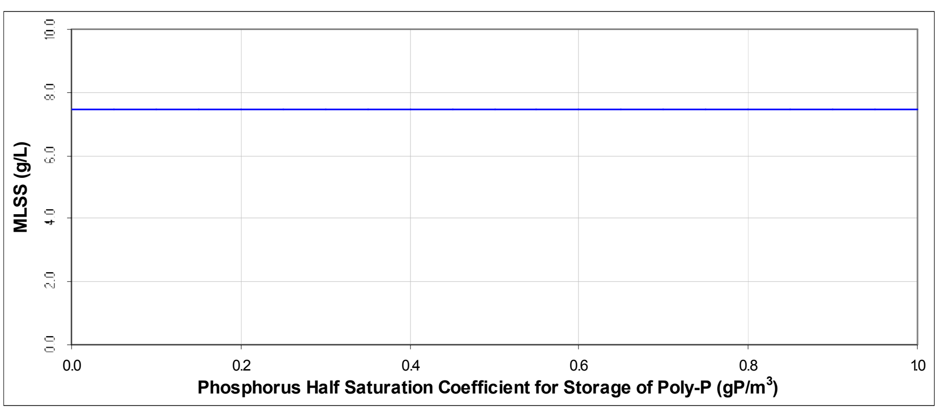

Figure D.12 Sensitivity Analysis for Phosphorus Half Saturation Coefficient for Storage of Poly-P

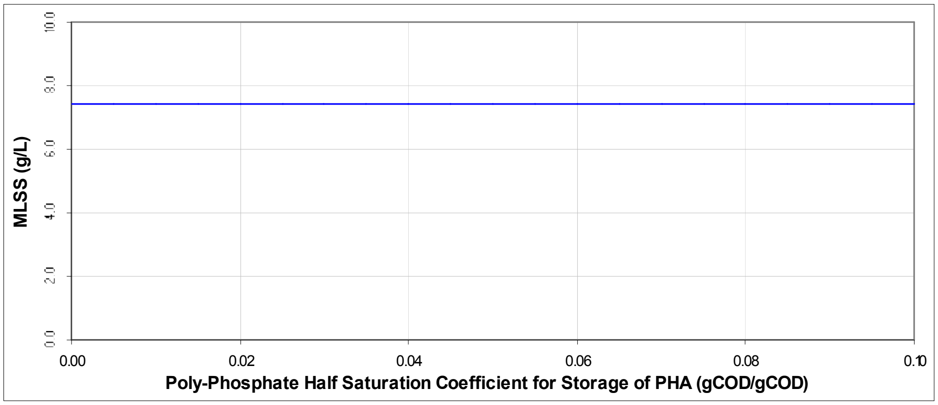

Figure D.13 Sensitivity Analysis for Poly-Phosphate Half Saturation Coefficient for Storage of PHA

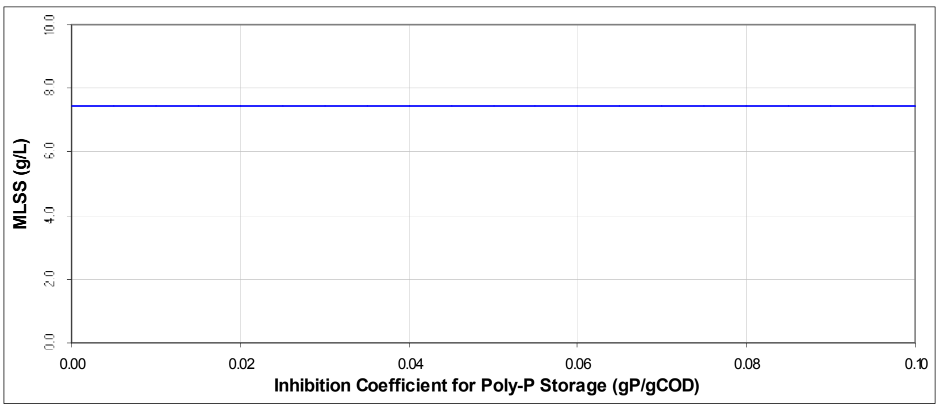

Figure D.14 Sensitivity Analysis for Inhibition Coefficient for Poly-P Storage

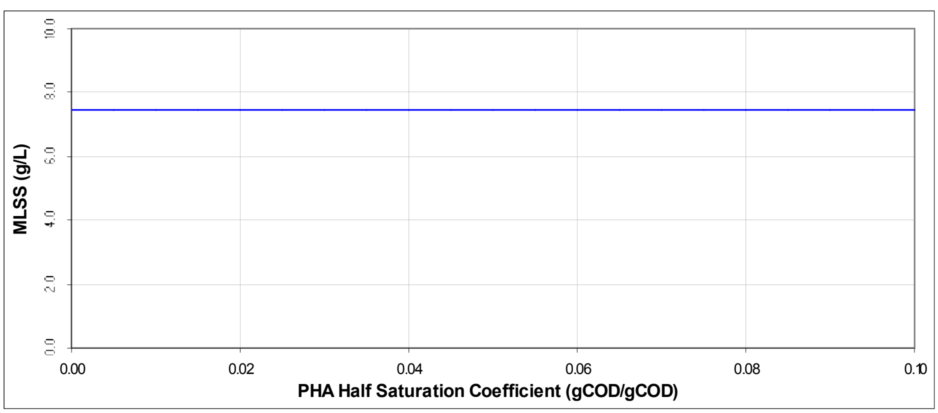

Figure D.15 Sensitivity Analysis for PHA Half Saturation Coefficient

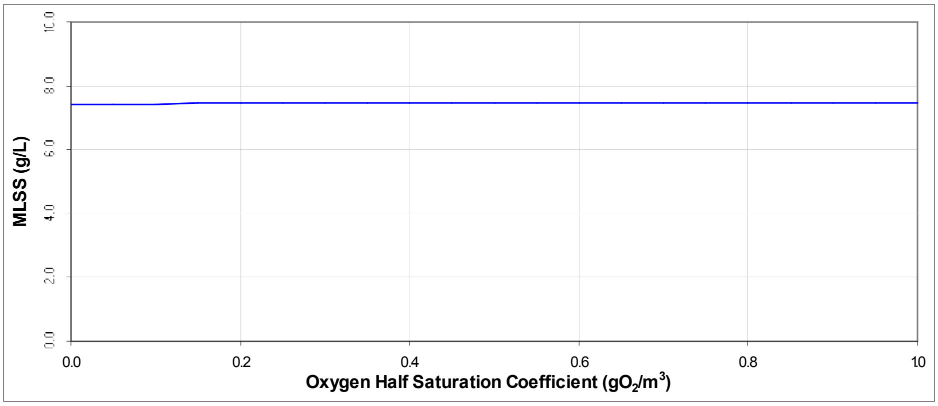

Figure D.16 Sensitivity Analysis for Oxygen Half Saturation Coefficient

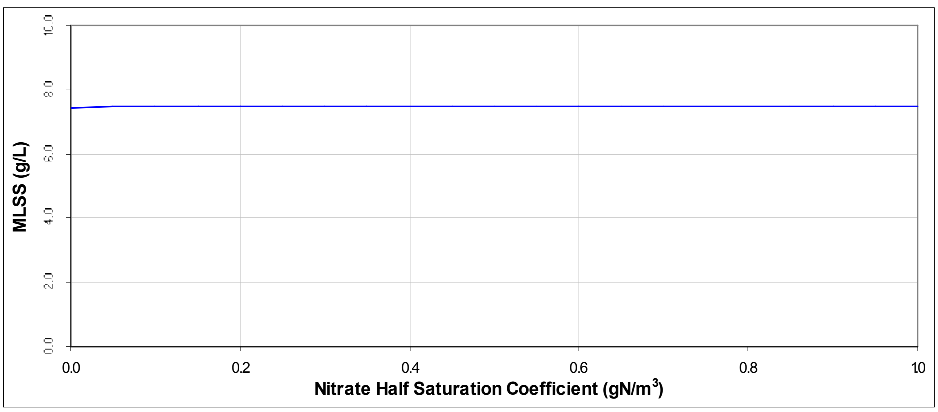

Figure D.17 Sensitivity Analysis for Nitrate Half Saturation Coefficient

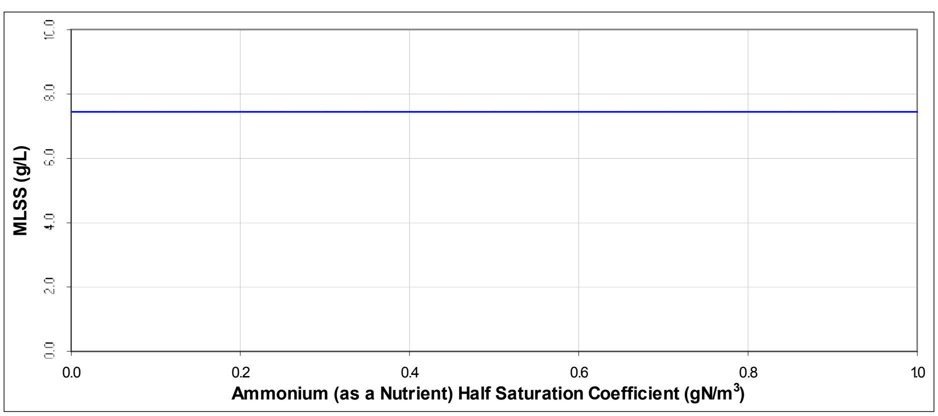

Figure D.18 Sensitivity Analysis for Ammonium Half Saturation Coefficient

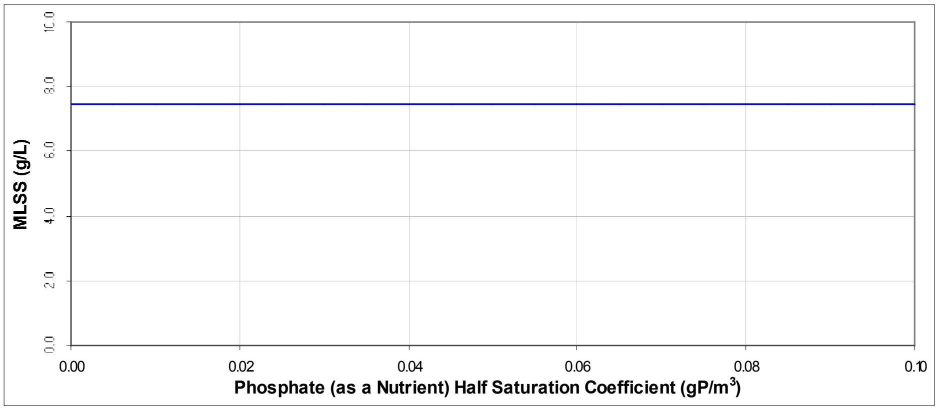

Figure D.19 Sensitivity Analysis for Phosphate Half Saturation Coefficient

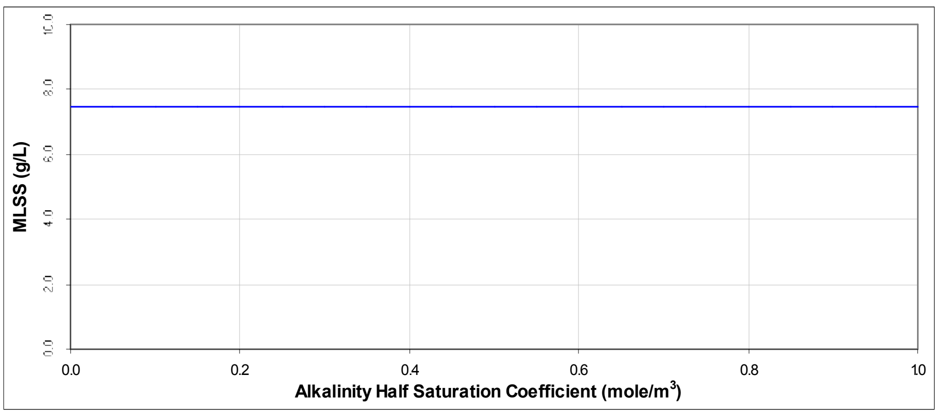

Figure D.20 Sensitivity Analysis for Alkalinity Half Saturation Coefficient

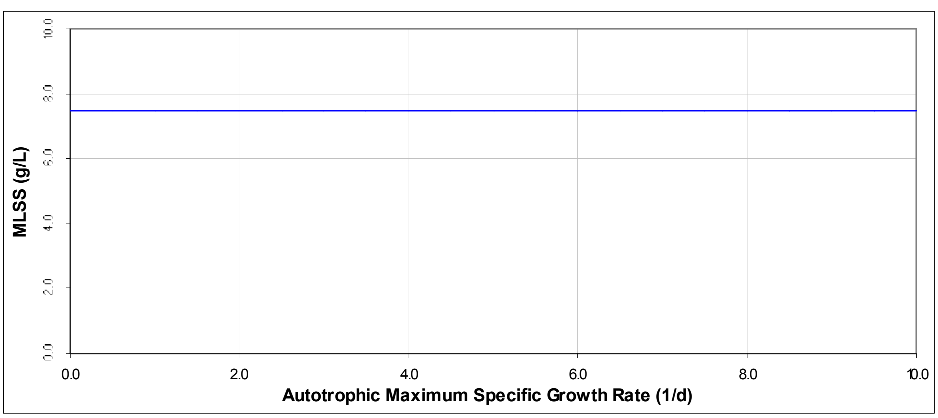

Figure D.21 Sensitivity Analysis for Autotrophic Maximum Specific Growth Rate

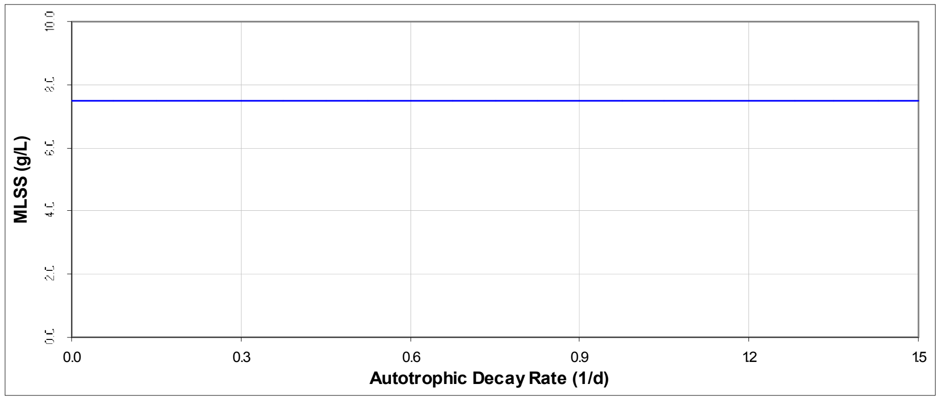

Figure D.22 Sensitivity Analysis for Autotrophic Decay Rate

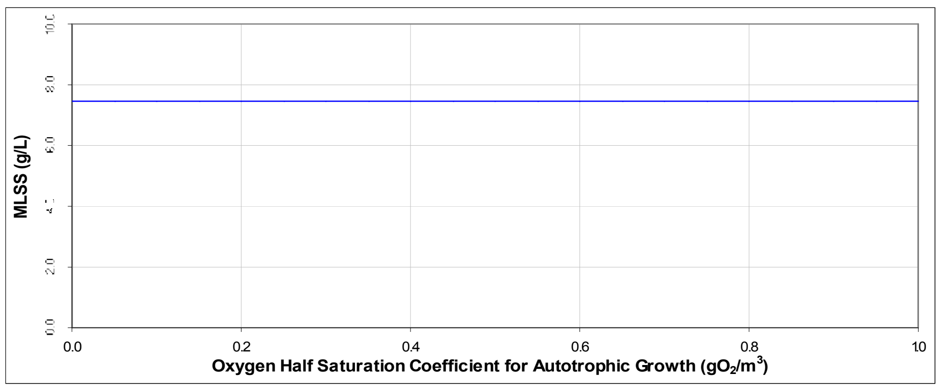

Figure D.23 Sensitivity Analysis for Oxygen Half Saturation Coefficient for Autotrophic Growth

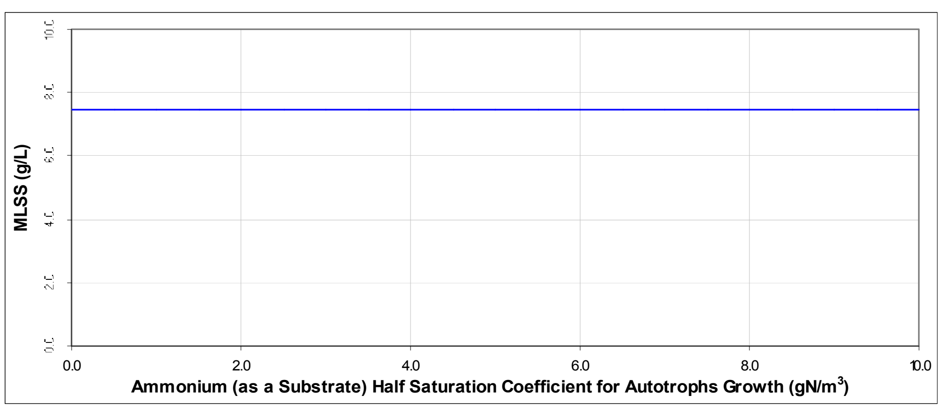

Figure D.24 Sensitivity Analysis for Ammonium Half Saturation Coefficient for Autotrophic Growth

