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Dynamic Modeling of an Advanced Wastewater Treatment Plant

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by

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DEDICATION

I would like to dedicate this thesis to the memory of my uncle, Mr. Lokesh Singh Rathore [October 13^{th}, 1973 – October 9^{th}, 2015], who always believed in me and showed me the right path to fulfill my dreams. I hope I have made him proud.

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ABSTRACT

Advanced wastewater treatment plants have complex biological kinetics, time variant influent rates and long processing times. The modeling and operation control of wastewater treatment plant gets complicated due to these characteristics. However, a robust operational system for a wastewater treatment plant is necessary to increase the efficiency of the plant, reduce energy cost and achieve environmental discharge limits. These discharge limits are set by the National Pollutant Discharge Elimination System (NPDES) for municipal and industrial wastewater treatment plants to limit the amount of nutrients being discharged into the aquatic systems.

This document summarizes the research to develop a supervisory operational and control system for the Valrico Advanced Wastewater Treatment Plant (AWWTP) in the Hillsborough County, Florida. The Valrico AWWTP uses biological treatment process and has four oxidation ditches with extended aeration where simultaneous nitrification and denitrification (SND) takes place. Each oxidation ditch has its own anaerobic basin where in the absence of oxygen, the growth of microorganisms is controlled and which in return also helps in biological phosphorus removal. The principle objective of this research was to develop a working model for the Valrico AWWTP using BioWin which mimics the current performance of the plant, predicts the future effluent behavior and allows the operators to take control actions based on the effluent results to maintain the discharge permit limits. Influent and experimental data from online and offline sources were used to tune the BioWin model for the Valrico Plant.

The validation and optimization of the BioWin model with plant data was done by running a series of simulations and carrying out sensitivity analysis on the model which also allowed the

development of operation policies and control strategies. The control strategies were developed for the key variables such as aeration requirements in the oxidation ditch, recycle rates and wastage flow rates. A controller that manipulates the wasting flow rate based on the amount of mixed liquor suspended solids (MLSS) was incorporated in the model. The objective of this controller was to retain about 4500-4600 mg/L of MLSS in the oxidation ditch as it is maintained by the Valrico Plant. The Valrico AWWTP recycles around 80% of their effluent and hence, the split ratios were adjusted accordingly in the model to recycle the desired amount. The effluent concentrations from the BioWin model for the parameters such as Total Nitrogen (TN), Ammonia, Nitrate, Nitrite, Total Kjeldahl Nitrogen (TKN) complied with the discharge limits which is usually less than 2 mg/L for all the parameters.

CHAPTER 1: INTRODUCTION

Over the last century, major part of the world has been facing degradation of environment because of the continuous growth in population. With the growing population, there is a striking increase in usage and wastage of water for domestic purposes. Domestic wastewater is usually the water discharged from household purposes such as toilets, dishwashers, showers, sinks, washing machines etc. These types of discharges are usually rich in inorganic pollutants and can increase load on the environment in terms of Total Suspended Solids (TSS), Chemical Oxygen Demand (COD) or Biological Oxygen Demand (BOD). Hence, in an effort to minimize the pollution caused by the discharge of wastewater in other water bodies, a system called the National Pollutant Discharge Elimination System (NPDES) was established to set some strict permit limits and monitor the discharge from the wastewater treatment plants.

The wastewater treatment process can be broken into two major sections: primary treatment and secondary treatment. The first stage is the removal of rock solids and suspended solids physically by using screens. The second stage is biological treatment where microorganisms consume organic matter and convert it into inorganic compounds. According to the United States Environmental Protection Agency (EPA), most of the organic matter is removed from wastewater during biological treatment. The two major goals of wastewater treatment are nitrogen and phosphorus removal. These two processes can be carried out biologically in an economically feasible and environmentally friendly manner. In recent years, Simultaneous Nitrification and Denitrification (SND) has taken over the conventional methods for nitrogen removal because of its efficiency in operation and cost effectiveness. In case of phosphorus, sometimes biological methods are not efficient because of lack of carbon. This is because there are only limited easily biodegradable organic matter which leads to a competition between phosphorus removal and denitrification for the carbon source. Hence, to make up for the lack of carbon, some additional organic matter is added to the biological reactors which increases the cost of operation and results in generation of one more pollutant. However, there is an alternative for this problem which is the use of enhanced biological phosphorus removal which works efficiently for domestic waters with low C/N ratio [1].

Nowadays, with the increment in number of wastewater treatment plants, it has become challenging to manage the wastewater systems. Therefore, to ensure proper discharge from the wastewater treatment plants, new and stricter regulations for nutrient removal have being incorporated. To comply with these limits, there is a need for modeling and operation control of wastewater treatment plants. However, the modeling of wastewater treatment systems tends to become intricate due to certain characteristics such as unusually long residence times, plenty of tunable kinetic parameters and large variations in influent component flow rates.

Nevertheless, with the advancements in technology, activated sludge modeling, flowsheet simulators and computational fluid dynamics have emerged as some significant tools for modeling wastewater treatment plants. Over the years, dynamic modeling has come across as a remarkable approach for developing operational models in process design and management. Moreover, these models help in establishing operating policies and control strategies for the wastewater treatment plants which in turn maximizes the plant performance and comply with the required permit limits.

BioWin, a flowsheet simulator software by EnviroSim Associates Ltd., Canada is used for modeling wastewater treatment plants. The software can model the plant operations, controls, and activated sludge kinetics. BioWin has a set of kinetic and stoichiometric parameters which can be tuned with based on the data obtained from online sources such as SCADA data. The BioWin software package comes with a controller called the BW Controller which allows the user to develop control strategies based on the requirement of the treatment plant. Usually, there are three main types of control schemes used in activated sludge processes: 1) Dissolved Oxygen (DO) and Aeration, 2) Return Activated Sludge (RAS) and 3) Waste Activated Sludge (WAS). The amount of dissolved oxygen supplied to the oxidation ditch plays a key role in operating the oxygen ditch efficiently. On the other hand, it is of immense importance to manage the amount of sludge that is being recycled and wasted to make sure that the right amount of activated sludge is sent back to the head of the plant.

The several chapters of this thesis go over the basic operations and dynamic modeling of the wastewater treatment systems. In Chapter 2, the microbiology and ecology of the wastewater system with general kinetics and characterization is discussed.

In Chapter 3, several types of conversion processes occurring in a wastewater system are discussed.

In Chapter 4, the wastewater treatment process is described with some information about the diverse types of control strategies being used in the wastewater systems.

In Chapter 5, diverse ways to model the wastewater systems have been discussed. This includes the use of various simulation software and several types of activated sludge modeling is also described.

Chapter 6 covers the development of the BioWin model and the comparison of simulation results with the data collected from the treatment plant.

Chapter 7 provides a conclusion and some discussion about the future work related to this project.

CHAPTER 2: MICROBIOLOGY OF WASTEWATER TREATMENT

Biological wastewater treatment plants are based on natural processes occurring in a water body. These natural processes include the decomposition of the organic matter with the help of existing microorganisms in the wastewater. Since, wastewater treatment systems are complicated with several types of reactions such nitrification, denitrification, etc. taking place, it has become utterly important to utilize the enormous amount of existing technology to optimize and design such complex systems. The main goal of introducing this technology is to have the purification process operated at higher rates and under restrained conditions [2].

Most of the wastewater treatment plants are designed in an engineering fashion but these plants also depend on organisms like bacteria, algae, fungi and protozoa to break down organic substances. On the other hand, the efficiency of a biological wastewater treatment plant can be determined by the activity of the microorganisms occurring in the water body [3]. Therefore, it is important to understand the microbiology and ecology of the wastewater treatment.

In biological wastewater treatment plants, autotrophs and heterotrophs are naturally occurring and can be influenced by various operating conditions of the system, location of the plant and typical wastewater characteristics [3] [4]. Heterotrophs depend on absorption of carbon to sustain their life and are responsible for degradation of readily biodegradable COD (rbCOD) under aerobic, anoxic or aerobic conditions. On the other hand, autotrophic organisms depend on either light or inorganic substances for sustaining their life and are responsible for oxidation of ammonia to nitrate or nitrite (nitrification) [5]. WWTP's with nitrification by autotrophs are comparatively more expensive than aerobic heterotrophs because autotrophic nitrifiers have slow growth rate and lower oxygen utilization kinetics [5].

2.1 Ecology

Microorganisms play an essential role in wastewater treatment plants depending on the process being used. To biodegrade a wider range of substrates, they are arranged in species-rich structure rather than pure cultures. Two main types of microorganisms involved in aerobic treatment are bacteria and protozoa. Fungi, rotifers and other organisms are comparatively less important [2].

Bacteria and protozoa are the two main groups for the conversion of organic substances. Bacteria are unicellular prokaryotic microorganisms which have rigid cell wall. Autotrophic bacteria are more sensitive than heterotrophic bacteria. Also, there are limited ranges of temperature and pH for optimal growth rate of bacteria [2]. Organic matter can be separated as a) easily biodegradable and b) slowly biodegradable. Mostly, easily biodegradable matter is available in typical domestic sewage.

Protozoa are unicellular eukaryotic microorganisms without a cell wall. The main function of protozoa in wastewater treatment is decomposition of organic and inorganic nutrients. In wastewater treatment plants with high sludge retention time and low load, several types of protozoa such as flagellates, amoebas and ciliates are present [6]. Other than removal of organic matter, protozoa clarifies the effluent in terms of suspended solids. Some researchers could determine that the absence of protozoa in mixed liquor resulted in an increase of organic carbon, Biological oxygen Demand (BOD) of the effluent, and mixed liquor suspended solids (MLSS) [7].

The two basic configurations for biomass growth are a) Dispersed growth and b) Attached growth. Dispersed growth has no supporting structure for the biomass and grows in liquid medium in a dispersed form [2]. It is usually used in systems such as stabilization ponds, activated sludge, and up-flow anaerobic sludge blanket reactors. In attached growth, biomass is aggregated in the form of biofilms. These biofilms allow the biomass to attach to the reactor and doesn't let it wash out when the flow rate is high [8]. In [9] a study was performed comparing biofilms with dispersed growth resulting in a list of several advantages over dispersed growth such as different biological particles of numerous sizes, shapes etc. and ability to modify growth rates, operating in continuous reactors.

2.2 Reaction Kinetics

In any biological wastewater treatment plant, the knowledge of the type of reactor being used, the knowledge of the components going in and out (mass balance) and reaction kinetics are of foremost importance. The reactions taking place in wastewater treatment plants are mostly slow and hence it is important to consider the reaction kinetics. One of the most common expressions used for relating substrate concentration and specific growth rate in any biological wastewater treatment plant was proposed by Monod. The expression is given as:

$$\frac{dS}{dt} = r_{max}\frac{S}{K_s + S} \tag{2.1}$$

where:

$\frac{ds}{dt} = reaction\ rate$

$r_{max} = maximum\ reaction\ rate$

$S = substrate\ concentration$

$K_S = half\ saturation\ coefficient$

This equation can be expressed in both zero order and first order kinetics. For zero order kinetics ds/dt = r_{max} where the rate of reaction becomes constant and is not dependent on the concentration of the substrate anymore. In first order kinetics, the substrate conversation is directly proportional to the reaction rate which starts from a very low concentration and reaches the concentration where reaction rate is maximum.

2.3 Wastewater Characterization

In wastewater treatment plants, several conversion processes such as oxidation of organic matter under aerobic and anaerobic conditions result in formation of various products such as CO_2, CH_4, N_2, etc. Hence, it is important to describe the interaction of biomass with these nitrogenous and carbonaceous matter.

2.3.1 Organic Matter

For more than 20 years, Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) have been used to characterize wastewater. In activated sludge systems, usually COD is preferred as it is measured easily and quickly as compared to BOD which is a long and cumbersome process [10]. The several COD components can be represented as shown in figure 2-1.

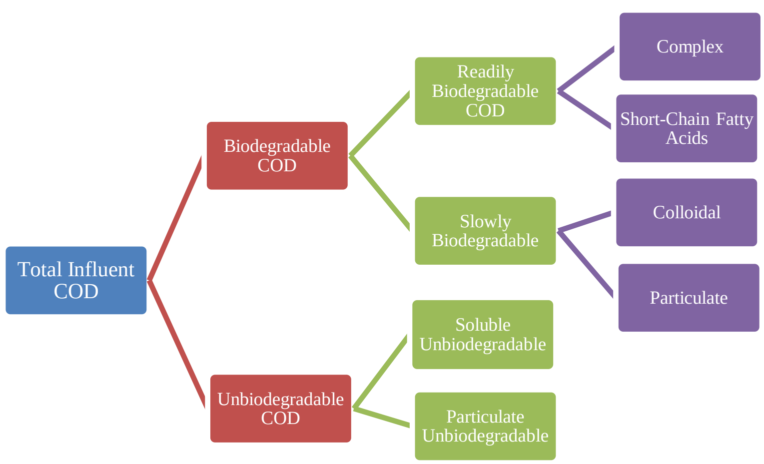

Figure 2-1 Characterization of Organic Matter

2.3.2 Biomass

Biomass is usually represented in terms of suspended solids as these are solids that settle in the reactor. These solids are categorized further as not all the solids take part in the conversion processes. Therefore, the most frequently used terms for biomass are volatile suspended solids (VSS) and total suspended solids (TSS). A more detailed characterization is shown in figure 2-2.

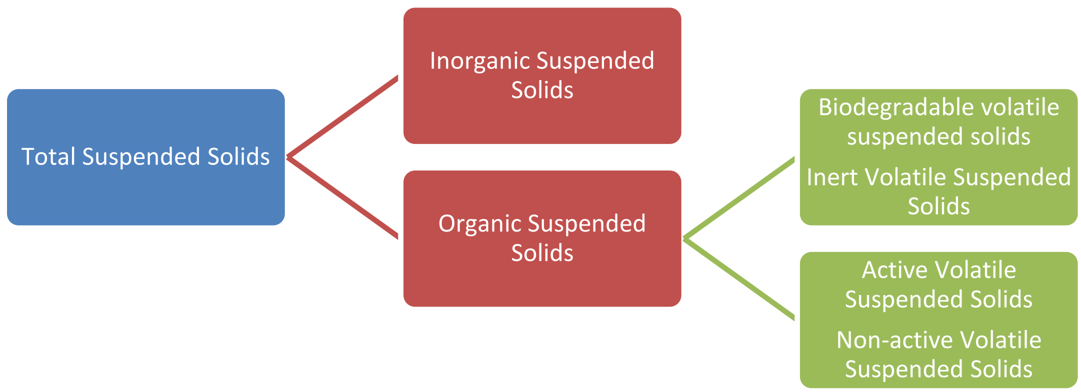

Figure 2-2 Characterization of Biomass

2.3.3 Nitrogenous Matter

Nitrogen containing compounds are important to characterize in wastewater systems as nitrogen directly relates to the pollution caused by sewage. The nitrogen detected in wastewater is in the form organic nitrogen if the pollution is caused recently. Although, if the pollution is not recent, the nitrogen is present in the form of nitrate which attributes for problems such as eutrophication of rivers and other harmful situations in water [11]. Hence, under different conditions, various forms of nitrogen are relatively distributed. Organic nitrogen and ammonia combine to give Total Kjeldahl Nitrogen (TKN) and the characterization is shown in figure 2-3.

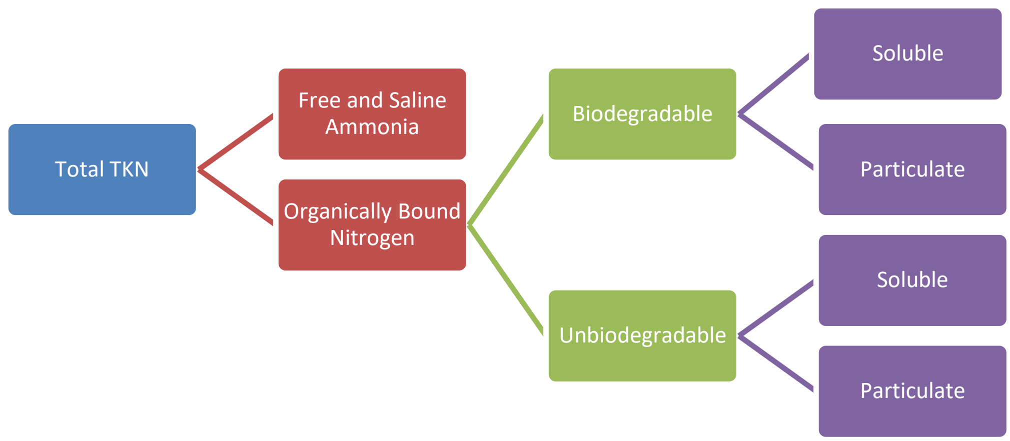

Figure 2-3 Characterization of Nitrogenous Matter

2.3.4 Phosphorus Content

Phosphorus is essential for the growth of microorganisms but the overuse of fertilizers these days is causing many consequences [12]. Also, phosphorus being a non-renewable resource which might exhaust in next 50-100 years, it is of immense importance to recover phosphorus and limit its pollution [12]. Polyphosphates and orthophosphates are inorganic forms of phosphates and the other forms are characterized as shown in figure 2-4.

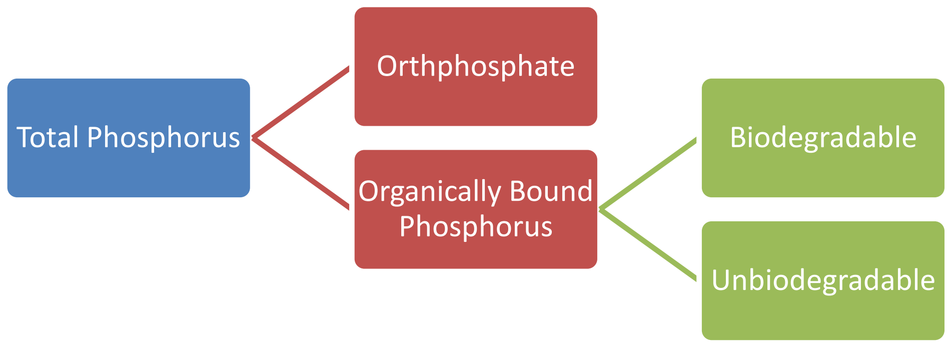

Figure 2-4 Characterization of Phosphorus Content

CHAPTER 3: BIOLOGICAL REACTIONS IN WASTEWATER TREATMENT

The biological nutrient removal technology has been widely used in the wastewater treatment systems over the last 20 years. The use of well-defined aerated and non-aerated zones helps in achieving nutrient removal of varying degrees. Nutrient removal has been noticed in treatment facilities where the anaerobic and anoxic zones are not designed explicitly. Nevertheless, several biological reactions such as nitrification, denitrification, simultaneous nitrification and denitrification, biological phosphorus removal etc. take place in wastewater treatment systems and the kinetics related to these reactions are significantly useful in developing the dynamic models for the wastewater treatment systems.