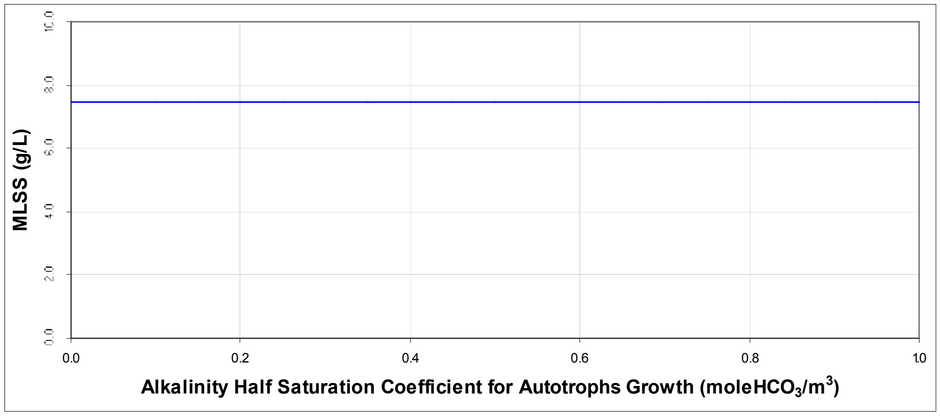

Figure D.25 Sensitivity Analysis for Alkalinity Half Saturation Coefficient for Autotrophs Growth

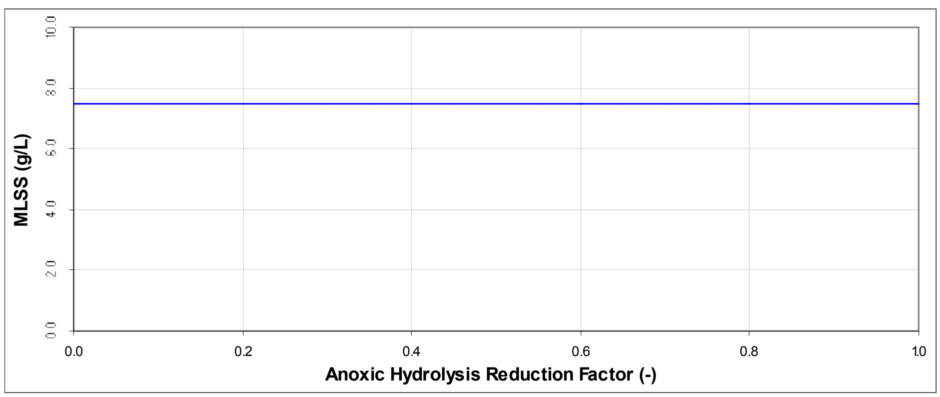

Figure D.26 Sensitivity Analysis for Anoxic Hydrolysis Reduction Factor

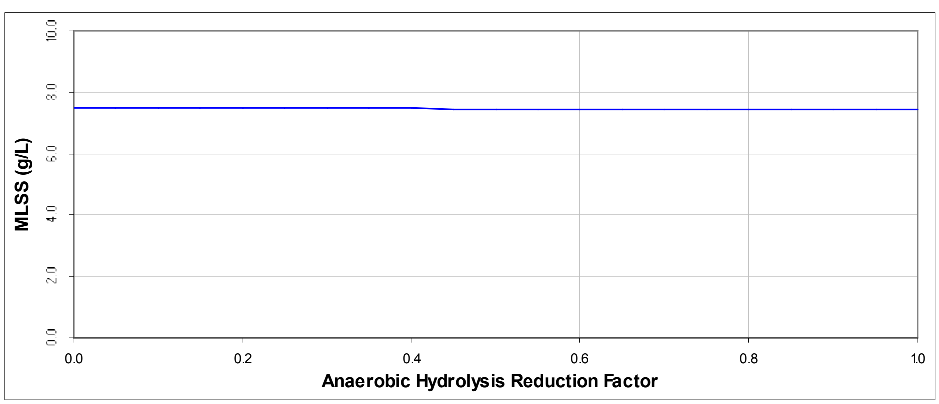

Figure D.27 Sensitivity Analysis for Anaerobic Hydrolysis Reduction Factor

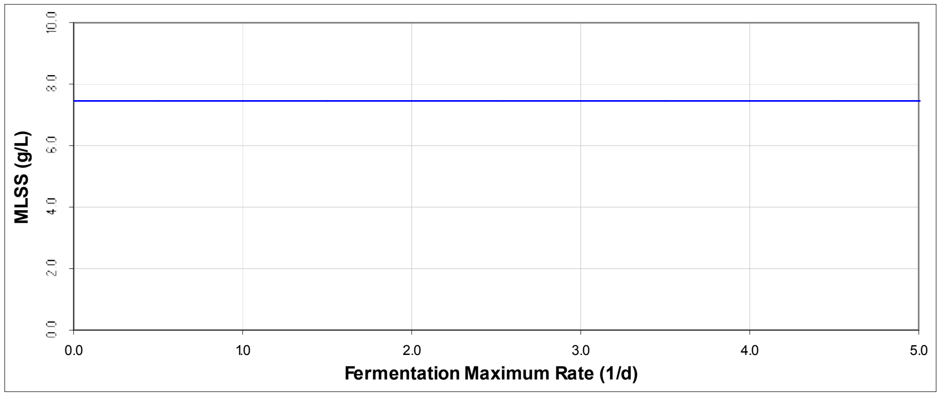

Figure D.28 Sensitivity Analysis for Fermentation Maximum Rate

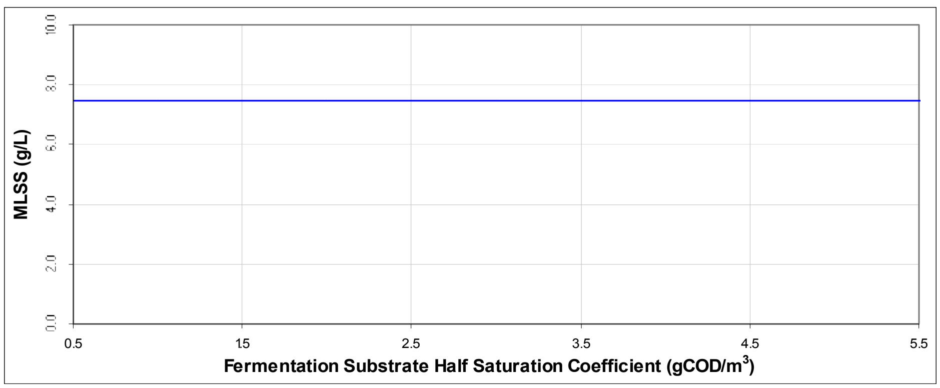

Figure D.29 Sensitivity Analysis for Fermentation Substrate Half Saturation Coefficient

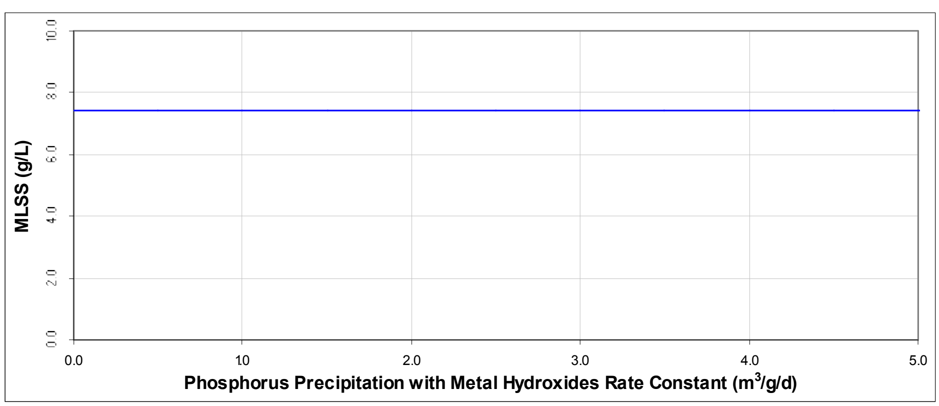

Figure D.30 Sensitivity Analysis for Phosphorus Precipitation with Metal Hydroxides Rate Constant

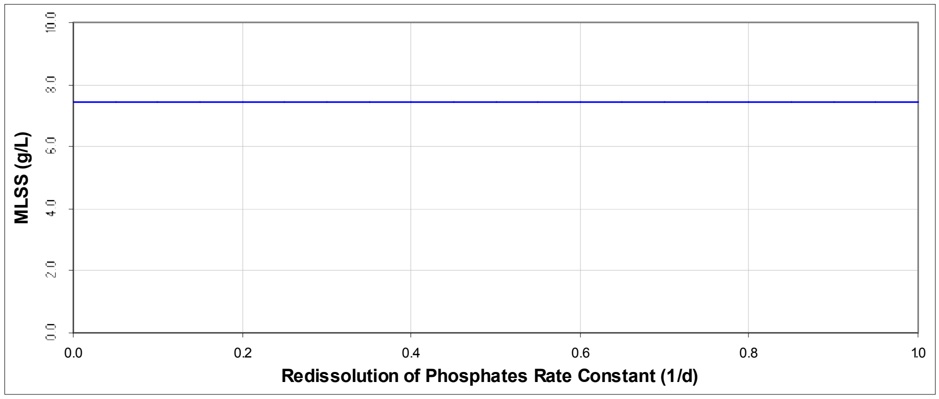

Figure D.31 Sensitivity Analysis for Redissolution of Phosphates Rate Constant

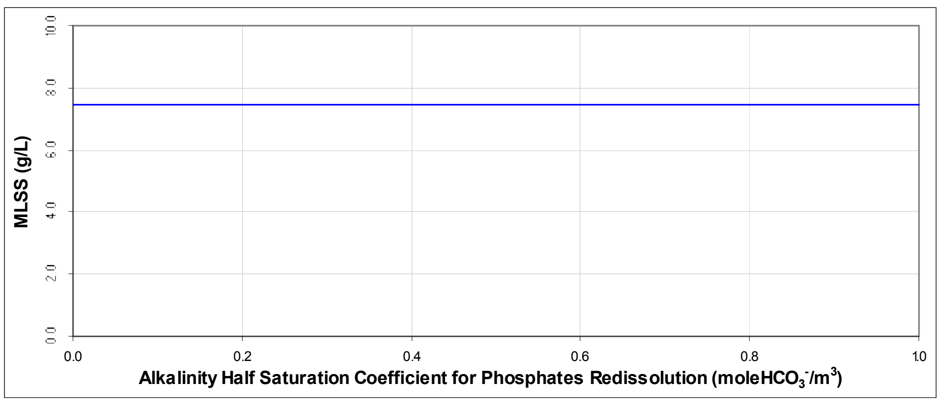

Figure D.32 Sensitivity Analysis for Alkalinity Half Saturation Coefficient for Phosphates Redissolution

Table D.1 Results of the Dynamic Runs for Aeration Tanks (MLSS)

Time (days)	Measured MLSS (g/L)	Default		Absolute Difference		Relative Difference		Sum of Squares		Relative Sum of Squares		Maximum Likelihood	
		Predicted MLSS (g/L)	x	Predicted MLSS (g/L)	x	Predicted MLSS (g/L)	x	Predicted MLSS (g/L)	x	Predicted MLSS (g/L)	x	Predicted MLSS (g/L)	x
1	4.88	5.31	1.09	5.66	1.16	5.63	1.15	5.53	1.13	5.53	1.13	5.55	1.14
2	5.30	5.31	1.00	5.66	1.07	5.63	1.06	5.53	1.04	5.53	1.04	5.56	1.05
3	5.15	5.37	1.04	5.72	1.11	5.69	1.11	5.59	1.09	5.59	1.09	5.62	1.09
4	5.49	5.32	0.97	5.67	1.03	5.64	1.03	5.54	1.01	5.54	1.01	5.57	1.01
5	5.17	5.45	1.06	5.81	1.13	5.78	1.12	5.68	1.10	5.68	1.10	5.71	1.10
6	5.15	5.44	1.06	5.80	1.13	5.77	1.12	5.67	1.10	5.67	1.10	5.69	1.10
7	5.65	5.47	0.97	5.84	1.03	5.81	1.03	5.70	1.01	5.70	1.01	5.73	1.01
8	6.41	5.52	0.86	5.89	0.92	5.86	0.91	5.76	0.90	5.76	0.90	5.78	0.90
9	6.40	5.62	0.88	5.99	0.94	5.96	0.93	5.86	0.92	5.86	0.92	5.88	0.92
10	6.10	5.64	0.92	6.02	0.99	5.99	0.98	5.88	0.96	5.88	0.96	5.90	0.97
11	5.69	5.67	1.00	6.05	1.06	6.02	1.06	5.91	1.04	5.91	1.04	5.93	1.04
12	6.14	5.65	0.92	6.04	0.98	6.01	0.98	5.90	0.96	5.90	0.96	5.92	0.96
13	6.11	5.71	0.94	6.09	1.00	6.06	0.99	5.95	0.98	5.95	0.98	5.98	0.98
14	5.49	5.74	1.04	6.12	1.12	6.09	1.11	5.98	1.09	5.98	1.09	6.01	1.09
15	6.21	5.74	0.93	6.13	0.99	6.10	0.98	5.99	0.96	5.99	0.97	6.01	0.97
16	6.23	5.74	0.92	6.12	0.98	6.09	0.98	5.98	0.96	5.98	0.96	6.01	0.96
17	5.72	5.71	1.00	6.10	1.07	6.07	1.06	5.96	1.04	5.96	1.04	5.98	1.05
18	5.80	5.69	0.98	6.08	1.05	6.05	1.04	5.94	1.02	5.94	1.02	5.96	1.03
19	6.20	5.66	0.91	6.04	0.97	6.01	0.97	5.90	0.95	5.90	0.95	5.92	0.96
20	5.89	5.64	0.96	6.01	1.02	5.98	1.02	5.88	1.00	5.88	1.00	5.90	1.00
21	6.44	5.64	0.88	6.02	0.94	5.99	0.93	5.88	0.91	5.88	0.91	5.91	0.92
22	6.06	5.68	0.94	6.06	1.00	6.03	1.00	5.92	0.98	5.92	0.98	5.95	0.98
23	5.01	5.65	1.13	6.02	1.20	5.99	1.20	5.89	1.17	5.89	1.17	5.91	1.18
24	5.75	5.57	0.97	5.94	1.03	5.91	1.03	5.80	1.01	5.80	1.01	5.83	1.01
25	5.93	5.50	0.93	5.86	0.99	5.83	0.98	5.73	0.97	5.73	0.97	5.75	0.97
26	6.01	5.42	0.90	5.77	0.96	5.74	0.96	5.64	0.94	5.64	0.94	5.66	0.94
27	5.73	5.33	0.93	5.68	0.99	5.65	0.99	5.55	0.97	5.55	0.97	5.57	0.97
28	5.78	5.27	0.91	5.61	0.97	5.59	0.97	5.49	0.95	5.49	0.95	5.51	0.95
29	5.97	5.24	0.88	5.58	0.93	5.55	0.93	5.45	0.91	5.45	0.91	5.48	0.92
30	5.96	5.24	0.88	5.58	0.94	5.55	0.93	5.45	0.91	5.45	0.91	5.47	0.92
31	5.43	5.16	0.95	5.49	1.01	5.46	1.01	5.37	0.99	5.37	0.99	5.39	0.99
Average	5.78	5.52	0.96	5.89	1.02	5.86	1.02	5.75	1.00	5.75	1.00	5.78	1.00
σ			0.07		0.07		0.07		0.07		0.07		0.07