3.1 Conversion of Carbonaceous Matter

Usually in biological treatment systems, an anaerobic treatment is done before aerobic treatment. Some authors evaluated the cost effectiveness of anaerobic processes with aerobic processes and found out that capital costs for the anaerobic systems were less sensitive to the increase in wastewater strength as compared to aerobic systems. They also stated that, operating and maintenance costs for the aerobic systems were much higher because of the constant use of aeration which is not applicable in case of anaerobic systems [13].

3.1.1 Aerobic Conversion

In aerobic conversion, free dissolved oxygen acts as an electron acceptor. Heterotrophic bacteria are the main organisms responsible for the aerobic conversion of the carbonaceous matter [13]. To obtain high degree of efficiency in wastewater treatment plants mostly aerobic processes are used as the removal of organic matter is higher and the biomass produced is well flocculated which results in a lower concentration of suspended solids in effluent. They are more suitable for treating wastewater with low strength (COD < 1000 mg/L) and are most effective when operated in a pH range of 6.5 to 8.5 [14]. The common equation for aerobic conversion can be written as:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Energy \tag{3.1}$$

The more general form of this equation can be written as:

$$C_xH_yO_z + \frac{1}{4}(4x + y - 2z)O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O \tag{3.2}$$

This equation allows us to calculate the oxygen required and carbon dioxide produced [2].

3.1.2 Anaerobic Conversion

In anaerobic conversion, organic matter is converted in to methane (CH_4), carbon dioxide (CO_2) and water (H_2O) in the absence of oxygen via three processes which are hydrolysis, acidogenesis with acetogenesis and methanogenesis. Anaerobic conversion is not as efficient as aerobic conversion but its progressing using the concept of resource recovery and utilization and working towards achieving pollution control [15]. Anaerobic conversion is used for treatment of wastewater with high strength (COD > 4000 mg/L. When treating wastewater with high strength, anaerobic process is more efficient than aerobic as it requires less energy with potential bioenergy and nutrient recovery, but it is impossible to completely stabilize the organic matter and hence a series of aerobic treatments are required after to meet the effluent discharge limits [14]. The common equation for anaerobic conversion is given as:

$$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2 + Energy \tag{3.3}$$

This equation can be simplified and written in a more general fashion as follows:

$$C_xH_yO_z + \frac{4x - y - 2z}{4}H_2O \rightarrow \frac{4x - y + 2z}{8}CO_2 + \frac{4x + y - 2z}{8}CH_4 \tag{3.4}$$

3.2 Conversion of Nitrogenous Matter

In the past 20 years, simultaneous biological nutrient removal (SBNR) has been widely applied in wastewater treatment systems [16]. In such treatment systems, there are no defined anoxic or aerobic zones. The minimum conditions required for SBNR processes are usually a macro-environment (bioreactor with microorganisms) and a floc microenvironment for developing anaerobic and aerobic zones within the floc [17]. The processes occurring in such systems are usually nitrification, denitrification, simultaneous nitrification-denitrification and biological phosphorus removal.

3.2.1 Nitrification

Nitrification is a simple conversion of ammonia to nitrites and further to nitrates. In wastewater treatment plants, nitrification takes place in two steps: at first, oxidation of ammonia (NH_4+-N) takes place in the presence of Nitrosomonas and is converted into nitrite (NO_2—N) and which is further transformed to nitrate (NO_3—N) by Nitrobacter. The nitrifying bacteria involved in the process are autotrophs which use carbon to convert the inorganic matter into mineralized products [18]. The first reaction is the conversion to nitrite in the presence of Nitrosomonas:

$$2NH_4^+ + 3O_2 \xrightarrow{Nitrosomonas} 2NO_2^- + 4H^+ + 2H_2O \tag{3.5}$$

and the second reaction is the conversion of nitrites to nitrate in the presence of Nitrobacter:

$$2NO_2^- + O_2 \xrightarrow{Nitrobacter} 2NO_3^- \tag{3.6}$$

The above two equations when combined can be written as:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \tag{3.7}$$

These autotrophs have a chemo lithotrophic nature which results in a smaller maximum specific growth rate and increased minimum solids retention time and signifies slow growth rate of nitrifiers [19]. This leads to a higher value of oxygen half saturation coefficient (K_o) for autotrophs signifying that nitrifiers cannot tolerate low oxygen concentration. If in a continuous process, the concentration of dissolved oxygen is lower than the oxygen half saturation coefficient (K_o), minimum solids retention time will increase resulting in rise of ammonia concentration in the effluent and washout of biomass from the system [5].

3.2.2 Denitrification

The reduction of nitrate (NO_3—N) to nitrogen gas (N_2) is called denitrification which takes place under anoxic conditions. The main organisms involved are heterotrophic, which act as an electron acceptor instead of oxygen. There is a slight possibility that aerobic heterotrophs are competing with denitrifiers for the same substrate and hence this can cause a disruption in the denitrification process [5]. The reaction for denitrification is as follows:

$$2NO_3^- + 2H^+ \rightarrow N_2 + 2.5O_2 + H_2O \tag{3.8}$$

Both oxygen and nitrate are accepted as electron acceptors by denitrifiers. They tend to use oxygen when its concentration is high in the reactor, hence they need a medium with low oxygen for denitrification [20]. The process of denitrification takes place via several intermediate products such as nitric oxide, nitrite and nitrous oxide. Hence, during the reduction process, there is a possibility of accumulation of these intermediates if the concentration of dissolved oxygen is higher and the concentration of substrate (electron donor) is low [5].

3.2.3 Simultaneous Nitrification and Denitrification

This process occurs when nitrification and denitrification take place simultaneously in one reactor without any clear distinction between the aerated and non-aerated zones. Several environmental conditions are to be maintained for simultaneous occurrence of nitrification and denitrification. Some of those conditions are as follows:

- Concentration of dissolved oxygen should be optimum so that it can support autotrophic nitrification and is also ample for denitrification to occur.

- Nitrifiers have slow growth rate hence sufficient solids retention time should be provided in order to let them grow.
- For heterotrophic denitrification to take place, adequate amount of electron donor should be available [5].

Since nitrification and denitrification are two conflicting processes, it is logical to carry out the processes in two different reactors but SND takes place in a single reactor with controlled oxygen which is much more feasible and has several advantages over nitrification and denitrification. These advantages include less carbon usage (22-40%), less energy requirements, neutral pH, use of a single tank and 30% reduced sludge yield [20].

Some researchers have investigated the process of SND in activated sludge systems with low concentration of oxygen which was obtained as 0.3-0.8 mg/L for the process to occur efficiently. The SRT for this investigation was set to 45 days and resulted in the removal of nitrogen at a rate of 66.7% [21]. Also, the efficiency of Nitrification and Denitrification depends on various parameters such as: Chemical Oxygen Demand (COD), Hydraulic and Solid Retention Time (HRT and SRT), pH etc. [22].

3.3 Biological Phosphorus Removal

Phosphorus is known to be one of the factors that limits the biomass growth. Hence, its removal is very important to reduce the nutrients and meet the quality standards for the discharge of water from wastewater treatment plants [23]. There are biological and chemical processes used for the removal of phosphorus but compared to chemical processes, biological processes are much more feasible and environmentally friendly. A discharge limit of 50 μg/L in Europe and 10 μg/L in North America is required for phosphorus content in the effluent from wastewater treatment plants [1]. For municipal discharge in the USA, the permit limit for total phosphorus is set as 1 mg/L by EPA as of 2017 and may be improved to 0.23 mg/L in future [24].

Biological processes are categorized as aerobic, anaerobic and anoxic, which are extensively for domestic wastewater treatment plants [1]. Wastewater treatment systems using biological processes make use of phosphorus accumulating organisms (PAOs) which can uptake excess phosphorus. These PAOs are used to uptake volatile fatty acids (VFAs) and store them as polyhydroxyalkanoic acids (PHAs). Later, the stored PHAs are oxidized by PAOs followed by uptake of phosphate and are finally removed from the system upon the discharge of the sludge.

There are several chemical processes for phosphorus removal as well such as chemical coagulation with various metals typically aluminum, iron, and magnesium. The process is very complex but being well-studied and is still used in many treatment systems. In short, the process can be described as a combination of precipitation, coagulation and adsorption on the surface of formed metal hydroxide of which adsorption is considered to be the dominating mechanism. More research is being done to see the effect of activated sludge on the process of phosphorus removal by trying to collect mixed liquor from the aeration tank [24].

3.4 Modeling of Biological Reactions in Wastewater Treatment

In order to develop a dynamic model for an advanced wastewater treatment plant, the above-mentioned reactions and their kinetics must be considered. Researchers have been developing several models to simplify the existing activated sludge kinetics. The simplified kinetics can be further used for model validation, operation and control purposes. Various kinetic models such as Monod's kinetics, Contois kinetics, Haldane kinetics etc. have been used to develop the kinetics for the biological reactions in wastewater treatment.