x = Predicted MLSS / Measured MLSS, σ = standard deviation

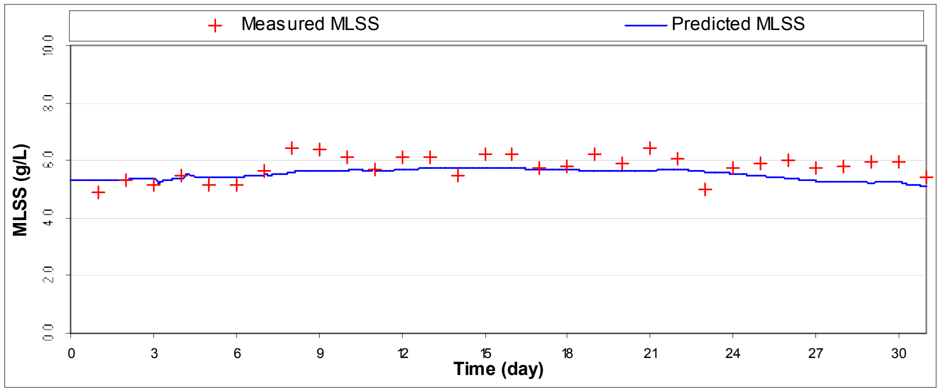

Figure D.33 Dynamic Run for Aeration Tanks by Using Default Values

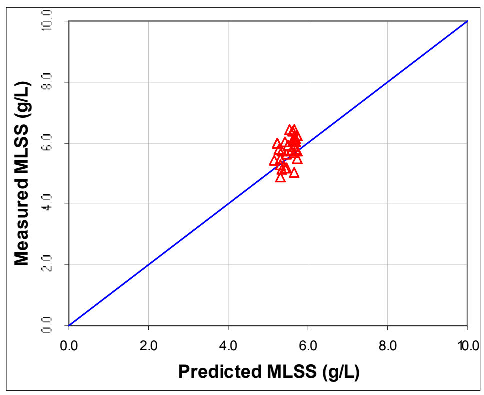

Figure D.34 Predicted MLSS versus Measured MLSS for Default Values

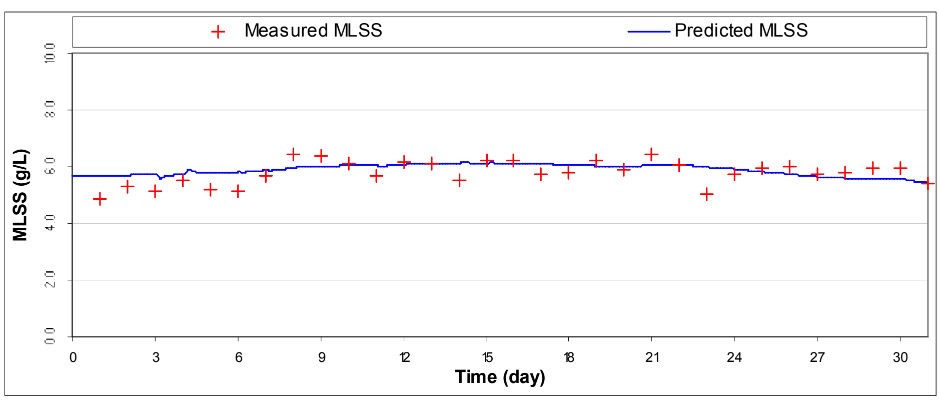

Figure D.35 Dynamic Run for Aerobic Tanks by Using Absolute Difference Results

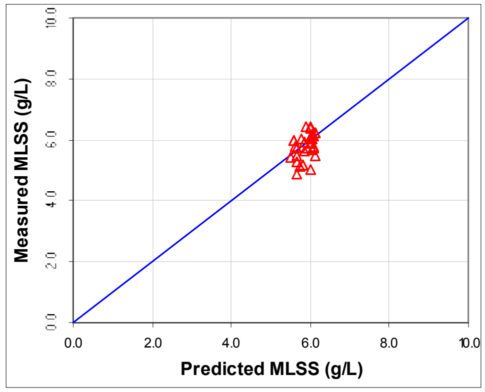

Figure D.36 Predicted MLSS versus Measured MLSS for Absolute Difference Results

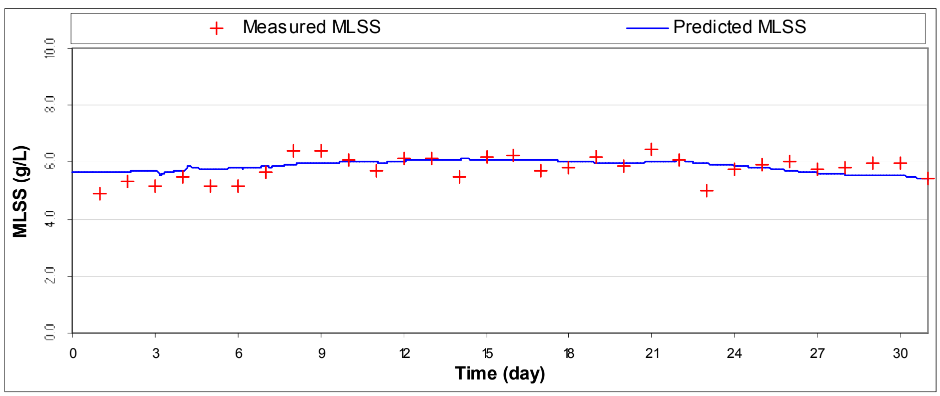

Figure D.37 Dynamic Run for Aerobic Tanks by Using Relative Difference Results

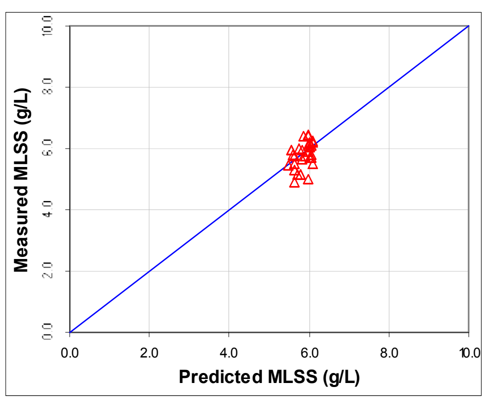

Figure D.38 Predicted MLSS versus Measured MLSS for Relative Difference Results

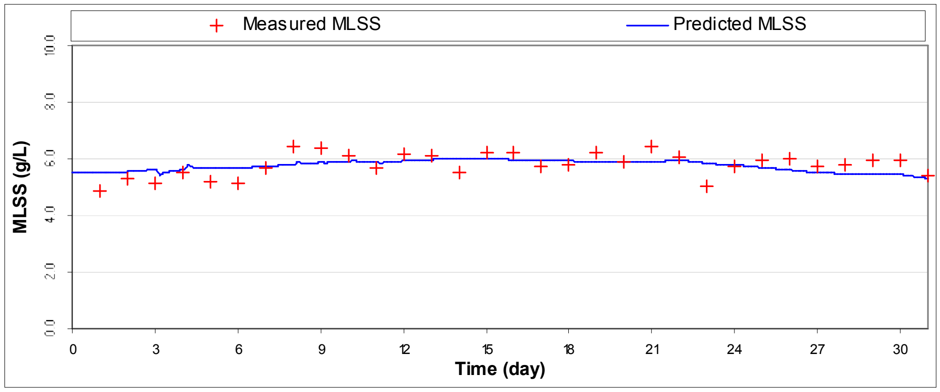

Figure D.39 Dynamic Run for Aerobic Tanks by Using Sum of Squares Results

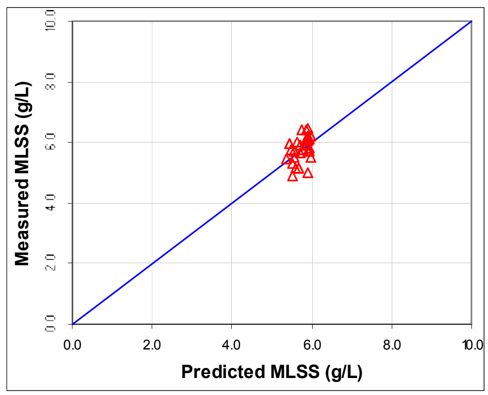

Figure D.40 Predicted MLSS versus Measured MLSS for Sum of Squares Results

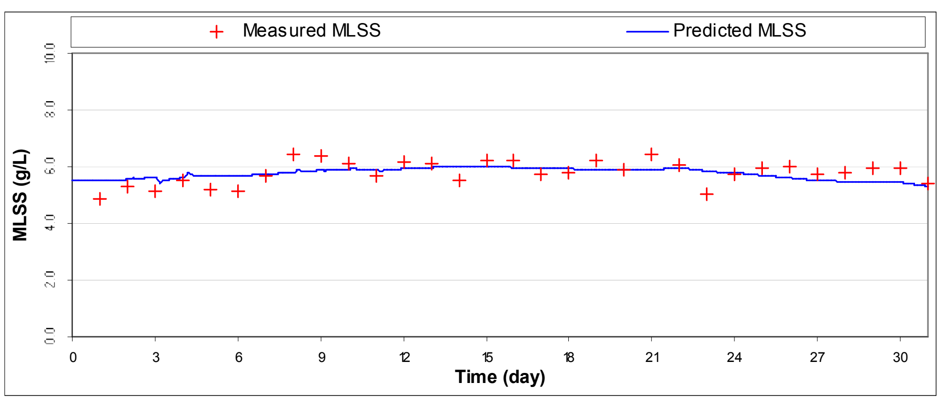

Figure D.41 Dynamic Run for Aerobic Tanks by Using Relative Sum of Squares Results

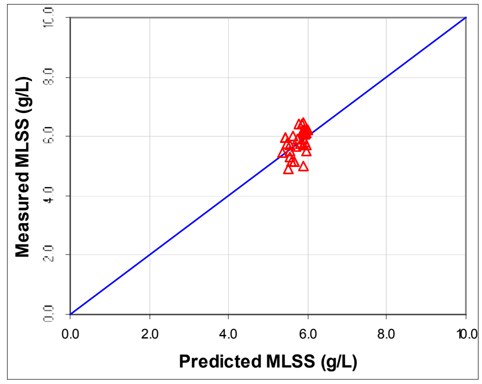

Figure D.42 Predicted MLSS versus Measured MLSS for Relative Sum of Squares Results

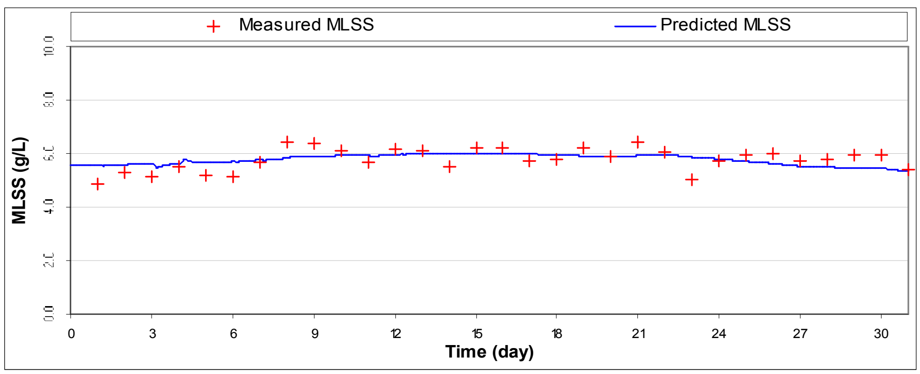

Figure D.43 Dynamic Run for Aeration Tanks by Using Maximum Likelihood Results

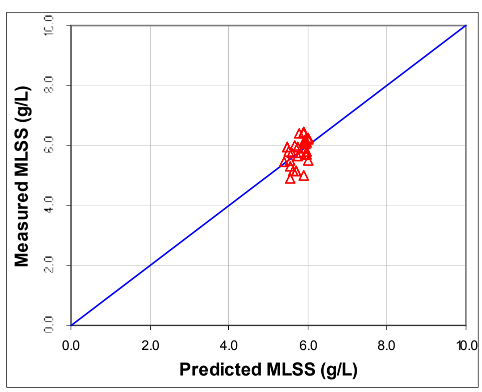

Figure D.44 Predicted MLSS versus Measured MLSS for Maximum Likelihood Results

APPENDIX E

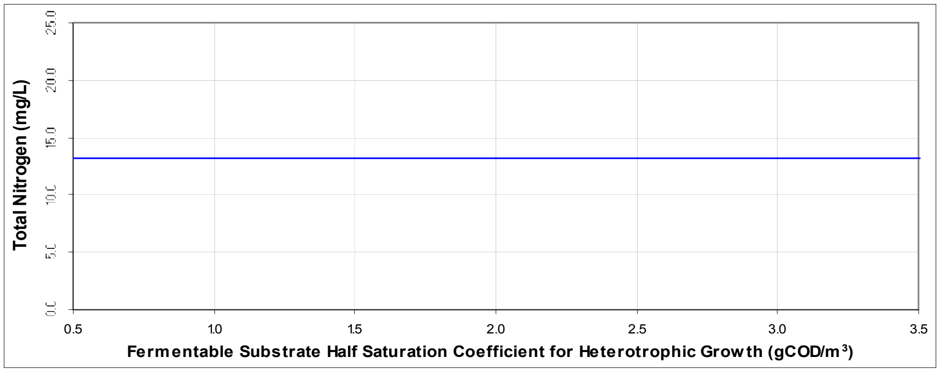

Figure E.1 Sensitivity Analysis for Fermentable Substrate Half Saturation Coefficient for Heterotrophic Growth

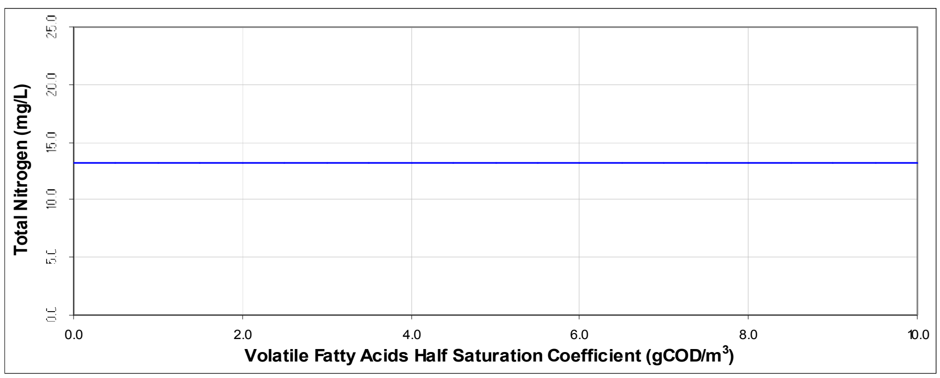

Figure E.2 Sensitivity Analysis for Volatile Fatty Acids Half Saturation Coefficient

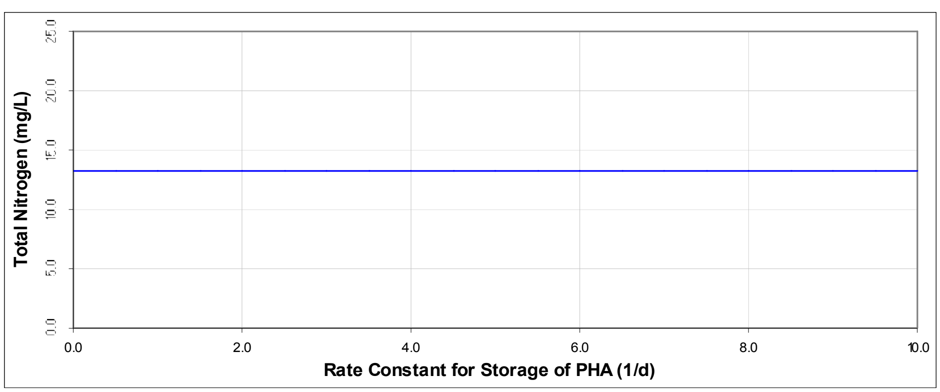

Figure E.3 Sensitivity Analysis for Rate Constant for Storage of PHA

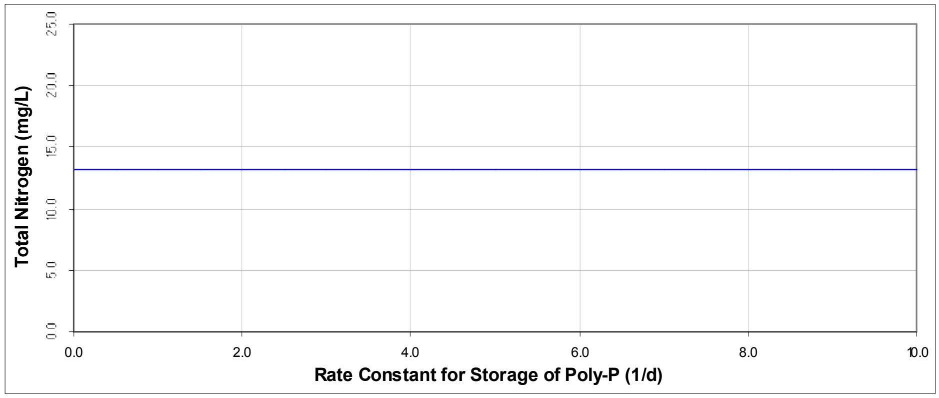

Figure E.4 Sensitivity Analysis for Rate Constant for Storage of Poly-P

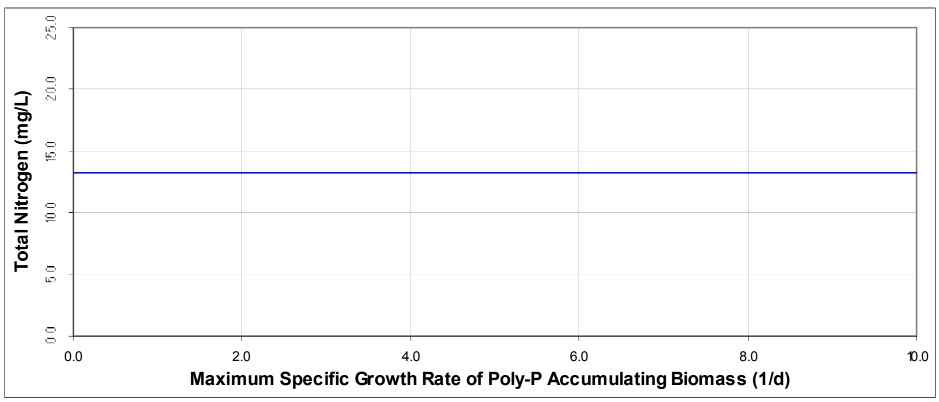

Figure E.5 Sensitivity Analysis for Maximum Specific Growth Rate of Poly-P Accumulating Biomass