3.4.1 Microbial Growth Rate

Monod kinetics has been used for years to describe the growth of bacteria, but some researchers stated that Monod kinetics cannot be used for describing growth rate without considering the effects of other factors such as pH, temperature and endogenous decay [25]. The Monod equation mentioned in equation 2.1 was then modified for predicting the growth of bacteria:

$$\mu = \frac{\mu_m S}{K_S + S} - K_d \quad (3.9)$$

where:

$S = substrate\ concentration$

$\mu_m = specific\ growth\ rate$

$K_s = half\ saturation\ coefficient$

$K_d = decay\ constant$

3.4.2 Biomass Concentration

The kinetics for biomass is usually obtained by carrying out a material balance around the reactor:

$$Input + Recycle + Formation - Output = Accumulation \quad (3.10)$$

where accumulation = 0, which gives:

$$X = \frac{\mu Y (S_0 - S)(K_S + S)}{\mu_m S\big(1 - R(E_a - 1)\big)} \quad (3.11)$$

where

$X = biomass\ concentration$

$Y = Yield$

$E_a = Activation\ Energy$

$S_0 = intial\ concentration\ of\ the\ substrate$

$S = substrate\ concentration$

$\mu_m = specific\ growth\ rate$

$K_s = half\ saturation\ coefficient$

3.4.3 Bio Floc Model

Biomass usually contains flocs made of organic and inorganic substances. These flocs are typically used in defining the performance of the activated sludge system in wastewater treatment process. Hence, it is important to study the reactions and kinetics associated with the flocs in the wastewater system. Some researchers have developed models to describe the main reactions occurring in the activated sludge systems while accounting for the metabolic reactions and mass transfer taking place inside the floc [26]. The figure 3-1 shows a typical spherical floc [26].

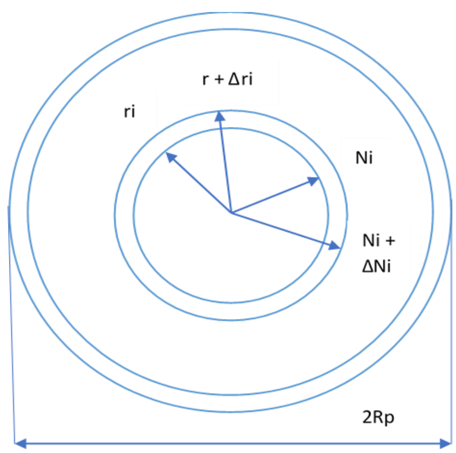

Figure 3-1 Representation of a Typical Spherical Floc

where

$N_i = The\ flux\ or\ mass\ transfer\ rate\ of\ component\ (i)\ per\ unit\ time\ per\ unit\ area$

$at\ radius\ (r)$

$N_i + \Delta N_i = That\ flux\ at\ radius\ (r + \Delta r)$

$r = The\ variable\ for\ floc\ radius$

$R_p = The\ floc\ radius$

$\Delta r = The\ thickness\ of\ the\ differential\ shell$

$i = Referes\ to\ the\ substrate\ S, nitrate\ Z, ammonia\ H\ and\ oxygen\ C.$

The following model was developed by carrying out a steady state mass balance for substrate:

$$\frac{d^2s}{dw^2} + \frac{2}{w}\frac{ds}{dw} = \frac{\varphi_1 sc}{(S+1)(C+1)} + \frac{\varphi_2 sz}{(S+1)(C+1)(Z+1)} \tag{3.12}$$

where:

$w = \frac{r}{R_p}$

$S = \frac{s\ (mg^{-1})}{K_s\ (mg^{-1})} = readily\ biodegradable\ substrate$

$Z = nitrate\ nitrogen$

$C = diffusional\ resistance\ of\ dissolved\ oxygen$

$\varphi_1 = \frac{\rho R_p^2 \mu H \eta g}{D_s K_s Y_H}$

$\varphi_2 = \frac{\rho R_p^2 \mu_H \eta_g}{D_s K_s Y_H}$

3.4.4 Dissolved Oxygen Model

Matson and Characklis developed a mass transfer model to represent the consumption of oxygen by estimating the radius of the anoxic core. The following assumptions were made for determining the size of the core: steady state, zero order kinetics and the dissolved oxygen (DO) gradient between floc surface and bulk liquid is negligible, the radius is derived as [27]:

$$r = \left[R^2 - \frac{6S_a D_a}{X_c k_a}\right]^{1/2} \tag{3.13}$$

where:

$R = radius\ \ of\ floc$

$S_a = electron\ acceptor\ concentration\ (DO)\ in\ bulk\ liquid$

$D_a = diffusion\ coefficient\ for\ electron\ acceptor\ in\ the\ floc$

$X_c = organism\ concentration\ in\ the\ floc, and$

$k_a = maximum\ substrate\ utilization\ rate\ for\ the\ electron\ acceptor$

CHAPTER 4: WASTEWATER TREATMENT PROCESS AND CONTROL STRATEGIES

For many years, the objective of wastewater treatment has been the removal of biological nitrogen and phosphorus combined with reduction of biological oxygen demand and total suspended solids. The objective has remained the same throughout the years except for the fact that the focus has now shifted to protect the environment and reduce long term health effects. There are several ways in which the wastewater can be treated such as by using physical, chemical and biological processes. The conventional wastewater treatment process includes five steps: 1) pretreatment, 2) primary treatment, 3) secondary treatment, 4) tertiary treatment and 5) disinfection. A generalized block flow diagram for an advanced wastewater treatment plant is shown in figure 4-1.

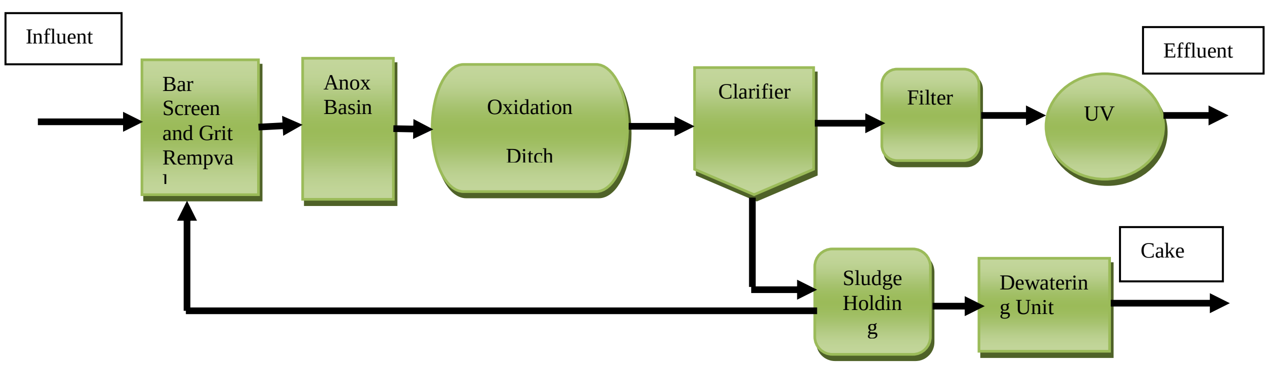

Figure 4-1 Generalized Block Flow Diagram of a Biological Wastewater Treatment Plant

4.1 Pretreatment

Pretreatment or preliminary treatment is done to prepare the wastewater in such a way that it does not hinder the further biological processes. It is mainly used for the removal of grits, oily scum and floating debris so that these do not damage the treatment equipment. There are several ways in which the pretreatment can be done, such as through screening, equalization, grit chambers, etc.

4.2 Primary Treatment

The main aim of primary treatment is to remove solids that can easily settle and float. Usually, settling tanks or clarifiers are used for primary treatment as the wastewater coming from pretreatment might contain some suspended solids which are removed by gravity settling. Most of these suspended solids are organic in nature and hence, a good amount of BOD is reduced at this stage and the remaining dissolved BOD can be removed in the secondary treatment [28]. Other than BOD, primary treatment also removes TSS and phosphorus. Some coagulants may also be added to carry out natural sedimentation which is followed by floatation which helps in oil and grease removal [29]. A picture showing the primary treatment at the Valrico Advanced Wastewater Treatment Plant is shown in figure 4-2.

Figure 4-2 Primary Treatment (Headworks) at the Valrico Plant

4.3 Secondary Treatment

Secondary treatment is a way of introducing the biological processes in the wastewater treatment system since the first two processes of the treatment are physical processes. Even after the reduction in levels of BOD, there is still a large amount of dissolved organic matter left in the wastewater to be removed [28]. Oxygen is one of the main components required for this decomposition along with favorable pH, temperature, and other environmental conditions. The solids retention time (SRT) for such treatment systems ranges from 12 – 30 days and the hydraulic retention time is about 9 – 20 hours [30]. Secondary treatment is divided in three parts: anoxic basin, oxidation ditch and clarifier as shown in figure 4-3, 4-4 and 4-5 respectively.

Figure 4-3 Secondary Treatment (Anoxic Basin) at the Valrico Plant

4.3.2 Activated Sludge System

In activated sludge system, the microorganisms are mixed with organic matter in an aeration tank. The mixture of the microorganisms and the organic matter is called mixed liquor. And the amount of suspended solids measured in the aeration tank is called mixed liquor suspended solids (MLSS). One of the important parameters for activated sludge is F/M ratio which is food (substrate or BOD) to biomass (MLVSS) ratio [31].

The effluent coming from the primary treatment has some BOD left in it. Therefore, it is passed through the aeration tanks where in the presence of oxygen, BOD is degraded. Mostly, in the aeration tank a particular amount of dissolved oxygen around 2 mg/L is maintained. But it can be anywhere in between 1.5 – 4.0 mg/L [28]. Adding more dissolved oxygen to the oxidation ditches, does not make the process of degradation efficient but only results in increasing the energy and costs required for the operation. But if the dissolved oxygen is low then there are chances of sludge bulking in the aeration tank. Sludge Bulking is one of the common problems in activated sludge systems which is caused by several filamentous organisms leading to poor settling characteristics. Activated sludge systems mainly consist of the following essential elements:

- Aeration Tank (Primary Clarifier)
- Settling Tank (Secondary Clarifier)
- Pumps
- Excess Sludge Removal

Figure 4-4 Secondary Treatment (Oxidation Ditch) at the Valrico Plant

The next stage after primary clarification is secondary clarification consisting of settling tanks. The microorganisms are sent to secondary clarification after they are done using all the dissolved organic matter. The output from the secondary clarifier is usually divided into two streams:

- Overflow: is collected from the top of the clarifier is the clarified water which is sent for further treatment which is called tertiary treatment or disinfection show in figure 4-6.

- Underflow: is collected from the bottom of the clarifier and is called suspended solids or sludge which are deactivated because of no food source in the clarifier.

Figure 4-5 Secondary Treatment (Clarifiers) at the Valrico Plant

Since the microorganisms are activated, they are ready to consume more nutrients and hence a fraction of the activated sludge is sent to the start of the treatment process. This sludge is called return activated sludge (RAS) and hence the process is started all over again. The remaining activated sludge which is not sent to the headworks, is disposed from the system and is called waste activated sludge (WAS).

4.4 Tertiary Treatment

After secondary treatment, the wastewater still needs to be treated more for the removal of nitrogen, phosphorus and other pollutants. There are several physical, chemical and biological processes used for nitrogen and phosphorus removal termed as tertiary treatment. Most of the inorganic nitrogen is removed during the biological process but a small amount of dissolved organic nitrogen still exists in the water and hence other advanced processes are used to remove the remaining nitrogen and phosphorus [32]. The details about nitrogen and phosphorus removal are discussed in later chapters.

4.5 Disinfection

The last and the final stage of treatment is called disinfection. The process is carried out to remove all the pathogenic organisms. Disinfection can be done in several ways:

- Adding various chemicals such as chlorine dioxide, chlorine gas or sodium hypochlorite.
- Ozonation
- Exposure to ultra violet (UV) radiation.

These processes are efficient enough to remove up to 99.99% or more of coliform. The details about these processes are out of scope of this thesis.

Figure 4-6 Disinfection (UV) at the Valrico Plant

4.6 Control Strategies

Wastewater plants with activated sludge system are very much reliable and can handle shock loads but still there is a need for much more control and monitoring. Hence, it is essential for wastewater treatment plants to have proper operation and control strategies in order to make the plant work more efficiently. To control the activated sludge process, it is very important to review the operating data and lab data and select the parameters which will provide the optimum performance in a cost-effective manner.

4.6.1 Dissolved Oxygen and Aeration Control

In biological nutrient removal systems, almost 50-60% of the total energy consumed is because of aeration. Hence, it is of great significance to maintain the Dissolved Oxygen (DO) level in aeration tank. One of the most efficient ways to control aeration is by controlling the concentration of dissolved oxygen based on the ammonia concentration in the effluent [33]. This is because most of the oxygen is consumed in the nitrification process. For such purposes mostly, a feedback controller with an integral coupled to an integral DO controller is known to save energy and have good effluent standards. Sometimes it is also good to use a combination of feed forward and feed backward controllers to achieve an optimum performance in case of systems with small reactors and highly dynamic fluid [34]. Usually, the dissolved oxygen concentration should be maintained around 1–4 mg/L. If the concentration drops below 1 mg/L, the activity of microorganisms will decrease and results in death of the microorganisms. Hence, it is important to maintain the DO level in order to achieve sufficient mixing, microorganism activity and propose decomposition of the organic wastes, all the time [35].

4.6.2 Returned Activated Sludge Control

Return Activated Sludge (RAS) is the amount of mixed liquor suspended solids (MLSS) which are sent back to the aeration tank once they are settled in the clarifier. Hence, it is important that the MLSS settles well in the clarifier in order to be returned. The RAS returned to the aeration in conventional processes is usually about 15-75% of the influent flow whereas in extended aeration it can range from 50-200% [36]. RAS control can be approached in two ways:

- Influent flow is controlling the RAS flow rate independently – In this case, the RAS flowrate is set constant and hence it results in a maximum concentration of MLSS when the influent flow rate is minimum and vice versa. This is because the amount of MLSS coming to the clarifier is changing based on the inflow, but the amount removed from the clarifier is the same.

- RAS flowrate is controlled as a constant percentage of the influent – In this case, a constant percentage of the influent flow rate is sent back to the aeration tank. This makes sure that the amount of MLSS returned to the aeration tank is constant through high and low flow rates [36].

4.6.3 Waste Activated Sludge Control

Waste Activated Sludge Control (WAS) is the amount of MLSS that is wasted. It is done to keep a balance between the amount of food available and the microorganisms. Since the microorganisms are continuously consuming BOD and COD from wastewater, they start growing and multiplying. Hence, it is important to waste the excess sludge. Instead of wasting sludge from the clarifier, it can also be wasted from the mixed liquor in the aeration tank. However, in this case because of the large quantity of sludge, sufficient sludge handling facilities are required which is not accessible to most of the plants [36]. When the sludge is wasted from RAS, it can be controlled by measuring the amount of volatile suspended solids (VSS) in the RAS. If the amount of VSS in RAS is decreasing, it is advised to increase the WAS flow rate so that a proper amount of VSS is wasted and vice versa. The main techniques for controlling the WAS are as follows:

- Constant MLVSS Control
- Constant Gould Sludge Age Control
- Constant F/M Control
- Constant MCRT Control
- Sludge Quality Control

There were several studies done using a BioWin model to run simulations based on trying to keep MLVSS, MCRT and F/M ratio constant but the results showed a variation in SRT and WAS flow rate. Hence, it leads to the conclusion that these three parameters cannot be held constant together [37].

CHAPTER 5: GENERAL PURPOSE MODELING AND COMPUTATIONAL PLATFORM

There have been several computer-based models used for simulation of wastewater treatment plants, but the question is, are these models suitable for the simulation of wastewater treatment plants and the answer is very positive. This is because, these days there are strict limits on the effluent from the plants. Hence, it is very important to have proper designed models with controls to meet the discharge limits and a maintain cost efficient and sustainable treatment environment.

5.1 Activated Sludge Modeling

Activated sludge modeling has been used for modeling of wastewater treatment plants for several years. These models are being used for various applications such as design, optimization, control and research. A Task Group was established by the International Association on Water Pollution Research and Control (IAWPRC) in 1982 to develop mathematical models for Activated Sludge Processes. The Task Group developed the first model for activated sludge process known Activated Sludge Mode No. 1 (ASM1), which was mainly developed for nitrogen removal [38]. Later, in 1995 when biological phosphorus removal came into light and the process was better understood the Task Group published Activated Sludge Model No. 2 (ASM2). This model was a combination of nitrogen removal and biological phosphorus removal. A third model was established shortly after ASM2 to incorporate the element of denitrification. It was named ASM2d and it included denitrifying PAOs [39]. And finally, in 1998 the Task Group established ASM3 which is the most updated model including a two-step model for nitrification and denitrification. Other than these models, the Task Group also presented a set of default values for the parameters which would give realistic results with minor changes. They also published a guideline for characterization of wastewater and developed a set of computer codes with the ASM3 model.

Table 5-1 Comparison of Activated Sludge Models

	UCT MODEL	ASM1	ASM2	ASM3
Process Equations	14	8	19	9
Model Components	14	19	20	13

5.1.1 Activated Sludge Modeling 1

The ASM1 model is still one of the most widely used models in wastewater treatment plants all over the world. This model consisted of concepts adapted from a model developed earlier in University of Cape Town (UCT), which were based on death-regeneration and bisubstrate hypotheses.

ASM1 had some similarities to the earlier UCT model. For describing the growth rate of autotrophs and heterotrophs, the model still uses the Monod relationship. COD was used for defining the carbonaceous material and act as a link between the biomass, the organic substrate and the oxygen utilized. There were some modifications as well which were introduced in ASM1, such as for enmeshed biodegradable material to be released in to the bulk liquid, it needs to be broken down to extracellular enzymatic action to be hydrolyzed in to readily biodegradable COD [40]. Switch functions were also added to ASM1 which worked as on and off functions and could control the process rate equations based on the environmental changes. Also, the sources of organic nitrogen were finally treated differently than organic nitrogen. The model parameters for ASM1 are listed in Table 5-2 and 5-3. As mentioned in Table 5-1, the activated sludge model 1 (ASM1) has 19 model components. Out of those 19 model components, 14 of the parameters are kinetic parameters (table 5-2) while the remaining five are stoichiometric parameters (table 5-3).