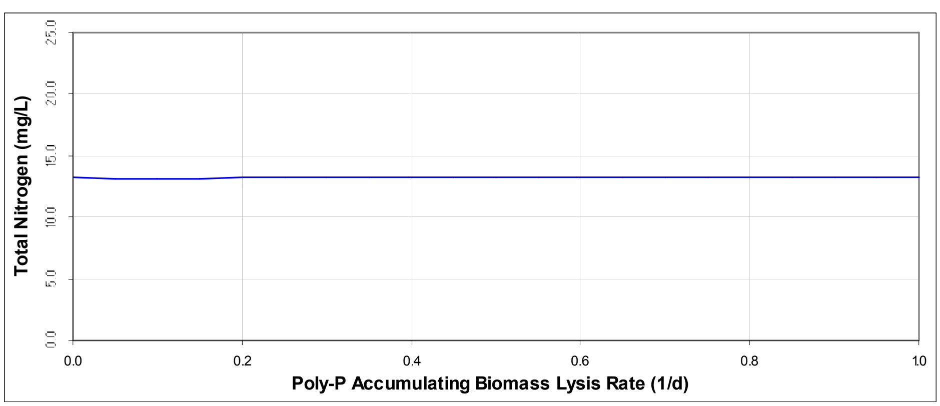

Figure E.6 Sensitivity Analysis for Poly-P Accumulating Biomass Lysis Rate

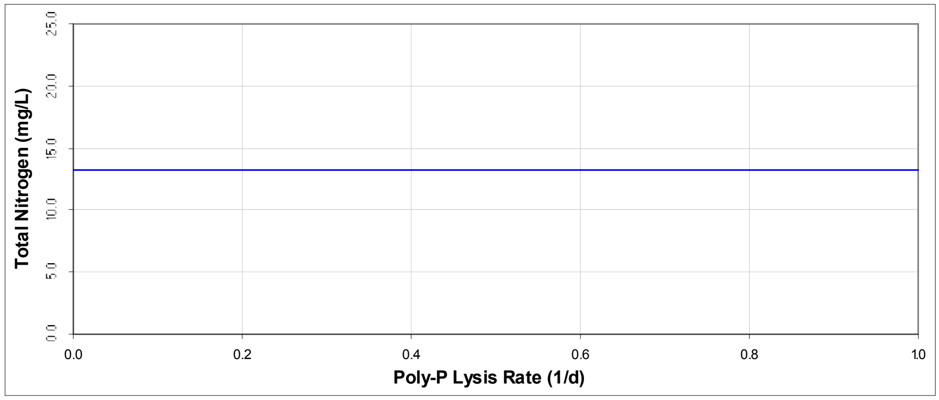

Figure E.7 Sensitivity Analysis for Poly-P Lysis Rate

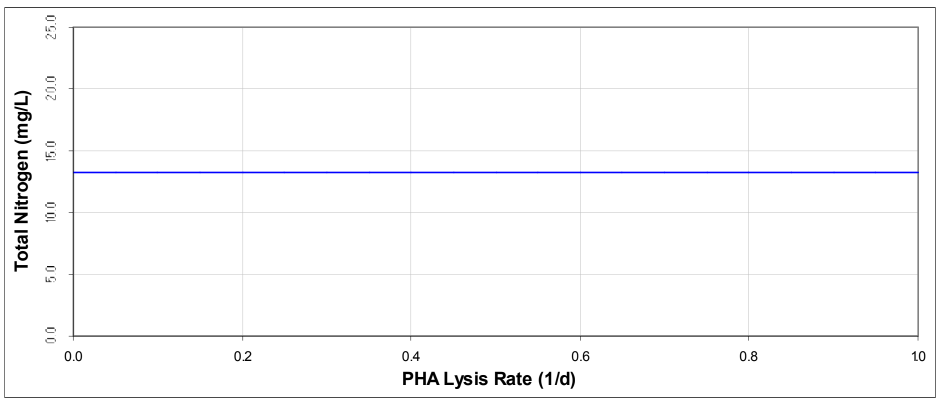

Figure E.8 Sensitivity Analysis for PHA Lysis Rate

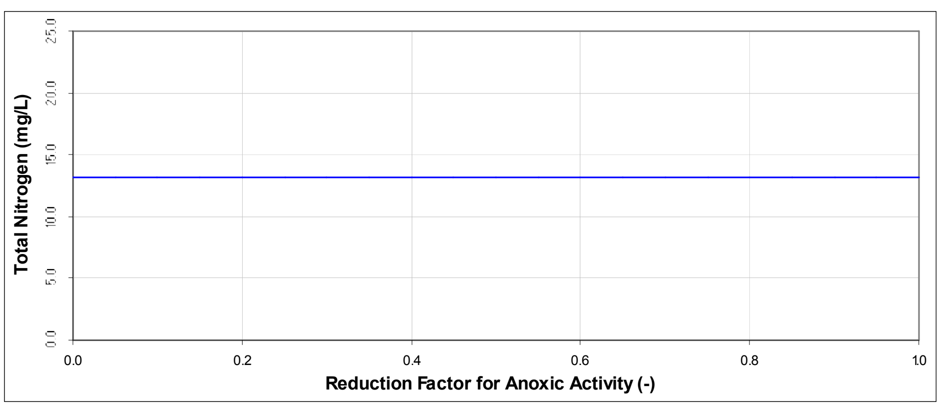

Figure E.9 Sensitivity Analysis for Reduction Factor for Anoxic Activity

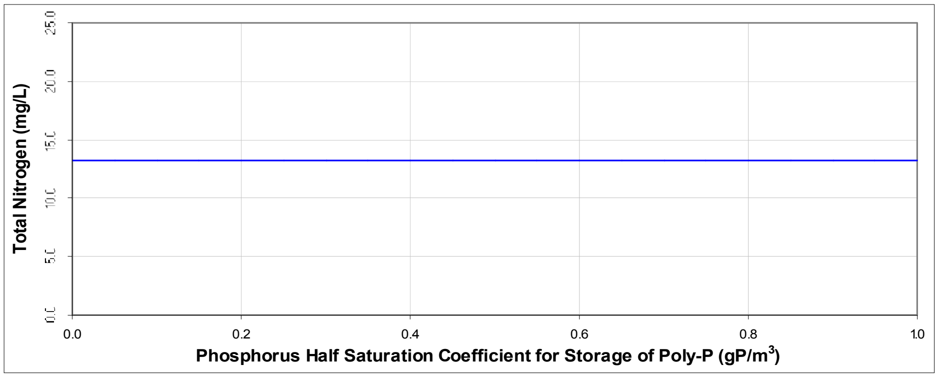

Figure E.10 Sensitivity Analysis for Phosphorus Half Saturation Coefficient for Storage of Poly-P

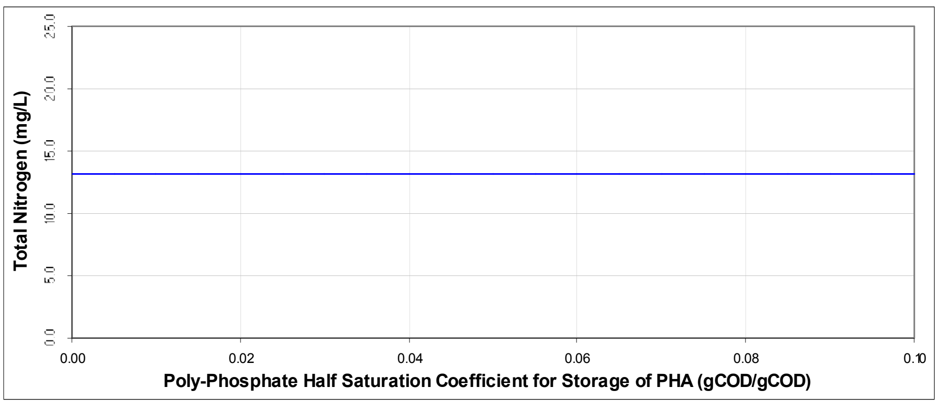

Figure E.11 Sensitivity Analysis for Poly-Phosphate Half Saturation Coefficient for Storage of PHA

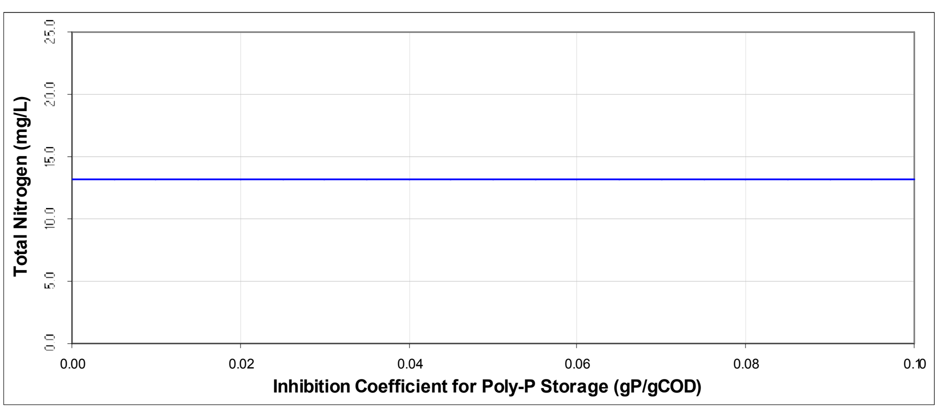

Figure E.12 Sensitivity Analysis for Inhibition Coefficient for Poly-P Storage

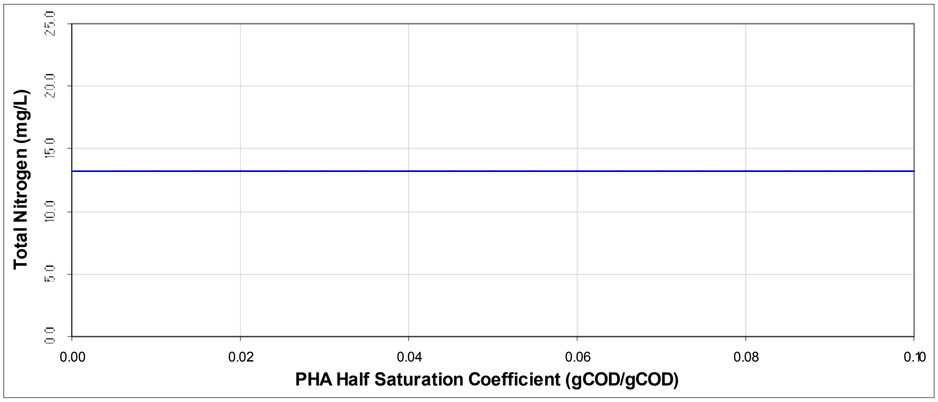

Figure E.13 Sensitivity Analysis for PHA Half Saturation Coefficient

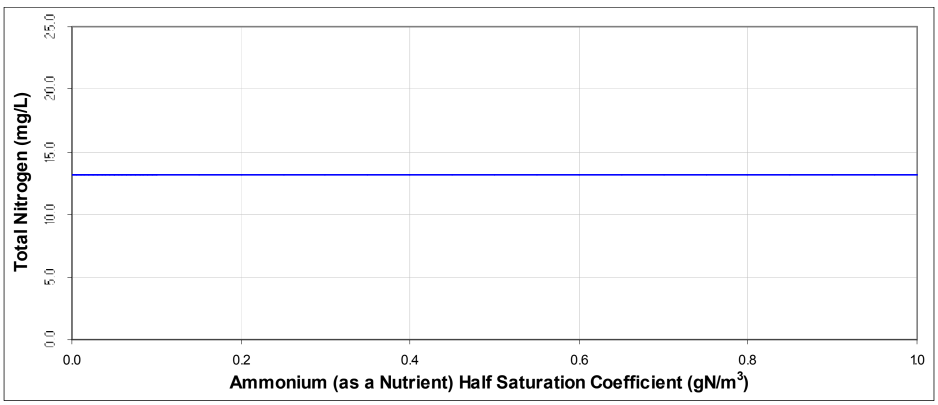

Figure E.14 Sensitivity Analysis for Ammonium Half Saturation Coefficient

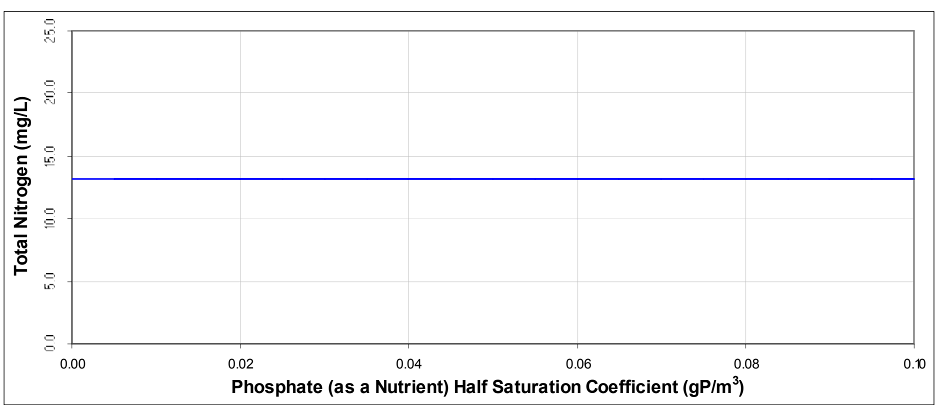

Figure E.15 Sensitivity Analysis for Phosphate Half Saturation Coefficient

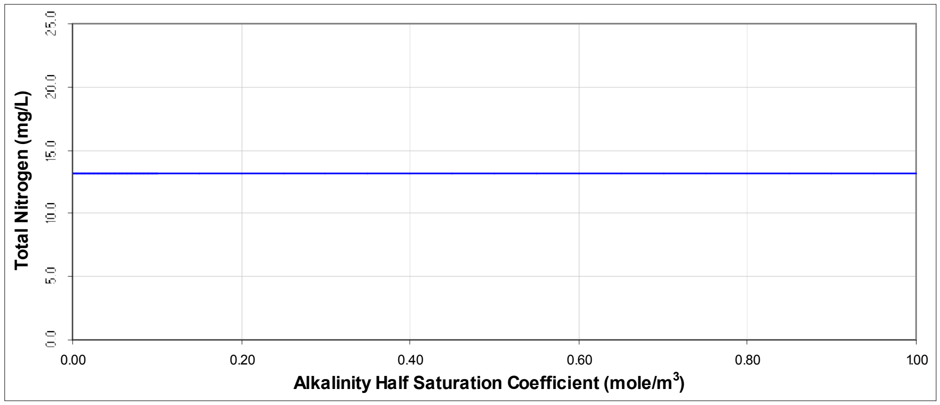

Figure E.16 Sensitivity Analysis for Alkalinity Half Saturation Coefficient

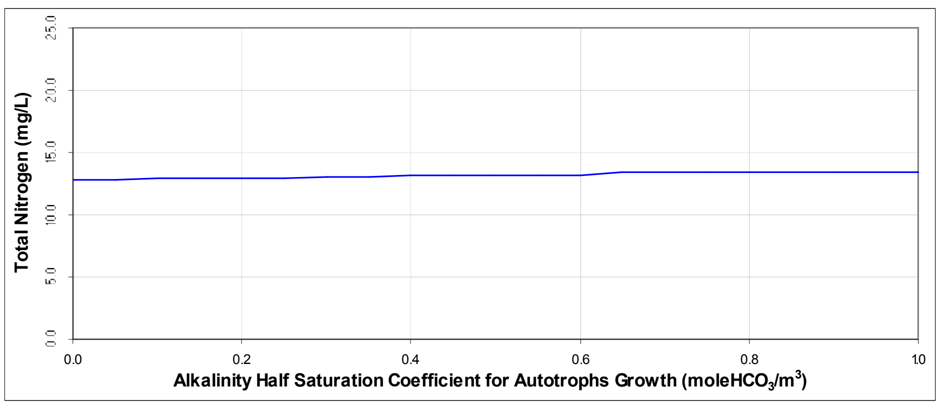

Figure E.17 Sensitivity Analysis for Alkalinity Half Saturation Coefficient for Autotrophs Growth

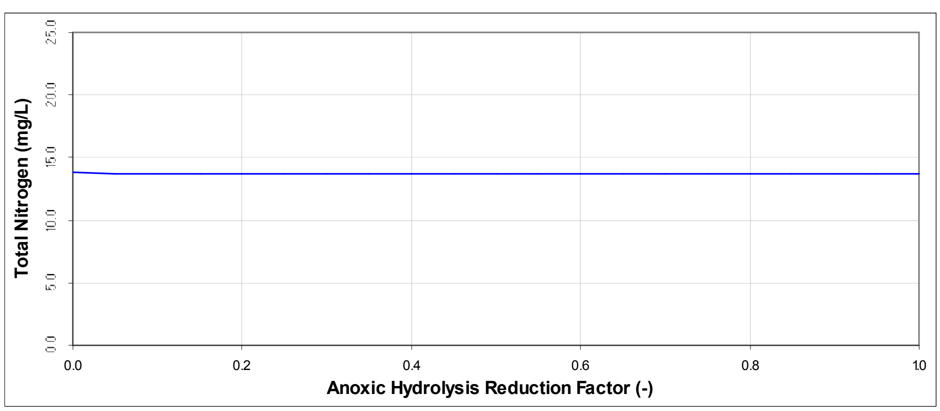

Figure E.18 Sensitivity Analysis for Anoxic Hydrolysis Reduction Factor

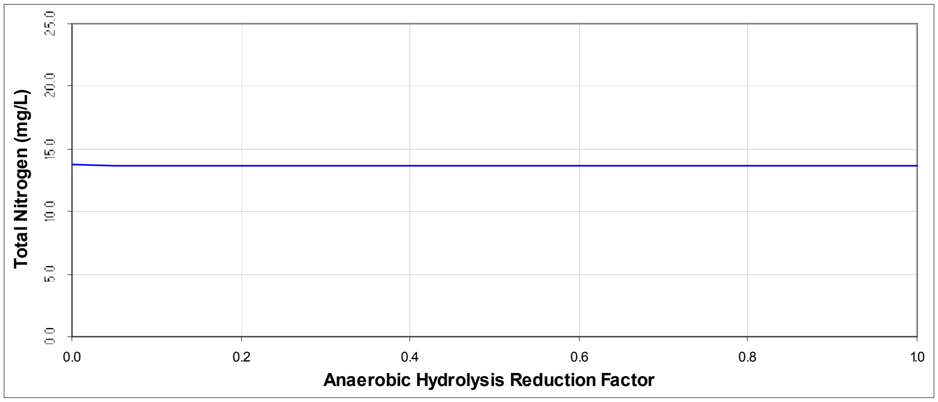

Figure E.19 Sensitivity Analysis for Anaerobic Hydrolysis Reduction Factor

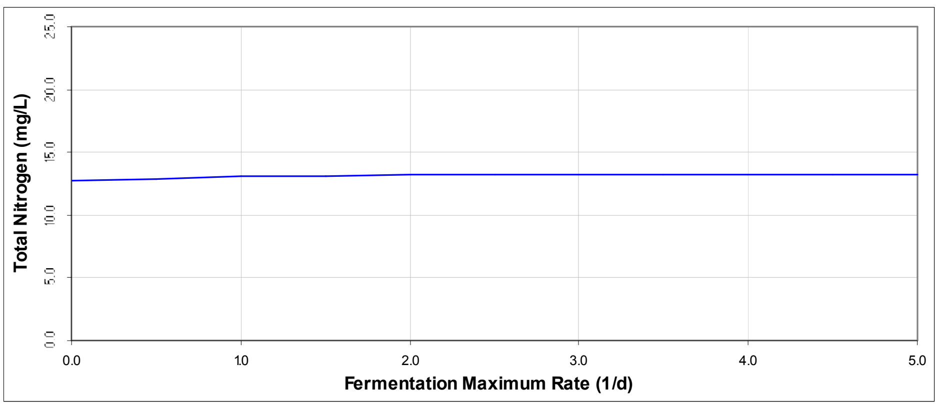

Figure E.20 Sensitivity Analysis for Fermentation Maximum Rate

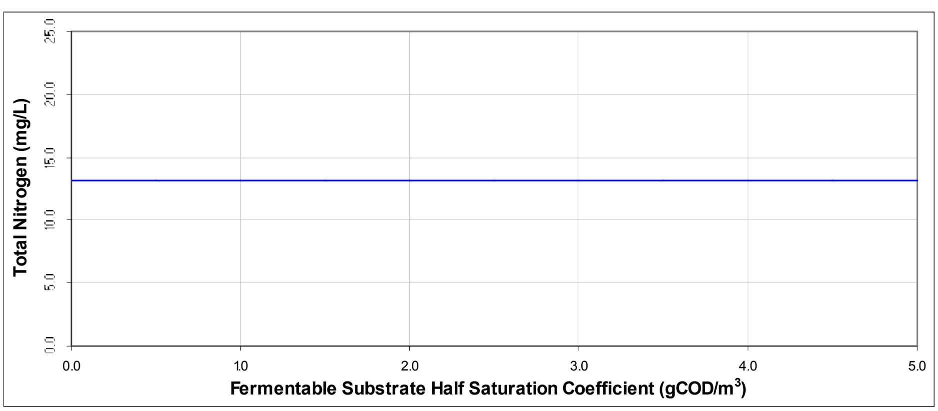

Figure E.21 Sensitivity Analysis for Fermentation Substrate Half Saturation Coefficient