Table 5-2 Kinetic Parameters for ASM1

S.No.	Kinetic Parameters	Symbol	Unit
1.	Heterotrophic max. specific growth rate	$\widehat{\mu_H}$	day^{-1}
2.	Heterotrophic decay rate	b_H	day^{-1}
3.	Half-saturation coefficient (hsc) for heterotrophs	K_S	$g\ COD\ m^{-3}$
4.	Oxygen hsc for heterotrophs	$K_{O,H}$	$g\ O_2\ m^{-3}$
5.	Nitrate hsc for denitrifying heterotrophs	K_{NO}	$g\ NO_3\text{-}N\ m^{-3}$
6.	Autotrophic max. specific growth rate	$\widehat{\mu_A}$	day^{-1}
7.	Autotrophic decay rate	b_A	day^{-1}
8.	Oxygen hsc for autotrophs	$K_{O,A}$	$g\ O_2\ m^{-3}$
9.	Ammonia hsc for autotrophs	K_{NH}	$g\ NH3\text{-}N\ m^{-3}$
10.	Correction factor for anoxic growth of heterotrophs	η_g	dimensionless
11.	Ammonification rate	k_a	$m^3\ (g\ COD\ day)^{-1}$
12.	Max. specific hydrolysis rate	k_h	g slowly biodeg. COD $(g\ cell\ COD\ day)^{-1}$
13.	Hsc for hydrolysis of slowly biodegradable substrate	K_X	g slowly biodeg. COD $(g\ cell\ COD)^{-1}$
14.	Correction factor for anoxic hydrolysis	η_h	dimensionless

Table 5-3 Stoichiometric Parameters for ASM1

S.No.	Stoichiometric Parameters	Symbol	Unit
1.	Heterotrophic yield	Y_H	g cell COF formed (g COD oxidized)$^{-1}$
2.	Autotrophic yield	Y_A	g cell COF formed (g N oxidized)$^{-1}$
3.	Fraction of biomass yielding particulate products	f_P	Dimensionless
4.	Mass N/mass COD in biomass	i_{XB}	g N (g COD)$^{-1}$ in biomass
5.	Mass N/mass COD in products from biomass	i_{XP}	g N (g COD)$^{-1}$ in endogeneous mass

There are various drawbacks in ASM1 such as the assumptions of constant temperature and pH. Several modifications and assumptions must be made to make it a practical wastewater treatment system. Various coefficients for rate expressions, nitrification, denitrification etc. are assumed to be constant. The process of hydrolysis for two processes, organic matter and organic nitrogen occur simultaneously and are grouped together. ASM1 lacks kinetic expressions for nitrogen and alkalinity of heterotrophic organisms. Furthermore, it cannot directly predict the concentration of mixed liquor suspended solids [41]. ASM1 is modeled in such a way that the hydrolysis process dominates for oxygen consumption predictions but in reality, this is a combination of lysis, hydrolysis and storage of substrates. ASM1 had several such limitations and therefore, there was a need for development of other models such as ASM2 and ASM3.

5.1.2 Activated Sludge Modeling 2 and 2d

ASM2 was introduced to add more processes to ASM1. ASM1 was extended to include biological process so as to remove biological phosphorus. In order to do so several components were added to the existing model (ASM1), making it more complex. ASM2 had polyphosphates, which for performance of activated sludge, is known to be of immense importance. As compared to ASM1, ASM2 does not depend on COD for its organic material and total concentrations of the activated sludge. The kinetics of ASM2 are complicated but can be simplified by making several assumptions and eliminating various components of lesser significance. ASM2 was then later extended to ASM2d by including PolyP storage and PAOs growth processes in anoxic condition. The kinetics for ASM2d was very much similar to ASM2 except for an extra reduction factor, nNO_3.

There were some limitations to ASM2 such as, the model was only made for domestic treatment. And there was a temperature range associated with this mode that is around 10-25 ^oC. It is only designed for pH range of 6.3 to 7.8 [41]. Also, ASM2 had an unsolved problem for denitrification related to PAOs. This lead to an extension of ASM2 model to ASM2d, which was introduced in order to reduce the number of processes and describe various configurations for biological phosphorus removal.

5.1.3 Activated Sludge Modeling 3

ASM3 was proposed to reduce all the limitations of ASM1 and hence be used for future modeling. ASM3 like ASM1 is used for nitrification, denitrification, sludge production and oxygen consumption in activated sludge wastewater treatment plants. The main difference between ASM1 and ASM3 was that ASM3 had a storage mediated growth of heterotrophic organisms. This concept assumed that firstly all the readily biodegradable substrate are collected and then stored into a component called internal cell polymer (XSTO) which is further used for growth [42]. The growth decay model in ASM1 was replaced by death regeneration model in ASM3, which made it easier to calibrate. ASM3 does not include biological phosphorus removal like ASM2 and ASM2d but it can be easily added to the model. The flow of COD was less complex in ASM3 as compared to ASM1. In ASM3, there is no flow of COD from one group to another and there is clear separation between nitrifiers and heterotrophs.

ASM3 and ASM1 were designed to work on a temperature scale of 8-23^{o}C. When the temperature is not in the range, the model gives significant errors and unsatisfactory results. ASM3 has some default values for the parameters but it only provides the structure of the model, and hence it totally depends on the user to manipulate values and identify significant parameters. ASM3 was designed only for domestic wastewater treatment plants with aerobic and anoxic treatments. Therefore, it would not give perfect results when used for treatment plants where the contribution of industries dominates. Also, ASM3 considers nitrification as a single-step process neglecting nitrite, which is acceptable for most of the wastewater treatment plants except for those where nitrite concentration may increase in the system and hence result in errors in the treatment plant [41] . ASM3 also cannot handle high load (small SRT) activated sludge systems because of insufficient flocculation and storage.

5.2 Flowsheet Simulators

BioWin is one of the plant design and flowsheet simulators which is used widely and is available from Envirosim and Associates (Canada). BioWin was mainly used for activated sludge modeling but with latest updates it has expanded to include models for other unit processes such as sedimentation, filtration, separation, and anaerobic digestion, etc.

BioWin is used to predict the behavior of wastewater treatment plants which is necessary because of the dynamic behavior of the plants under variable operating conditions. BioWin is very efficient and easy to use but the complexity comes in because of the kinetic models used in it. BioWin has large number of parameters as it uses integrated Activated Sludge Models (ASMs). It has default values for all the parameters but for certain application, these parameters might need to be varied accordingly. It also has a controller toolbox which allows BioWin to have control over aeration, RAS, WAS etc.

There are several other softwares such as ASIM, GPS-Z, WEST, etc. used for modeling wastewater treatment systems and most of them use activated sludge modeling [43]. They also follow few protocols for the calibration of the model, which are as follows:

- Defining the target
- Collection of the information from the treatment plant
- Steady state and dynamic simulation
- Decision making

5.3 Computational Fluid Dynamics

Simulation softwares such as ANSYS FLUENT are used for designing various engineering products. It is also used for simulations of fluid movements. For an efficient oxidation ditch, it is necessary to increase the bacteria growth rate and rate of reaction, hence it is very useful in modeling wastewater systems as it can track the fluid movements in oxidation ditches. Ansys uses thermodynamics and hydrodynamics to model the system. The designing of the oxidation ditch in ANSYS FLUENT is out of scope of this thesis.

CHAPTER 6: RESULTS AND DISCUSSION

This chapter describes the various steps taken to develop the dynamic model for the Valrico Advanced Wastewater Treatment Plant and the simulation results obtained from the model. The simulation results from the dynamic model were then compared with the plant results in order to validate the model.

6.1 Site Description

Hillsborough County, Florida has several wastewater treatment plants of which the Valrico Advanced Wastewater Treatment Plant is one. The Valrico plant is a biological nutrient removal (BNR) system which has an average influent rate of 8 MGD and a permitted annual average flow of 12 MGD. The plant receives domestic wastewater mostly but sometimes it also receives landfill leachate. It is also one of the most dynamic and challenging wastewater treatment plants because of the large variations in the influent. Hence, it becomes very difficult for the operators to optimize the plant with influent variations and meet the discharge limits. The NPDES permit limits set for the plant for total nitrogen, total phosphorus is 3 and 1 mg/L respectively. The Valrico AWWTP uses an extended aeration activated sludge system and can treat wastewater for longer duration having a mean residence time of 24 days. The Valrico facility also uses supervisory control and data acquisition (SCADA) for controlling various parameters such as aeration, RAS and WAS flowrates. The plant is divided into several sections based on type of treatment:

- Headworks: Primary Treatment
- Anoxic Basin, Oxidation Ditch, Clarifiers: Secondary Treatment
- Sand Filters and Ultraviolet Disinfection: Tertiary Treatment

A process flow diagram of the Valrico plant is shown in figure 6-1.