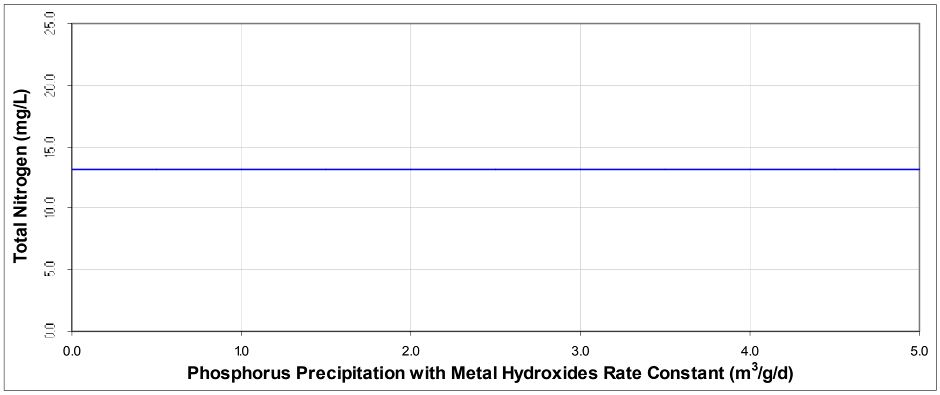

Figure E.22 Sensitivity Analysis for Phosphorus Precipitation with Metal Hydroxides Rate Constant

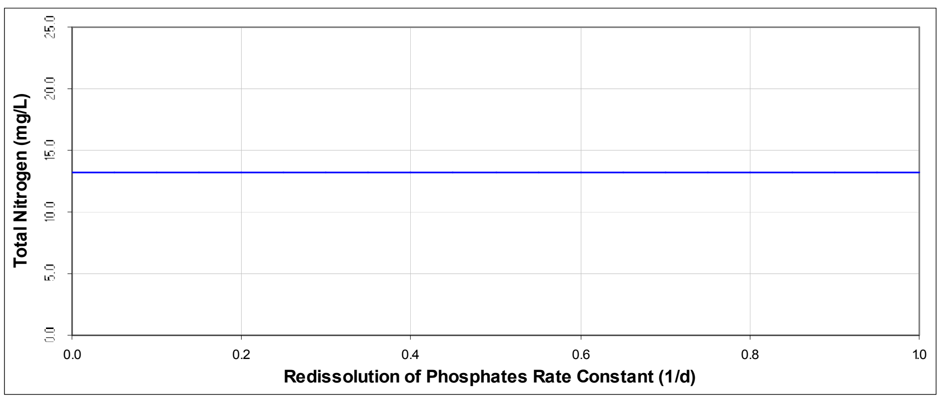

Figure E.23 Sensitivity Analysis for Redissolution of Phosphates Rate Constant

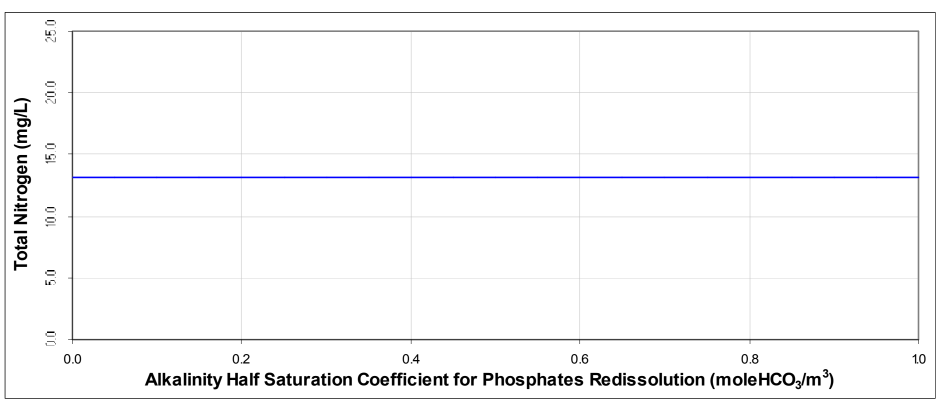

Figure E.24 Sensitivity Analysis for Alkalinity Half Saturation Coefficient for Phosphates Redissolution

Table E.1 Results of the Dynamic Runs for Aeration Tanks (Total Nitrogen)

Time (days)	Measured Total N (mg/L)	Default		Absolute Difference		Relative Difference		Sum of Squares		Relative Sum of Squares		Maximum Likelihood	
		Predicted Total N (mg/L)	x	Predicted Total N (mg/L)	x	Predicted Total N (mg/L)	x	Predicted Total N (mg/L)	x	Predicted Total N (mg/L)	x	Predicted Total N (mg/L)	x
1	5.63	13.30	2.36	6.11	1.09	5.73	1.02	6.69	1.19	4.73	0.84	5.99	1.06
2	7.89	13.30	1.69	5.88	0.75	5.52	0.70	6.37	0.81	4.39	0.56	5.63	0.71
3	8.25	12.16	1.47	5.10	0.62	4.74	0.57	5.49	0.67	3.67	0.44	4.80	0.58
4	7.45	12.19	1.64	6.33	0.85	5.81	0.78	6.92	0.93	4.78	0.64	6.15	0.83
5	6.11	13.93	2.28	6.74	1.10	6.17	1.01	7.20	1.18	4.97	0.81	6.37	1.04
6	5.98	13.26	2.22	5.62	0.94	5.23	0.88	6.08	1.02	4.09	0.68	5.33	0.89
7	8.42	12.51	1.49	5.53	0.66	5.11	0.61	6.01	0.71	4.03	0.48	5.28	0.63
8	8.01	12.99	1.62	6.46	0.81	5.91	0.74	6.97	0.87	4.85	0.61	6.19	0.77
9	9.56	12.46	1.30	5.44	0.57	4.86	0.51	5.80	0.61	3.79	0.40	5.02	0.53
10	9.03	10.50	1.16	4.09	0.45	3.70	0.41	4.51	0.50	2.72	0.30	3.82	0.42
11	8.63	11.05	1.28	4.80	0.56	4.55	0.53	5.32	0.62	3.51	0.41	4.63	0.54
12	9.06	12.24	1.35	5.57	0.62	5.24	0.58	6.03	0.67	4.15	0.46	5.32	0.59
13	8.35	12.07	1.45	5.40	0.65	5.00	0.60	5.84	0.70	3.93	0.47	5.13	0.61
14	8.64	11.31	1.31	4.60	0.53	4.19	0.49	4.99	0.58	3.13	0.36	4.29	0.50
15	9.85	10.44	1.06	4.04	0.41	3.75	0.38	4.48	0.45	2.73	0.28	3.80	0.39
16	8.45	10.14	1.20	3.96	0.47	3.70	0.44	4.39	0.52	2.68	0.32	3.73	0.44
17	8.08	11.39	1.41	5.02	0.62	4.84	0.60	5.56	0.69	3.76	0.46	4.88	0.60
18	8.84	13.17	1.49	6.01	0.68	5.74	0.65	6.50	0.73	4.56	0.52	5.78	0.65
19	8.71	13.10	1.50	5.57	0.64	5.26	0.60	6.00	0.69	4.07	0.47	5.28	0.61
20	8.15	12.23	1.50	5.03	0.62	4.76	0.58	5.47	0.67	3.64	0.45	4.78	0.59
21	9.02	11.61	1.29	4.78	0.53	4.54	0.50	5.21	0.58	3.44	0.38	4.54	0.50
22	9.85	11.38	1.16	4.81	0.49	4.57	0.46	5.26	0.53	3.49	0.35	4.60	0.47
23	8.78	12.26	1.40	5.49	0.63	5.29	0.60	5.99	0.68	4.16	0.47	5.31	0.60
24	8.29	13.22	1.59	6.14	0.74	5.84	0.70	6.61	0.80	4.68	0.56	5.91	0.71
25	6.72	13.45	2.00	6.08	0.91	5.76	0.86	6.53	0.97	4.59	0.68	5.81	0.87
26	7.12	12.88	1.81	5.59	0.78	5.28	0.74	6.01	0.84	4.14	0.58	5.32	0.75
27	7.04	13.12	1.86	6.03	0.86	5.84	0.83	6.54	0.93	4.71	0.67	5.86	0.83
28	7.54	17.40	2.31	9.72	1.29	9.61	1.27	10.52	1.40	8.34	1.11	9.73	1.29
29	5.47	20.70	3.78	11.37	2.08	10.68	1.95	11.88	2.17	9.24	1.69	10.91	1.99
30	6.78	20.30	2.99	10.07	1.49	9.49	1.40	10.69	1.58	8.03	1.18	9.69	1.43
31	7.89	19.99	2.53	9.97	1.26	9.55	1.21	10.57	1.34	8.18	1.04	9.68	1.23
Average	8.00	13.23	1.73	6.04	0.80	5.69	0.75	6.53	0.86	4.55	0.60	5.79	0.76
σ			0.60		0.35		0.34		0.37		0.30		0.34

x = Predicted Total N / Measured Total N, σ = standard deviation

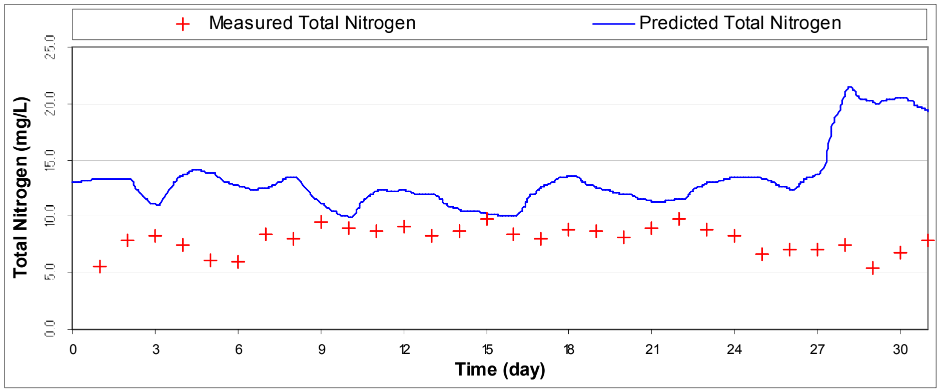

Figure E.25 Dynamic Run for Aeration Tanks by Using Default Values

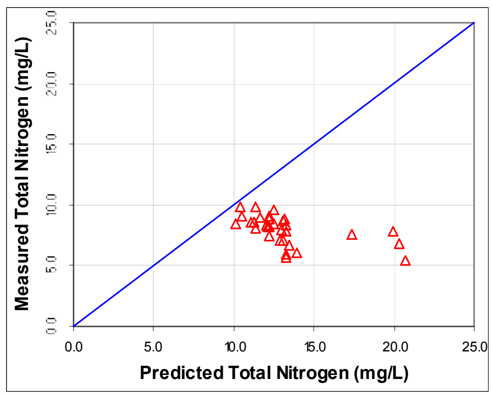

Figure E.26 Predicted Total N versus Measured Total N for Default Values

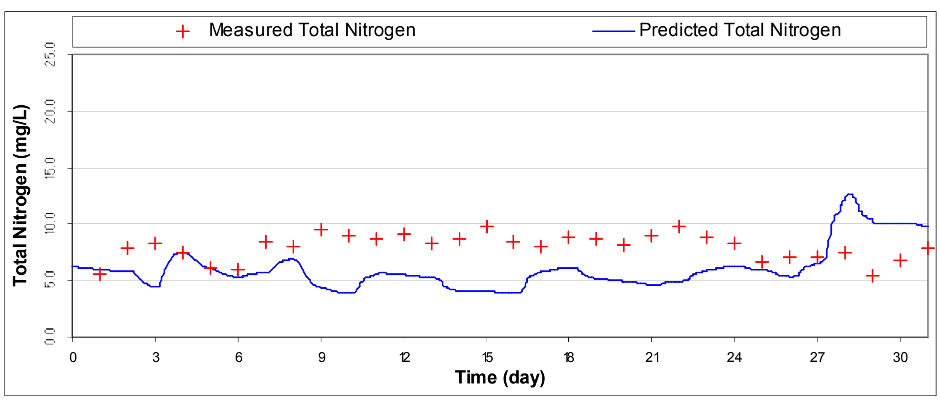

Figure E.27 Dynamic Run for Aerobic Tanks by Using Absolute Difference Results

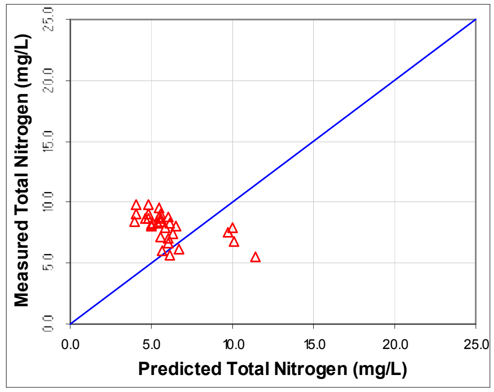

Figure E.28 Predicted Total N versus Measured Total N for Absolute Difference Results

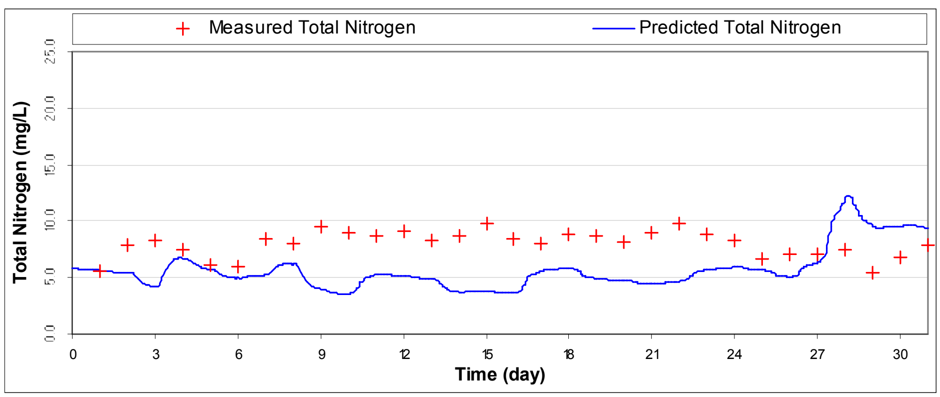

Figure E.29 Dynamic Run for Aerobic Tanks by Using Relative Difference Results

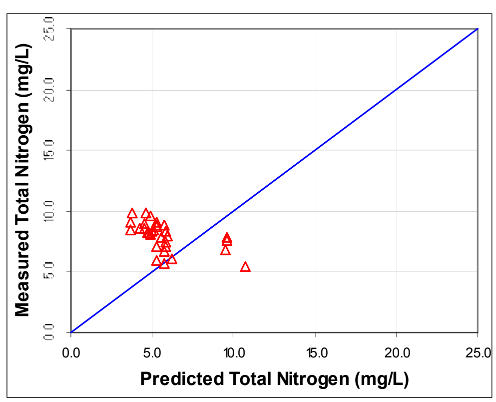

Figure E.30 Predicted Total N versus Measured Total N for Relative Difference Results

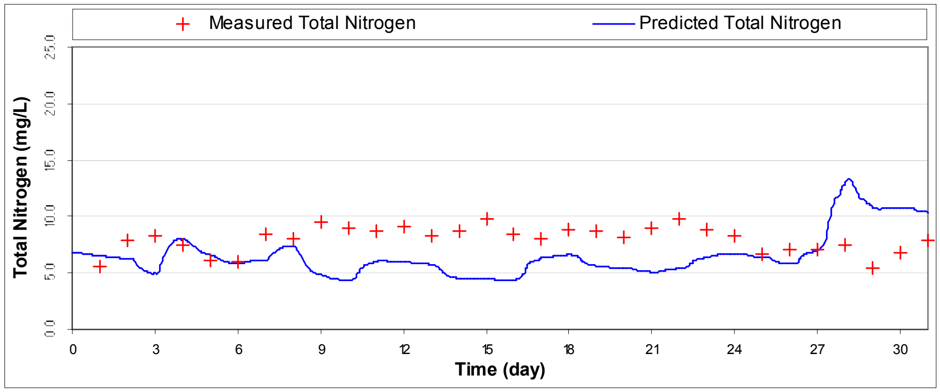

Figure E.31 Dynamic Run for Aerobic Tanks by Using Sum of Squares Results

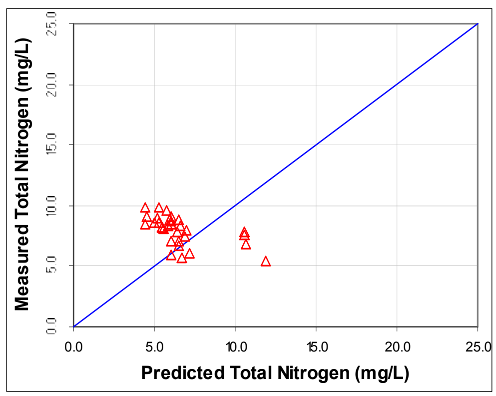

Figure E.32 Predicted Total N versus Measured Total N for Sum of Squares Results

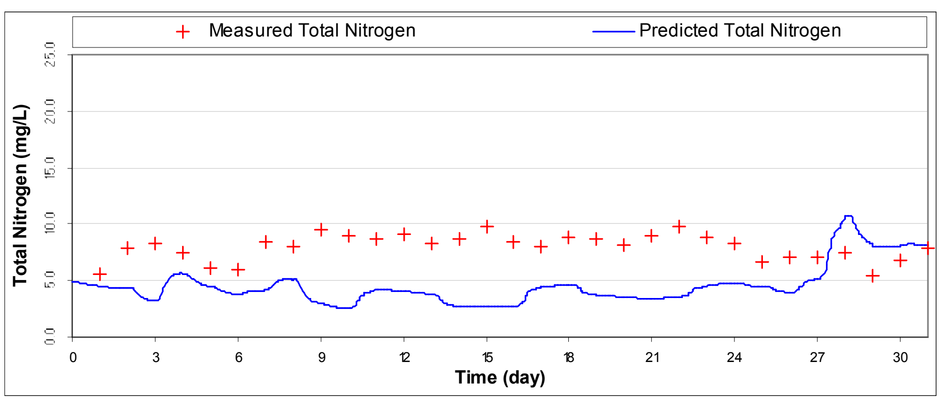

Figure E.33 Dynamic Run for Aerobic Tanks by Using Relative Sum of Squares Results