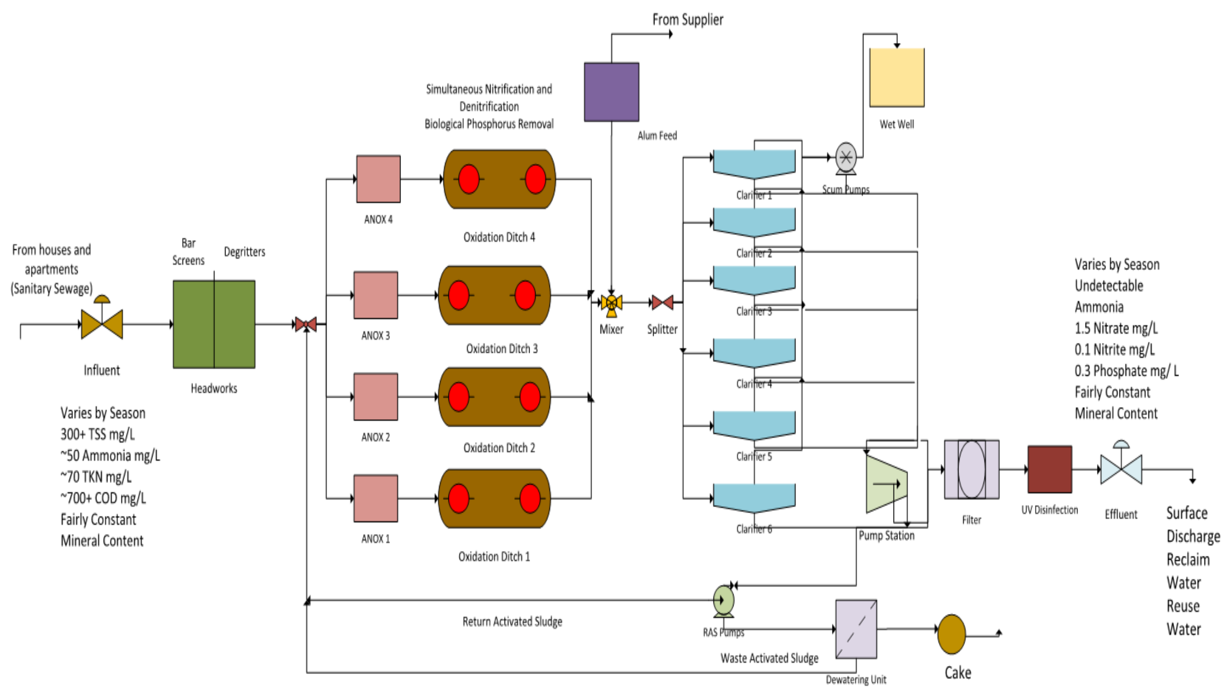

Figure 6-1 Layout of the Valrico Advanced Wastewater Treatment Plant

The influent coming into the plant goes through the headworks first where the primary treatment is carried out. Most of the inorganic waste such as rocks and sand are removed from the wastewater in the headworks. This process helps in preventing damage and wear to downstream equipment and reduces the need for maintenance of the process equipment. The next major step is the digestion of the organics which is the removal of nitrogen and phosphorus from the wastewater to prevent adverse health and ecological effects. The secondary treatment is a two-step biological process which begins in the anoxic basin and is followed by the oxidation ditch. In the anoxic basin, phosphorus removal is ensured with the help of heterotrophic bacteria as they ferment the organic material into volatile fatty acids. The Phosphorus Accumulating Organisms (PAOs) uptake VFAs by releasing orthophosphate into the mixed liquor. In this manner the mixed liquor is set-up for the next stage where PAOs uptake oxygen and orthophosphate produced in the basin in the oxygen rich environment. The next stage is the oxidation ditch where the wastewater is mixed with bacteria referred to as nitrifiers. These nitrifiers initiate the process of nitrification near the aerators in the presence of oxygen followed by the process of denitrification towards the center of the oxidation ditch where due to less dissolved oxygen, the nitrifier activity decreases converting the nitrates formed by the nitrification to nitrogen gas. The effluent coming out of the oxidation ditches is mixed with alum (aluminum sulfate) to promote phosphorus precipitation before it enters the clarifiers. Clarifiers used in Valrico are large circular settling tanks and using gravity settling for removal of the heavier solid sludge from the wastewater. Some portion of the sludge is recycled back to the oxidation ditches and some of it is wasted. The effluent from the clarifier is then dewatered and filtered before it is sent for UV disinfection. This is the final stage where the microorganisms are neutralized, ensuing that the microorganisms do not reproduce. Finally, the effluent is split in to portions of which some is stored as reclaimed water, some is aerated and discharged in to the environment and the rest is sent to a spray field.

Table 6-1 Physical Data for Valrico Advanced Wastewater Treatment Plant

Equipment	Area of each tank (ft^2)	Volume of each tank (ft^3)
ANOX Basin (1 & 2)	50130	0.75
ANOX Basin (3 & 4)	25070	1.5
Aerators (1 & 2)	4346	0.12
Aerators (3 & 4)	6519	0.18
Oxidation Ditch (1 & 2) (Including Aerators)	102656	1.67
Oxidation Ditch (3 & 4) (Including Aerators)	154000	2.5
Clarifiers (1-6)	19100	0.75

6.2 Plant Model Representation in BioWin

To represent the plant model in BioWin, data was collected from the plant. The physical data for the plant is shown in table 6-1. Other than the physical data, influent data and experimental data was also available from the plant. BioWin allows the user to specify typical influent characteristics of the plant and tune the kinetic parameters. Oxidation ditches are large tanks representing a plug flow reactor. The plant has four oxidation ditches and each oxidation ditch was modeled as a series to represent the plug flow. The oxidation ditch in BioWin was modeled as ten completely stirred tank reactors (CSTRs) of which two of the CSTRs were aerated and other eight were unaerated. The series of aerated and unaerated zones allow the simultaneous nitrification and denitrification to take place. The plant has six clarifiers which were modeled as six ideal clarifiers in BioWin. Several splitters, pumps, filters, mixers and pipes were used to complete the model. There are nine RAS lines which were lumped in to three RAS pumps for convenience and one WAS line in the plant was modeled as a WAS splitter. The model was created in a way to closely represent the SCADA process flow diagram of the plant which is visible to the operators. Since BioWin does not have a splitter which can split into multiple fractions, hence several splitters were used to divide the flow between the oxidation ditches and clarifiers. The split ratios for all the splitters were calculated according to the flow going into each oxidation ditch and clarifier. One of the two dewatering units was used for filtration and the other for wasting the sludge which is called cake. The BioWin model of the plant is shown in figure 6-2.

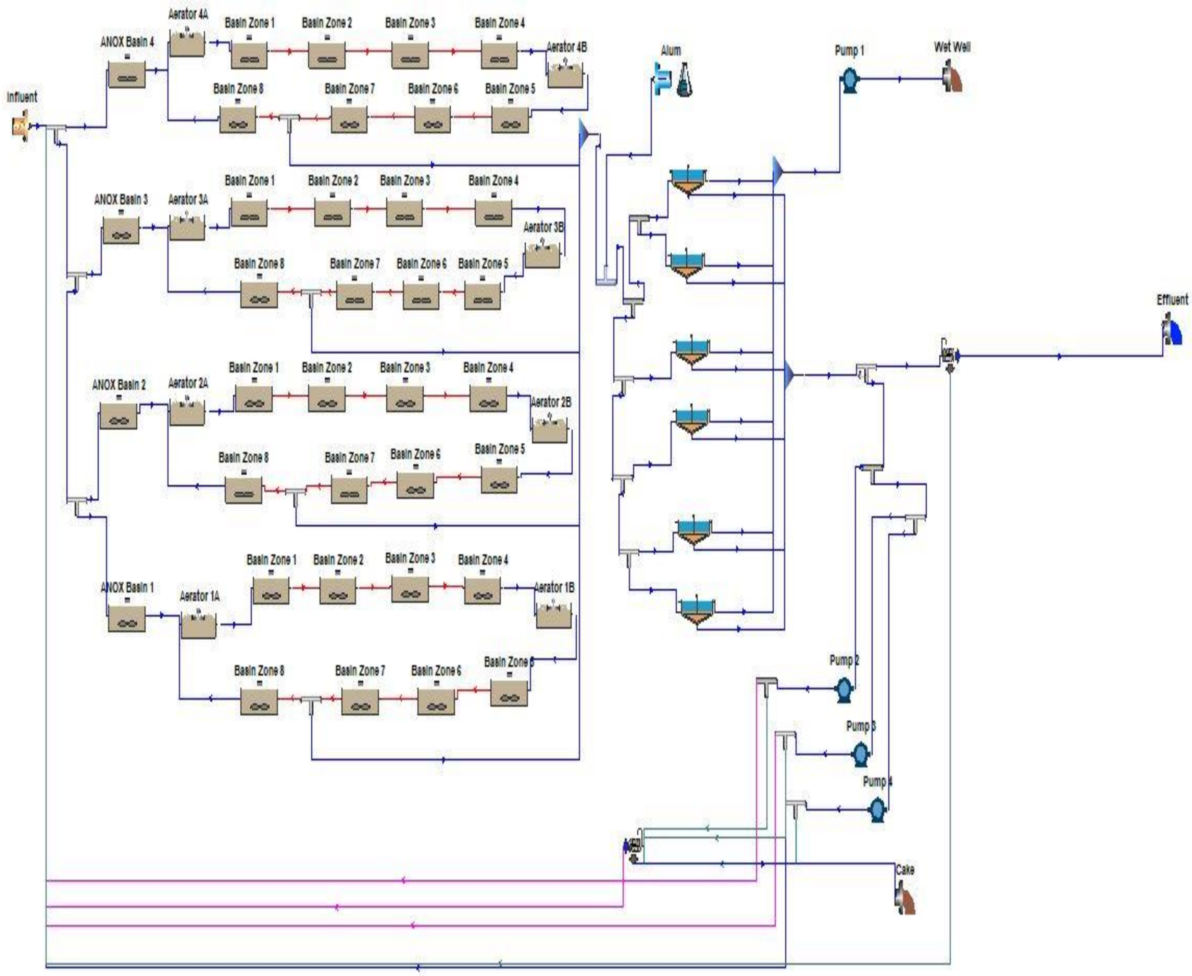

Figure 6-2 BioWin Model of the Valrico Advanced Wastewater Treatment Plant

To accurately represent the plant model in BioWin, various modeling considerations had to be considered. The oxidation ditches at the Valrico plant are of different size. Oxidation ditches 3 and 4 are bigger in size than oxidation ditches 1 and 2. The aeration requirements were set up according to the size of the oxidation ditch and hence, more aeration was required for oxidation ditches 3 and 4 than oxidation ditches 1 and 2. The aeration requirements were designed similar to the plant. The A set of aerators are always working on 100% efficiency, while the B set of aerators keeps varying between 60-80% depending on the requirements of the plant. The current operating policies of the plant are shown in table 6-2.