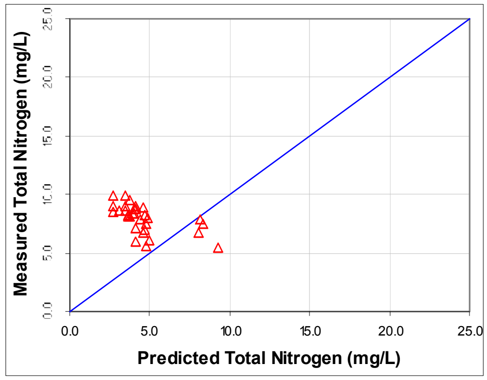

Figure E.34 Predicted Total N versus Measured Total N for Relative Sum of Squares Results

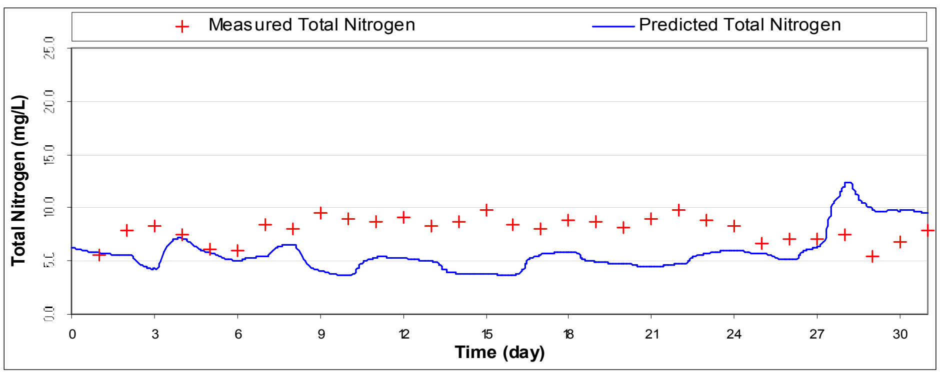

Figure E.35 Dynamic Run for Aeration Tanks by Using Maximum Likelihood Results

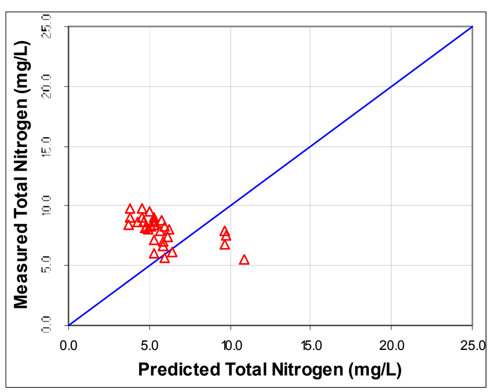

Figure E.36 Predicted Total N versus Measured Total N for Maximum Likelihood Results

APPENDIX F

Table F.1 Results of the Dynamic Runs for Total Phosphorus

Time (days)	Measured Total P (mg/L)	Before Calibration		After Calibration	
		Predicted Total P (mg/L)	x	Predicted Total P (mg/L)	x
1	1.99	8.97	4.51	8.03	4.04
2	1.65	8.99	5.45	8.08	4.89
3	1.78	9.13	5.13	8.24	4.63
4	1.88	8.94	4.76	7.97	4.24
5	1.62	8.82	5.44	7.89	4.87
6	1.56	9.34	5.99	8.41	5.39
7	2.54	9.51	3.74	8.59	3.38
8	2.86	9.09	3.18	8.09	2.83
9	2.44	8.83	3.62	7.84	3.21
10	1.89	9.29	4.91	8.32	4.40
11	1.93	9.54	4.95	8.66	4.49
12	2.08	9.56	4.59	8.68	4.17
13	1.87	9.37	5.01	8.40	4.49
14	1.83	9.24	5.05	8.29	4.53
15	2.10	9.42	4.49	8.49	4.04
16	2.09	9.53	4.56	8.63	4.13
17	2.00	9.65	4.83	8.79	4.40
18	1.87	9.70	5.19	8.82	4.71
19	1.94	9.66	4.98	8.79	4.53
20	1.99	9.72	4.89	8.88	4.46
21	1.85	9.73	5.26	8.88	4.80
22	1.89	9.69	5.13	8.85	4.68
23	1.96	9.67	4.93	8.81	4.50
24	1.98	9.57	4.83	8.70	4.39
25	1.95	9.51	4.87	8.63	4.42
26	1.98	9.14	4.62	8.28	4.18
27	1.96	8.53	4.35	7.71	3.93
28	1.93	8.04	4.17	7.15	3.71
29	2.17	7.78	3.59	6.78	3.12
30	1.80	7.80	4.33	6.87	3.81
31	1.51	7.77	5.14	6.79	4.50
Average	1.96	9.15	4.73	8.24	4.25
σ			0.60		0.56

x = Predicted Total P / Measured Total P, σ = standard deviation

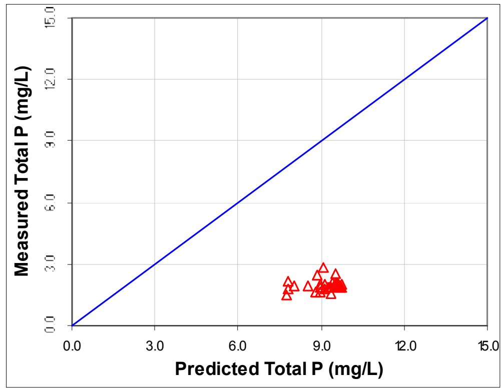

Figure F.1 Predicted versus Measured Total P Before Calibration

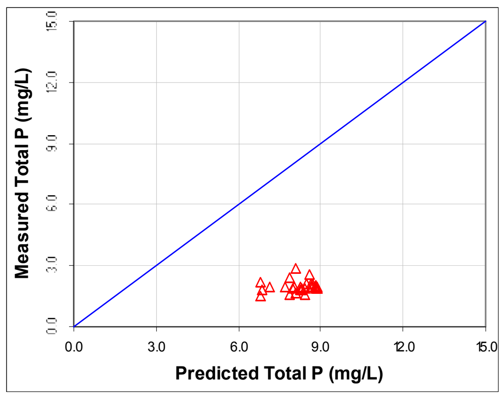

Figure F.2 Predicted versus Measured Total P After Calibration

APPENDIX G

Table G.1 Results of the Calibration

Time (days)	MLSS (Aeration)			TSS (Secondary Clarifier Underflow)			COD (Final Effluent)			TSS (Final Effluent)		
	Measured MLSS (g/L)	Predicted MLSS (g/L)	x	Measured TSS (g/L)	Predicted TSS (g/L)	x	Measured COD (mg/L)	Predicted COD (mg/L)	x	Measured TSS (mg/L)	Predicted TSS (mg/L)	x
1	4.88	5.61	1.15	8.86	11.00	1.24	21.80	29.80	1.37	10.00	10.30	1.03
2	5.30	5.61	1.06	10.18	11.40	1.12	26.00	29.42	1.13	11.00	10.11	0.92
3	5.15	5.66	1.10	10.32	10.30	1.00	29.40	29.10	0.99	13.00	10.38	0.80
4	5.49	5.61	1.02	11.63	13.29	1.14	25.00	30.65	1.23	11.00	13.09	1.19
5	5.17	5.77	1.12	11.33	11.31	1.00	26.00	28.92	1.11	17.00	10.35	0.61
6	5.15	5.76	1.12	10.94	11.35	1.04	24.00	29.47	1.23	14.00	10.10	0.72
7	5.65	5.78	1.02	11.92	11.49	0.96	27.00	29.83	1.10	12.00	11.01	0.92
8	6.41	5.84	0.91	12.25	11.70	0.96	24.50	30.81	1.26	20.00	12.76	0.64
9	6.40	5.95	0.93	12.56	11.32	0.90	23.40	30.12	1.29	20.00	10.97	0.55
10	6.10	5.97	0.98	11.72	11.70	1.00	27.70	30.08	1.09	12.00	10.71	0.89
11	5.69	5.98	1.05	11.76	11.41	0.97	21.00	29.06	1.38	13.00	10.43	0.80
12	6.14	5.97	0.97	12.35	12.06	0.98	26.00	29.44	1.13	12.00	11.23	0.94
13	6.11	6.05	0.99	11.85	11.75	0.99	25.00	30.22	1.21	14.00	11.30	0.81
14	5.49	6.07	1.11	11.93	12.11	1.02	24.00	29.95	1.25	10.00	10.57	1.06
15	6.21	6.07	0.98	12.94	11.91	0.92	26.00	29.72	1.14	17.00	10.35	0.61
16	6.23	6.06	0.97	11.35	11.74	1.03	20.00	29.42	1.47	12.00	10.04	0.84
17	5.72	6.04	1.06	11.40	11.70	1.03	24.00	29.50	1.23	14.00	10.10	0.72
18	5.80	6.02	1.04	11.52	11.60	1.01	21.70	29.84	1.38	15.00	9.99	0.67
19	6.20	5.97	0.96	12.49	11.53	0.92	24.70	29.70	1.20	10.00	9.97	1.00
20	5.89	5.94	1.01	11.40	11.51	1.01	24.58	29.14	1.19	16.00	10.00	0.62
21	6.44	5.95	0.92	12.31	11.65	0.95	25.00	28.88	1.16	7.00	10.10	1.44
22	6.06	5.98	0.99	6.85	11.71	1.71	24.30	28.88	1.19	14.00	10.20	0.73
23	5.01	5.96	1.19	9.20	11.50	1.25	23.50	28.97	1.23	17.00	9.99	0.59
24	5.75	5.87	1.02	10.62	11.37	1.07	24.50	29.40	1.20	13.00	10.29	0.79
25	5.93	5.79	0.98	11.25	11.20	0.99	25.00	29.12	1.16	9.00	10.11	1.12
26	6.01	5.68	0.95	11.95	10.98	0.92	45.40	28.30	0.62	6.00	9.91	1.65
27	5.73	5.60	0.98	11.26	10.86	0.96	40.70	27.83	0.68	12.00	9.93	0.83
28	5.78	5.58	0.97	11.26	10.80	0.96	51.20	29.35	0.57	15.00	9.78	0.65
29	5.97	5.55	0.93	10.42	10.72	1.03	42.90	31.43	0.73	6.00	9.66	1.61
30	5.96	5.51	0.92	11.33	10.71	0.95	23.50	30.53	1.30	9.00	9.22	1.02
31	5.43	5.45	1.00	10.09	10.50	1.04	26.80	31.16	1.16	15.00	9.84	0.66
Average	5.78	5.83	1.01	11.20	11.42	1.03	27.24	29.61	1.14	12.77	10.41	0.88
σ			0.07			0.15			0.22			0.28

Table G.1 Results of the Calibration (Continued)

Time (days)	Total N (Final Effluent)			NO_3-N (Final Effluent)			NH_4-N (Final Effluent)		
	Measured Total N (mg/L)	Predicted Total N (mg/L)	x	Measured NO_3-N (mg/L)	Predicted NO_3-N (mg/L)	x	Measured NH_4-N (mg/L)	Predicted NH_4-N (mg/L)	x
1	5.63	7.50	1.33	4.50	4.44	0.99	1.90	1.06	0.56
2	7.89	6.64	0.84	3.50	4.04	1.15	1.85	0.70	0.38
3	8.25	6.35	0.77	4.11	3.68	0.90	1.52	0.84	0.55
4	7.45	9.06	1.22	4.87	3.87	0.79	1.63	3.14	1.93
5	6.11	8.66	1.42	4.93	4.94	1.00	1.99	1.69	0.85
6	5.98	6.79	1.14	3.98	4.13	1.04	1.91	0.74	0.39
7	8.42	7.08	0.84	4.20	4.08	0.97	1.80	1.05	0.58
8	8.01	7.24	0.90	3.48	3.55	1.02	0.89	1.78	2.00
9	9.56	5.79	0.61	3.74	3.28	0.88	0.75	0.85	1.13
10	9.03	6.30	0.70	4.54	3.74	0.82	0.77	0.87	1.13
11	8.63	6.85	0.79	3.98	4.25	1.07	0.89	0.73	0.82
12	9.06	6.70	0.74	3.85	3.83	0.99	0.76	0.98	1.29
13	8.35	6.16	0.74	4.10	3.52	0.86	0.35	0.86	2.45
14	8.64	5.41	0.63	4.02	3.22	0.80	0.60	0.54	0.90
15	9.85	5.25	0.53	3.97	3.14	0.79	0.77	0.50	0.65
16	8.45	6.28	0.74	4.12	3.90	0.95	0.65	0.65	1.01
17	8.08	7.60	0.94	3.96	4.69	1.19	0.94	0.93	0.99
18	8.84	7.13	0.81	4.10	4.40	1.07	0.86	0.71	0.82
19	8.71	6.45	0.74	4.85	3.92	0.81	0.78	0.58	0.75
20	8.15	6.14	0.75	4.16	3.74	0.90	1.16	0.53	0.45
21	9.02	6.16	0.68	4.01	3.71	0.93	0.84	0.59	0.71
22	9.85	7.02	0.71	3.68	4.30	1.17	0.75	0.78	1.04
23	8.78	7.53	0.86	4.20	4.64	1.10	0.86	0.85	0.99
24	8.29	7.60	0.92	4.12	4.54	1.10	0.97	0.98	1.01
25	6.72	7.16	1.07	5.77	4.29	0.74	0.87	0.84	0.97
26	7.12	7.48	1.05	6.82	4.56	0.67	0.59	0.87	1.48
27	7.04	11.86	1.68	5.48	5.89	1.08	0.38	3.40	8.94
28	7.54	13.73	1.82	6.40	6.85	1.07	0.29	3.93	13.54
29	5.47	12.70	2.32	5.02	6.43	1.28	0.31	3.31	10.68
30	6.78	12.36	1.82	4.83	7.52	1.56	0.29	1.88	6.49
31	7.89	9.15	1.16	4.63	5.12	1.11	0.56	1.40	2.50
Average	8.00	7.68	1.01	4.45	4.39	0.99	0.95	1.24	2.19
σ			0.42			0.18			3.21

x = Predicted / Measured, σ = standard deviation

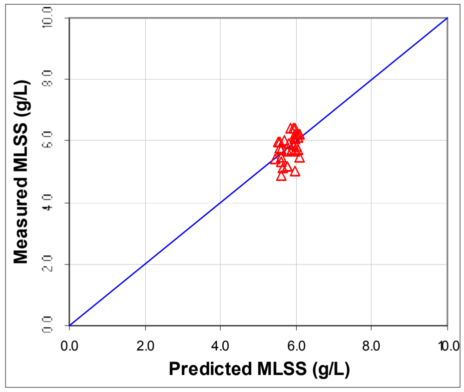

Figure G.1 Predicted versus Measured Effluent MLSS from Aeration Tanks

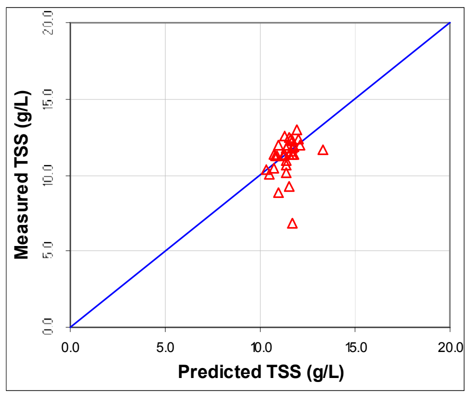

Figure G.2 Predicted versus Measured Underflow TSS from Secondary Clarifiers

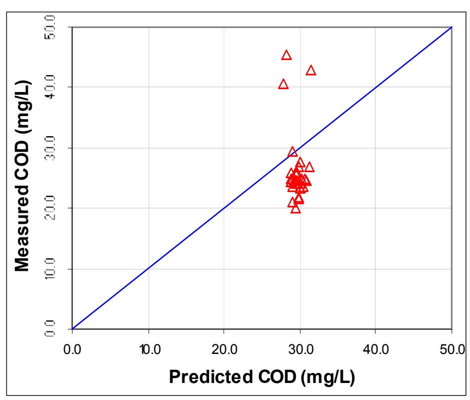

Figure G.3 Predicted versus Measured COD in the Final Effluent

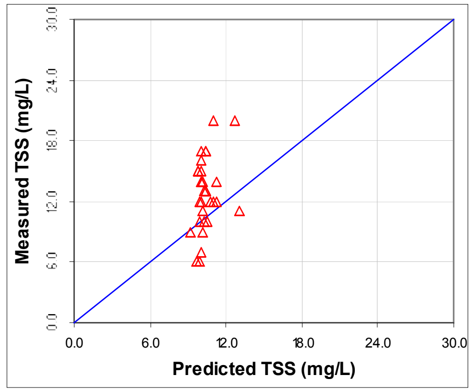

Figure G.4 Predicted versus Measured TSS in the Final Effluent

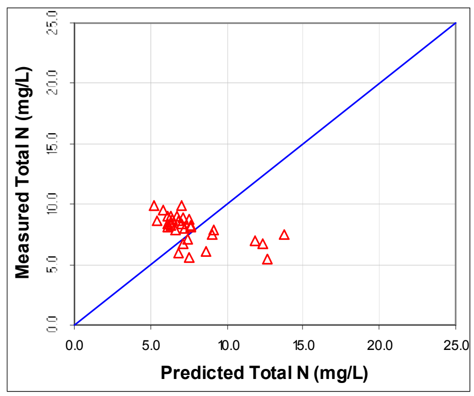

Figure G.5 Predicted versus Measured Total Nitrogen in the Final Effluent

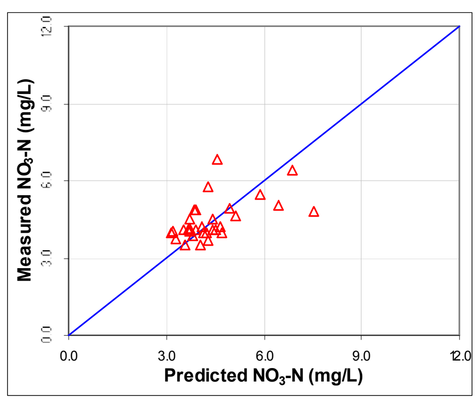

Figure G.6 Predicted versus Measured NO_3-N in the Final Effluent

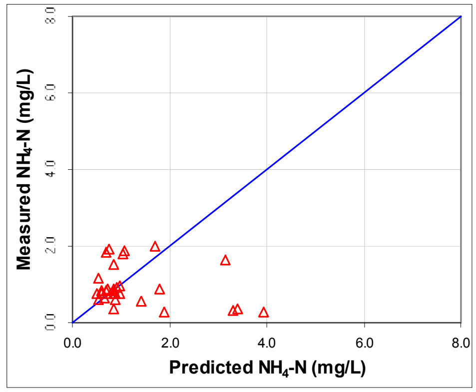

Figure G.7 Predicted versus Measured NH_4-N in the Final Effluent

APPENDIX H

Table H.1 Validation with May 2004 Data

Time (days)	TSS (Primary Clarifier Underflow)			MLSS (Aeration)			TSS (Secondary Clarifier Underflow)		
	Measured TSS (g/L)	Predicted TSS (g/L)	x	Measured MLSS (g/L)	Predicted MLSS (g/L)	x	Measured TSS (g/L)	Predicted TSS (g/L)	x
1	11.36	8.31	0.73	6.95	5.57	0.80	12.25	10.90	0.89
2	8.84	8.57	0.97	7.13	5.59	0.79	12.55	10.88	0.87
3	8.17	26.43	3.23	6.99	5.72	0.82	12.45	11.29	0.91
4	6.80	18.91	2.78	5.26	5.90	1.12	12.17	11.66	0.96
5	26.31	10.03	0.38	6.52	6.02	0.92	12.37	11.85	0.96
6	10.28	8.62	0.84	6.58	6.06	0.92	12.37	13.27	1.07
7	8.16	9.15	1.12	5.50	6.21	1.13	11.31	12.15	1.07
8	9.79	12.42	1.27	5.82	6.22	1.07	13.09	12.27	0.94
9	12.60	9.44	0.75	5.49	6.26	1.14	12.18	12.20	1.00
10	10.92	11.17	1.02	5.13	6.28	1.22	11.93	12.21	1.02
11	8.33	9.03	1.08	4.77	6.29	1.32	9.63	12.22	1.27
12	21.02	12.01	0.57	5.84	6.31	1.08	11.94	12.28	1.03
13	7.91	8.39	1.06	5.68	6.33	1.11	12.55	12.31	0.98
14	15.31	9.60	0.63	5.87	6.33	1.08	13.31	12.30	0.92
15	10.19	8.56	0.84	5.72	6.34	1.11	13.25	12.40	0.94
16	16.58	10.88	0.66	6.15	6.38	1.04	12.15	12.54	1.03
17	30.68	1.01	0.03	5.45	5.78	1.06	14.38	13.11	0.91
18	7.20	3.14	0.44	6.43	6.49	1.01	12.90	13.76	1.07
19	9.82	5.83	0.59	5.45	6.77	1.24	14.42	13.24	0.92
20	36.42	5.71	0.16	5.32	6.74	1.27	14.09	13.13	0.93
21	16.77	5.21	0.31	6.75	6.69	0.99	14.91	13.10	0.88
22	12.33	6.30	0.51	6.56	6.69	1.02	13.53	13.06	0.97
23	11.66	8.98	0.77	6.56	6.66	1.02	14.99	13.64	0.91
24	14.92	8.69	0.58	5.79	6.66	1.15	14.78	12.89	0.87
25	10.33	6.89	0.67	6.51	6.57	1.01	18.73	12.68	0.68
26	7.41	8.51	1.15	5.83	6.40	1.10	13.06	13.23	1.01
27	13.88	12.97	0.93	5.88	6.32	1.08	13.83	12.69	0.92
28	14.79	8.74	0.59	5.87	6.19	1.05	13.86	12.85	0.93
29	10.10	8.63	0.85	5.40	6.11	1.13	14.78	11.78	0.80
30	12.08	11.87	0.98	5.61	5.95	1.06	14.20	11.31	0.80
31	8.17	9.26	1.13	6.12	5.77	0.94	19.06	11.05	0.58
Average	13.20	9.46	0.89	5.97	6.24	1.06	13.45	12.39	0.94
σ			0.64			0.13			0.12

Table H.1 Validation with May 2004 Data (Continued)

Time (days)	COD (Final Effluent)			TSS (Final Effluent)			Total N (Final Effluent)		
	Measured COD (mg/L)	Predicted COD (mg/L)	x	Measured TSS (mg/L)	Predicted TSS (mg/L)	x	Measured Total N (mg/L)	Predicted Total N (mg/L)	x
1	22.00	29.70	1.35	10.00	10.20	1.02	2.70	6.98	2.58
2		29.81			10.20		2.65	6.69	2.52
3	48.00	33.98	0.71	11.00	9.76	0.89	5.50	5.43	0.99
4	41.00	39.19	0.96	16.00	9.73	0.61	4.89	4.95	1.01
5	21.00	37.31	1.78	17.00	10.25	0.60	6.27	5.03	0.80
6	38.00	35.42	0.93	15.00	12.67	0.84	5.76	5.25	0.91
7	40.00	32.01	0.80	6.00	10.33	1.72	3.20	5.67	1.77
8	20.00	32.27	1.61	9.00	10.10	1.12	3.73	5.47	1.47
9	25.00	32.74	1.31	8.00	10.27	1.28	2.91	5.81	1.99
10	14.00	32.26	2.30	10.00	10.20	1.02	1.61	7.00	4.35
11	24.00	31.97	1.33	12.00	9.90	0.82	1.63	6.81	4.18
12	25.00	32.26	1.29	20.00	10.25	0.51	2.38	4.96	2.08
13	50.00	32.19	0.64	8.00	10.14	1.27	2.41	4.65	1.93
14	29.00	30.99	1.07	12.00	9.95	0.83	3.80	6.37	1.68
15	39.00	30.74	0.79	12.00	9.92	0.83	3.90	9.55	2.45
16	23.00	31.21	1.36	13.00	10.23	0.79	3.58	13.92	3.89
17	17.00	42.85	2.52	5.00	18.27	3.65	2.73	11.28	4.13
18	20.00	36.37	1.82	11.00	13.28	1.21	3.63	4.83	1.33
19	25.00	29.25	1.17	10.00	11.25	1.12	3.98	6.86	1.72
20	32.00	27.70	0.87	7.00	10.76	1.54	3.44	10.74	3.12
21	20.00	27.98	1.40	5.00	12.69	2.54	4.15	9.18	2.21
22	22.00	26.65	1.21	5.00	11.07	2.21	6.36	6.41	1.01
23	19.00	27.50	1.45	10.00	10.52	1.05	6.28	6.21	0.99
24	18.00	28.81	1.60	13.00	10.27	0.79	5.50	6.63	1.20
25	21.00	28.56	1.36	20.00	10.03	0.50	4.55	10.03	2.20
26	33.00	28.70	0.87	14.00	10.36	0.74	8.80	10.82	1.23
27	18.00	30.54	1.70	7.00	10.16	1.45	7.10	8.01	1.13
28	26.00	32.03	1.23	11.00	10.95	1.00	7.50	12.28	1.64
29	30.00	30.49	1.02	9.00	10.04	1.12	7.99	15.34	1.92
30	32.00	30.72	0.96	10.00	9.48	0.95	8.10	12.75	1.57
31	25.00	31.25	1.25	11.00	9.40	0.85	7.89	9.57	1.21
Average	27.23	31.72	1.29	10.90	10.73	1.16	4.67	7.92	1.98
σ			0.44			0.65			1.02

Table H.1 Validation with May 2004 Data (Continued)

Time (days)	NO_3-N (Final Effluent)			NH_4-N (Final Effluent)			Total P (Final Effluent)		
	Measured NO_3-N (mg/L)	Predicted NO_3-N (mg/L)	x	Measured NH_4-N (mg/L)	Predicted NH_4-N (mg/L)	x	Measured Total P (mg/L)	Predicted Total P (mg/L)	x
1	1.53	3.55	2.32	0.50	1.43	2.86	1.51	8.04	5.32
2	1.99	3.42	1.72	1.05	1.31	1.25	1.95	7.93	4.07
3	1.09	2.46	2.26	1.00	1.30	1.30	1.90	7.67	4.04
4	1.98	2.47	1.25	0.32	1.05	3.28	2.10	7.50	3.57
5	3.58	2.67	0.75	1.52	0.88	0.58	2.20	7.99	3.63
6	3.27	2.20	0.67	1.27	1.58	1.25	2.00	7.96	3.98
7	3.02	3.05	1.01	0.33	1.10	3.33	2.10	7.97	3.80
8	3.28	2.96	0.90	0.33	0.89	2.69	2.06	8.38	4.07
9	2.01	3.12	1.55	0.40	1.01	2.53	2.08	8.58	4.12
10	1.96	3.79	1.93	0.23	1.29	5.59	2.30	9.10	3.96
11	1.57	3.85	2.45	0.24	0.94	3.90	2.42	9.69	4.00
12	2.38	2.53	1.06	0.90	0.62	0.68	2.36	10.42	4.41
13	1.50	2.45	1.63	0.30	0.62	2.06	2.20	10.45	4.75
14	1.86	3.62	1.94	0.27	0.91	3.37	2.26	10.08	4.46
15	2.02	5.11	2.53	0.31	2.11	6.81	2.38	9.74	4.09
16	0.82	6.60	8.05	0.63	4.20	6.67	2.18	9.95	4.56
17	1.63	1.95	1.20	0.54	6.77	12.54	2.40	8.42	3.51
18	2.79	1.74	0.62	0.20	1.54	7.69	2.40	5.96	2.48
19	2.99	3.38	1.13	0.71	1.65	2.33	2.68	7.25	2.71
20	2.50	6.04	2.42	1.68	2.13	1.27	2.18	9.08	4.16
21	2.68	4.66	1.74	0.37	1.84	4.96	1.40	9.04	6.45
22	3.73	3.46	0.93	0.45	0.68	1.51	2.34	8.43	3.60
23	3.69	3.43	0.93	0.50	0.63	1.26	2.34	8.69	3.71
24	2.60	3.81	1.46	0.29	0.66	2.27	2.30	8.80	3.83
25	3.14	5.73	1.82	0.31	1.70	5.47	2.29	9.44	4.12
26	1.85	6.34	3.43	0.44	1.56	3.55		10.27	
27	3.70	4.37	1.18	0.13	1.06	8.18	2.41	10.24	4.25
28	2.90	5.25	1.81	0.21	4.16	19.80	2.35	9.64	4.10
29	3.21	7.56	2.36	0.32	4.39	13.70	2.48	9.55	3.85
30	3.95	6.88	1.74	0.35	2.52	7.21	2.19	9.77	4.46
31	2.60	5.30	2.04	0.29	1.26	4.35	2.30	9.37	4.07
Average	2.51	3.99	1.83	0.53	1.73	4.65	2.20	8.88	4.07
σ			1.33			4.27			0.70

x = Predicted / Measured, σ = standard deviation

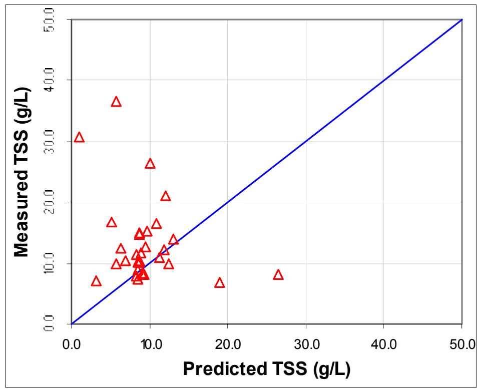

Figure H.1 Predicted versus Measured Underflow TSS from Primary Clarifiers

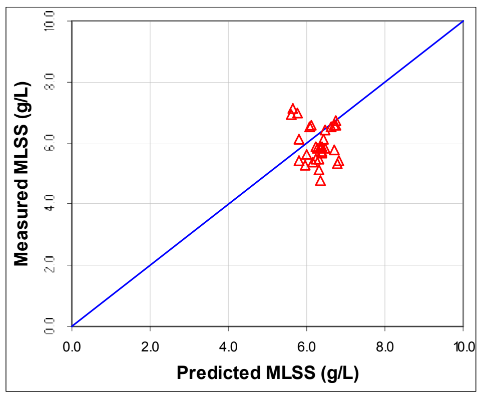

Figure H.2 Predicted versus Measured Effluent MLSS from Aeration Tanks

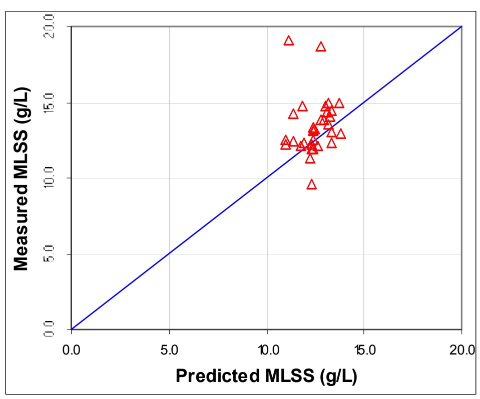

Figure H.3 Predicted versus Measured Underflow TSS from Secondary Clarifiers

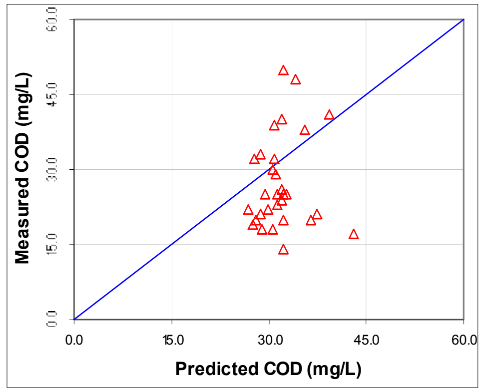

Figure H.4 Predicted versus Measured COD in the Final Effluent

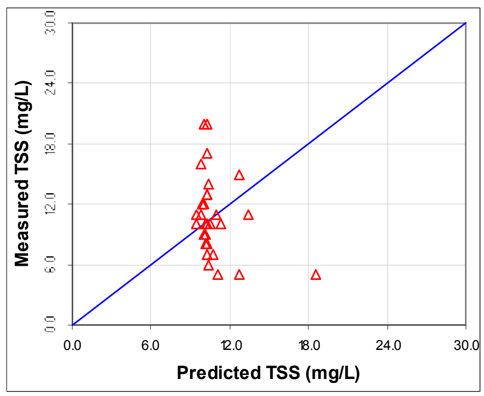

Figure H.5 Predicted versus Measured TSS in the Final Effluent

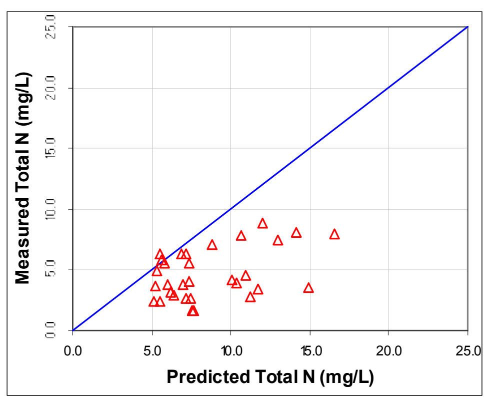

Figure H.6 Predicted versus Measured Total Nitrogen in the Final Effluent

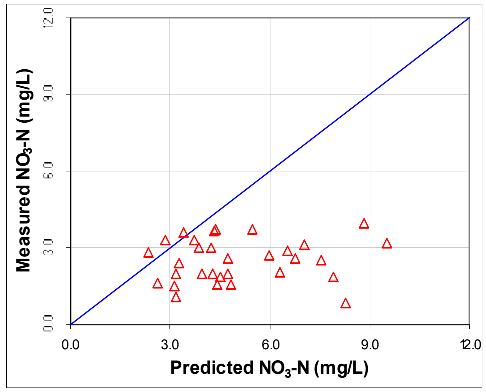

Figure H.7 Predicted versus Measured NO_3-N in the Final Effluent

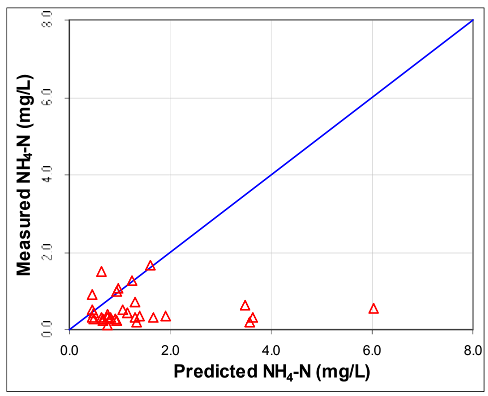

Figure H.8 Predicted versus Measured NH_4-N in the Final Effluent

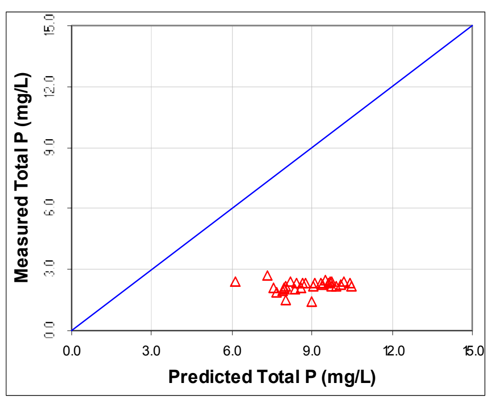

Figure H.9 Predicted versus Measured Total Phosphorus in the Final Effluent

APPENDIX I

Table I.1 Validation with July 2004 Data

Time (days)	TSS (Primary Clarifier Underflow)			MLSS (Aeration)			TSS (Secondary Clarifier Underflow)		
	Measured TSS (g/L)	Predicted TSS (g/L)	x	Measured MLSS (g/L)	Predicted MLSS (g/L)	x	Measured TSS (g/L)	Predicted TSS (g/L)	x
1	21.79	8.31	0.38	4.28	5.49	1.28	8.45	10.70	1.27
2	9.26	8.23	0.89	3.94	5.50	1.39	7.82	10.62	1.36
3	16.95	7.77	0.46	4.27	5.43	1.27	9.17	10.34	1.13
4	19.72	7.60	0.39	4.48	5.34	1.19	9.39	10.16	1.08
5	14.73	9.02	0.61	4.48	5.26	1.17	9.78	10.00	1.02
6	10.96	8.23	0.75	4.42	5.19	1.18	9.75	9.86	1.01
7	17.45	5.22	0.30	4.81	5.10	1.06	9.15	9.80	1.07
8	18.26	12.17	0.67	3.70	5.06	1.37	8.81	9.70	1.10
9	19.08	9.29	0.49	3.98	5.04	1.27	8.58	9.86	1.15
10	25.69	9.52	0.37	4.25	4.99	1.17	7.51	9.55	1.27
11	16.26	8.61	0.53	4.29	4.90	1.14	8.83	9.36	1.06
12	15.51	6.79	0.44	4.16	4.83	1.16	9.00	9.26	1.03
13	18.84	7.38	0.39	3.29	4.83	1.47	8.30	9.49	1.14
14	20.61	7.61	0.37	3.84	4.87	1.27	8.07	9.56	1.18
15	24.16	7.38	0.31	4.32	4.84	1.12	9.21	9.23	1.00
16	23.08	12.18	0.53	3.81	4.75	1.25	8.29	9.00	1.09
17	19.00	10.69	0.56	4.38	4.68	1.07	8.30	8.90	1.07
18	50.00	8.50	0.17	3.70	4.60	1.24	8.29	8.78	1.06
19	26.18	7.53	0.29	4.42	4.54	1.03	8.46	8.71	1.03
20	19.26	12.23	0.64	4.05	4.53	1.12	8.69	8.64	0.99
21	16.94	12.61	0.74	3.71	4.50	1.21	8.67	8.66	1.00
22	15.64	13.00	0.83	4.03	4.49	1.11	8.97	8.60	0.96
23	17.50	7.58	0.43	4.01	4.42	1.10	8.23	8.39	1.02
24	15.45	19.77	1.28	4.12	4.41	1.07	8.24	8.46	1.03
25	15.27	17.47	1.14	4.41	4.47	1.01	8.25	8.60	1.04
26	45.84	16.14	0.35	4.08	4.50	1.10	6.81	8.70	1.28
27	14.58	12.53	0.86	3.98	4.49	1.13	7.72	8.76	1.13
28	16.04	12.26	0.76	3.69	4.48	1.22	7.06	8.62	1.22
29	20.35	9.03	0.44	3.80	4.48	1.18	8.01	8.62	1.08
30	19.95	12.04	0.60	3.74	4.49	1.20	7.46	8.57	1.15
31	19.11	10.27	0.54	3.84	4.49	1.17	7.79	8.60	1.11
Average	20.11	10.22	0.56	4.07	4.81	1.18	8.42	9.23	1.10
σ			0.25			0.10			0.10

Table I.1 Validation with July 2004 Data (Continued)

Time (days)	COD (Final Effluent)			TSS (Final Effluent)			Total N (Final Effluent)		
	Measured COD (mg/L)	Predicted COD (mg/L)	x	Measured TSS (mg/L)	Predicted TSS (mg/L)	x	Measured Total N (mg/L)	Predicted Total N (mg/L)	x
1	23.40	29.60	1.26	13.00	10.20	0.78	0.27	7.11	26.32
2	23.10	28.73	1.24	7.00	9.00	1.29	0.32	5.98	18.69
3	21.40	28.29	1.32	4.00	8.72	2.18	2.44	5.72	2.35
4	20.10	27.92	1.39	9.00	8.69	0.97	3.20	5.87	1.84
5	23.20	27.99	1.21	6.00	8.56	1.43	4.92	6.90	1.40
6	32.00	28.05	0.88	8.00	8.19	1.02	10.50	8.70	0.83
7	22.60	27.17	1.20	7.00	8.57	1.22	4.17	12.59	3.02
8	17.00	27.36	1.61	6.00	8.52	1.42	4.80	12.03	2.51
9	25.70	29.42	1.14	2.00	8.55	4.27	5.75	6.12	1.07
10	22.00	29.17	1.33	16.00	8.34	0.52	3.00	7.96	2.65
11	30.00	29.18	0.97	9.00	8.37	0.93	2.72	10.03	3.69
12	30.00	28.27	0.94	6.00	8.29	1.38	3.46	10.06	2.91
13	26.00	27.10	1.04	7.00	7.94	1.13	3.73	8.04	2.16
14	26.00	27.18	1.05	8.00	8.24	1.03	3.29	6.57	2.00
15	29.00	27.08	0.93	9.00	8.23	0.91	2.73	6.29	2.30
16	25.00	28.19	1.13	17.00	8.14	0.48	2.25	5.58	2.48
17	32.00	30.05	0.94	10.00	8.19	0.82	3.70	5.62	1.52
18	36.00	29.96	0.83	8.00	8.46	1.06	2.48	11.18	4.51
19	24.00	28.96	1.21	13.00	8.55	0.66	2.20	14.62	6.64
20	21.50	28.56	1.33	8.00	7.55	0.94	7.00	11.53	1.65
21	38.00	30.48	0.80	7.00	7.78	1.11	5.40	11.06	2.05
22	20.00	31.72	1.59	5.00	7.91	1.58	4.20	11.53	2.75
23	39.00	30.97	0.79	4.00	7.85	1.96	6.80	12.07	1.78
24	33.00	31.86	0.97	8.00	7.89	0.99	5.10	13.18	2.58
25	25.00	35.45	1.42	9.00	8.10	0.90	5.01	13.17	2.63
26	27.00	36.13	1.34	11.00	7.90	0.72	7.40	12.72	1.72
27	33.00	35.48	1.08	12.00	7.70	0.64	7.38	10.41	1.41
28	34.00	34.41	1.01	18.00	7.91	0.44	7.80	7.76	1.00
29	35.00	33.00	0.94	9.00	8.07	0.90	4.93	6.77	1.37
30	38.00	32.03	0.84	12.00	8.08	0.67	7.50	5.57	0.74
31	36.00	32.01	0.89	11.00	8.11	0.74	4.33	5.41	1.25
Average	28.00	30.05	1.12	9.00	8.28	1.13	4.48	8.97	3.54
σ			0.23			0.71			5.29

Table I.1 Validation with July 2004 Data (Continued)

Time (days)	NO_3-N (Final Effluent)			NH_4-N (Final Effluent)			Total P (Final Effluent)		
	Measured NO_3-N (mg/L)	Predicted NO_3-N (mg/L)	x	Measured NH_4-N (mg/L)	Predicted NH_4-N (mg/L)	x	Measured Total P (mg/L)	Predicted Total P (mg/L)	x
1	1.11	2.95	2.66	0.92	2.18	2.37	1.78	7.99	4.49
2	1.54	2.86	1.85	0.82	1.24	1.51	1.92	8.77	4.57
3	0.75	2.81	3.75	0.21	1.02	4.88	1.99	9.96	5.00
4	1.82	2.94	1.62	0.44	1.00	2.28	1.91	10.20	5.34
5	3.57	3.19	0.89	0.22	1.70	7.71	4.95	10.29	2.08
6	3.03	4.42	1.46	1.06	1.98	1.87	4.60	10.52	2.29
7	1.89	5.38	2.85	0.58	4.33	7.46	4.61	10.75	2.33
8	2.71	5.10	1.88	0.69	3.88	5.63	3.30	10.77	3.26
9	2.25	2.67	1.19	0.22	1.15	5.24	3.23	10.10	3.13
10	1.18	3.63	3.07	0.42	2.03	4.82	2.99	9.63	3.22
11	1.10	4.43	4.03	0.59	3.06	5.18	1.33	9.56	7.19
12	1.01	4.72	4.67	0.47	2.68	5.69	1.58	9.76	6.17
13	2.10	4.12	1.96	0.25	1.39	5.57	1.60	10.17	6.36
14	1.37	3.21	2.34	7.60	1.06	0.14	1.95	10.40	5.33
15	1.05	3.08	2.93	0.20	1.08	5.40	1.06	10.02	9.46
16	1.30	2.51	1.93	0.15	1.20	7.97	0.80	9.46	11.83
17	1.27	2.43	1.91	0.12	1.51	12.61	0.48	9.04	18.82
18	1.18	3.45	2.93	0.30	5.49	18.30	1.48	8.79	5.94
19	1.10	4.57	4.15	0.30	7.21	24.02	0.80	8.73	10.91
20	4.96	4.73	0.95	0.90	4.02	4.46	2.30	8.74	3.80
21	2.00	4.21	2.10	0.40	4.09	10.23	2.10	9.04	4.30
22	1.00	4.16	4.16	0.80	4.58	5.73	1.20	9.63	8.02
23	3.98	4.70	1.18		4.49		2.20	9.91	4.51
24	2.70	4.20	1.56	0.10	5.97	59.67	1.78	9.68	5.44
25	2.20	3.77	1.72	0.20	6.49	32.45	1.82	9.23	5.07
26	3.00	4.16	1.39	0.03	5.68	189.40	2.60	9.23	3.55
27	5.75	4.28	0.74	0.17	3.42	20.14	2.31	9.46	4.09
28	5.70	3.38	0.59	0.12	2.00	16.63	2.98	9.81	3.29
29	3.34	3.01	0.90	0.26	1.60	6.14	3.11	10.00	3.21
30	4.40	2.42	0.55	0.10	1.26	12.65	3.30	9.89	3.00
31	3.34	2.31	0.69	0.23	1.42	6.17	3.44	9.49	2.76
Average	2.38	3.67	2.08	0.63	2.91	16.41	2.31	9.65	5.44
σ			1.17			34.73			3.46

x = Predicted / Measured, σ = standard deviation

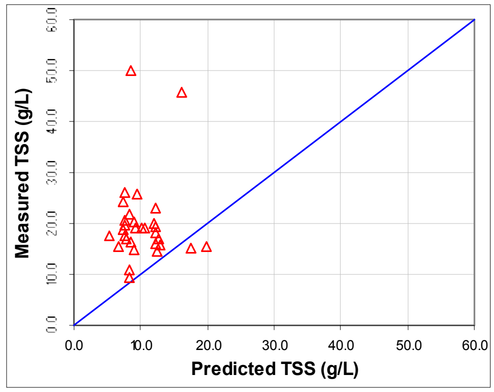

Figure I.1 Predicted versus Measured Underflow TSS from Primary Clarifiers

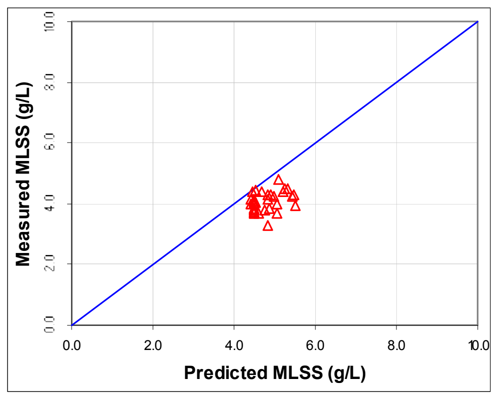

Figure I.2 Predicted versus Measured Effluent MLSS from Aeration Tanks

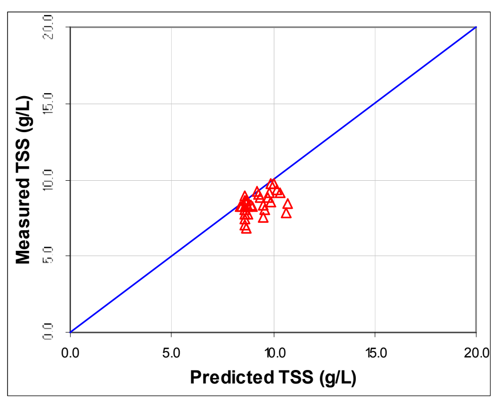

Figure I.3 Predicted versus Measured Underflow TSS from Secondary Clarifiers

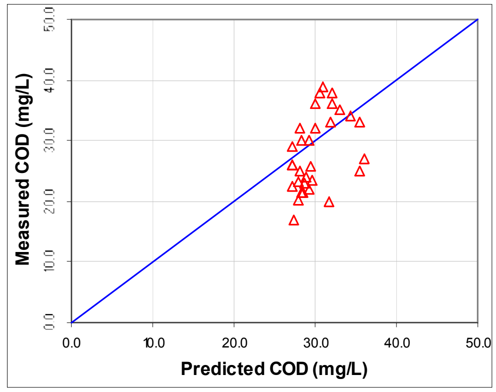

Figure I.4 Predicted versus Measured COD in the Final Effluent

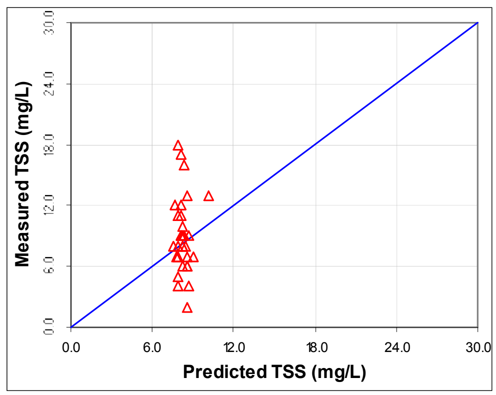

Figure I.5 Predicted versus Measured TSS in the Final Effluent

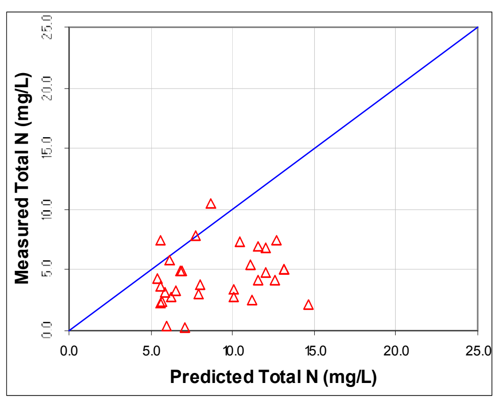

Figure I.6 Predicted versus Measured Total Nitrogen in the Final Effluent

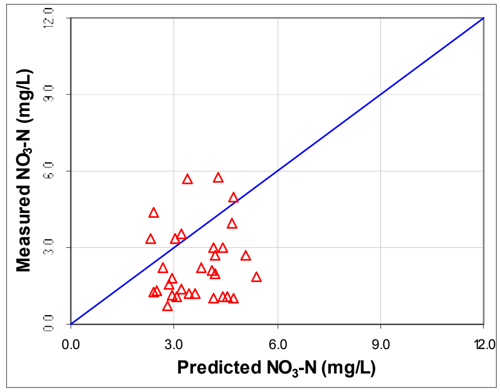

Figure I.7 Predicted versus Measured NO_3-N in the Final Effluent

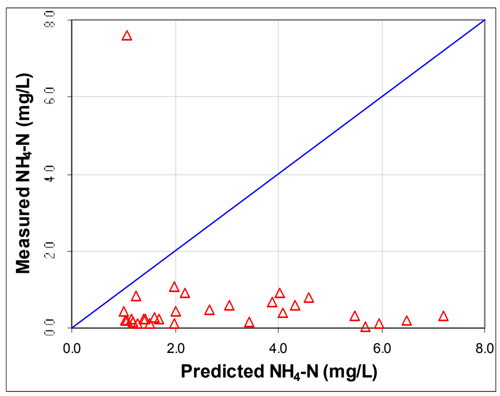

Figure I.8 Predicted versus Measured NH_4-N in the Final Effluent

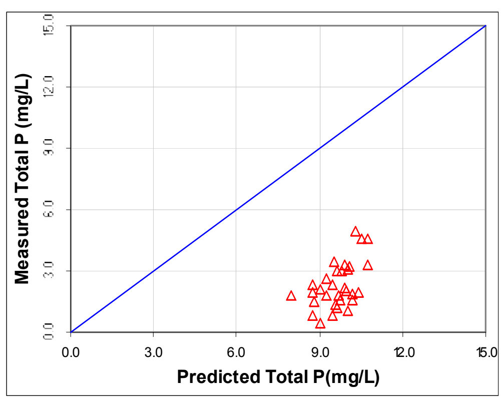

Figure I.9 Predicted versus Measured Total Phosphorus in the Final Effluent