Table 6-2 Modeling Considerations for the BioWin Model

Equipment	Settings in BioWin
Anox Basins (1 - 2)	Unaerated, 0.75 MG each
Anox Basins (3 - 4)	Unaerated, 1.5 MG each
Aerators (1A - 2A)	Aerated, 105 hp each, 0.12 MG each
Aerators (3A - 4A)	Aerated 120 hp each, 0.18 MG each
Aerators (1B - 2B)	Scheduled Aeration, 50.39 hp (average) each, 0.12 MG each
Aerators (3B – 4B)	Scheduled Aeration, 57.74 hp (average) each, 0.18 MG each
Basin Zones (1 – 8) (Oxidation Ditch 1 & 2)	Unaerated, 0.18 MG each, Total = 1.67 MG for each ditch (including aerators)
Basin Zones (1 – 8) (Oxidation Ditch 3 & 4)	Unaerated, 0.27 MG each, Total = 2.5 MG for each ditch (including aerators)
Clarifiers (1 – 6)	0.75 MG each
RAS Splitters	Split ratio = 0.8
WAS Splitters	Split ratio varies based on the MLSS in the oxidation ditch

6.3 Model Calibration and Validation

BioWin has various kinetic, stoichiometric and wastewater fractions with default values. When default wastewater fractions are not good enough it becomes necessary to change them to calibrate the model. This requires influent data which can be used in the influent specifier excel file (appendix B) to calculate the fractions. The Valrico plant tests their data in the labs managed by the Hillsborough County Public Utilities Department and records it as part of their Excel files. This data was used in the influent specifier excel file to calculate the fractions. The input data and the fractions are shown below in table 6-3.

Table 6-3 Influent Input Data for the BioWin Model

Parameter	Units	Value
Flow	mgd	8.799
Total cBOD	mgBOD/L	318.84
VSS	mg/L	182.5
TSS	mg/L	204.5
TKN	mgN/L	51.15
TP	mgP/L	10
Nitrate	mgN/L	0
pH	-	7.3
Alkalinity	mmol/L	6
Calcium	mg/L	80
Magnesium	mg/L	15
Dissolved Oxygen	mg/L	0

For kinetic and stoichiometric parameters, n-factorial sensitivity analysis was carried out on certain parameters which were used to design a previous BioWin model called the lumped model. These parameters are shown in table 6-4. The goal of this study was to see which parameters will have a notable change on the effluent of the new expanded model. For each kinetic parameter, the numerical value was increased by 10%, and a simulation for 15 days was run to ensure a constant trend. Similarly, these values were decreased by 10% and a simulation was run for 15 days. The results from the simulation were compared to the base case scenario. Since, the expanded model is more complicated, the kinetic parameters did not really have a notable change in the effluent. BioWin has its own kinetics which resembles the ASM3 kinetics and the various kinetic parameters associated with it. The categories of kinetic parameters in BioWin are listed below:

- Common Parameters
- Ammonia Oxidizing Bacteria (AOB)
- Nitrite Oxidizing Bacteria (NOB)
- Anaerobic-Anoxic-Oxic Parameters (AAO)
- Ordinary Heterotrophic Organisms (OHO)
- Phosphate Accumulating Organisms (PAO)

The parameters which were used for sensitivity analysis and their default values are shown in table 6-4.

Table 6-4 Kinetic Parameters for the BioWin Model

Kinetic Parameter	Default Value	Changed Value (+10%)	Changed Value (-10%)
Common Parameters			
Hydrolysis	2.1	2.31	1.89
Hydrolysis half sat	0.06	0.066	0.054
Anoxic hydrolysis factor	0.28	0.308	0.252
Anaerobic hydrolysis factor (AS)	0.04	0.044	0.036
Anaerobic hydrolysis factor (AD)	0.5	0.55	0.45
AOB			
Byproduct NH4 logistic slope	50	55	45
Aerobic decay rate	0.17	0.187	0.153
Anoxic/Anaerobic decay rate	0.08	0.088	0.072
KiHNO2	0.005	0.0055	0.0045
OHO			
Max specific growth rate	3.2	3.52	2.88
Anoxic growth factor	0.75	0.825	0.675
Aerobic decay rate	0.62	0.682	0.558
Anaerobic decay rate	0.131	0.1441	0.1179
PAO			
Max spec growth rate, P-limited	0.42	0.462	0.378
Calcium half sat	0.1	0.11	0.09
Anaerobic decay rate	0.04	0.044	0.036
Anoxic growth factor	0.33	0.363	0.297

6.4 Control Strategies and Operational Policies

One of the other challenges in BioWin is to incorporate control schemes which are consistent with the plant. BioWin comes with a controller package called the BW Controller. There are several parameters in the plant that need controlling such as aeration, wastage flow rate and recycle flow rate. To make sure that all the four aerators are working efficiently, accurate operating policies for the aerators were collected from the plant. To maintain the right amount of dissolved oxygen, the second (B) set of aerators were made to run on a scheduled power supply. Typically, the first (A) set of aerators are mostly run all the time.

The other parameter that needs controlling is mixed liquor suspended solids (MLSS). The Valrico Plant operations staff maintains a MLSS concentration based on various seasons because of the effect of temperature. The MLSS concentration is related to the amount of solids that are recycled back and amount that is being wasted. The wastage and recycling can be controlled by either the splitter flowrates or their split fractions. The problem with operating the plant with high MLSS is the increase in the amount of inert solids in the system result in increasing the load of solids on the clarifiers and hence results in a decreased sludge quality. Therefore, the Valrico Plant maintains an MLSS concentration of around 4500 mg/L.

A controller scheme was applied to the BioWin model to keep the MLSS concentration between 4500-4600 mg/L. MLSS was measured in the oxidation ditch and was manipulated based on the split fractions of the dewatering unit from where the solids are wasted. If the MLSS concentration in the oxidation ditch rises to more than 4600 mg/L, the controller makes sure to start wasting more solids and hence increases the wasting fraction. Similarly, if the MLSS concentration reaches below 4500 mg/L the wasting fraction is decreased.

6.5 Simulation and Result Interpretation

A 30-day simulation starting from the project start date 4/4/2016 was run with the assumptions and settings as listed in the table 6-2. The settings are modified according to the operation log of the plant. The influent data closely represented the flow pattern usually expected at the Valrico Plant. The MLSS concentration was controlled after communicating with the plant operations. The data collected from the BioWin for parameters such as total nitrogen (TN), total kjeldahl nitrogen (TKN), nitrate (NO_3), nitrite (NO_2), total phosphorus (TP), ammonia (NH_4), pH, dissolved oxygen (DO), etc. were compared with the data collected from the county lab. The data collected from the county lab represents the daily average data and the data collected from the BioWin represents hourly data. In order to compare, the BioWin data was converted in to daily averages and was plotted against the lab data from the plant and are show in figure 6-3 to 6-10.

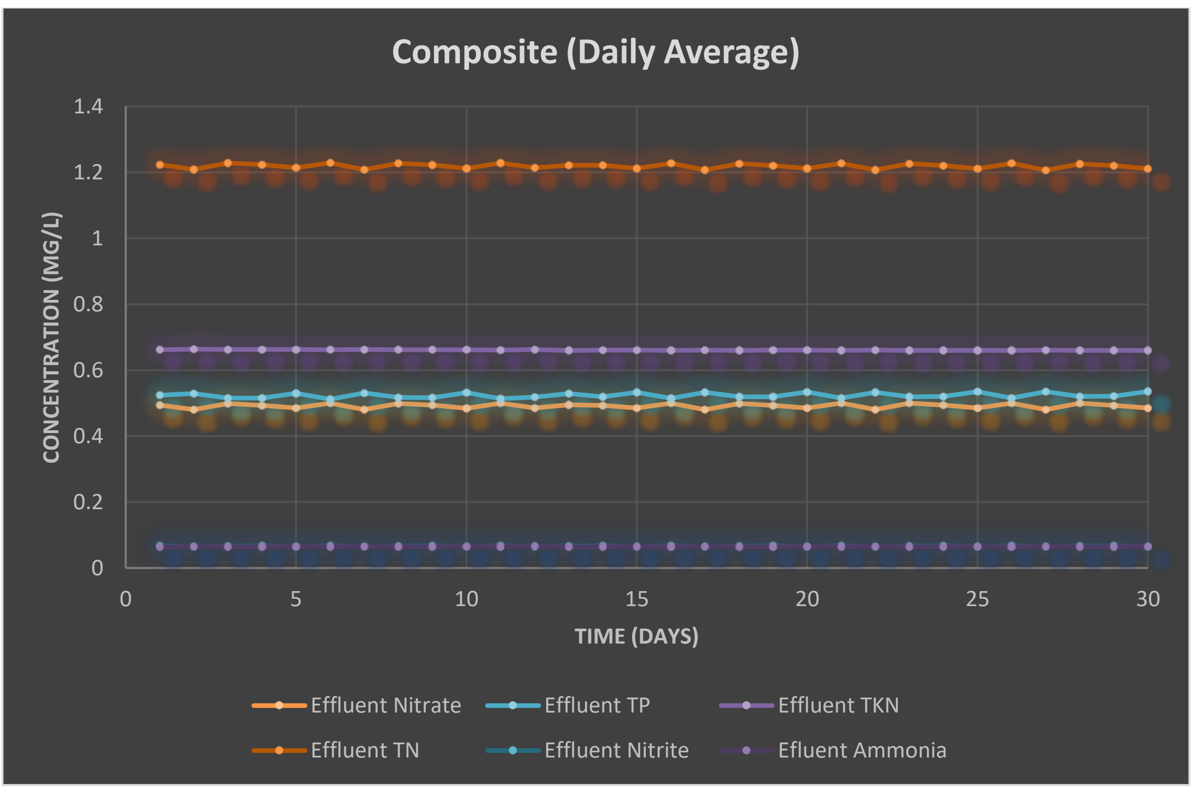

Figure 6-3 Daily Average of Effluent Parameter Concentration vs Time

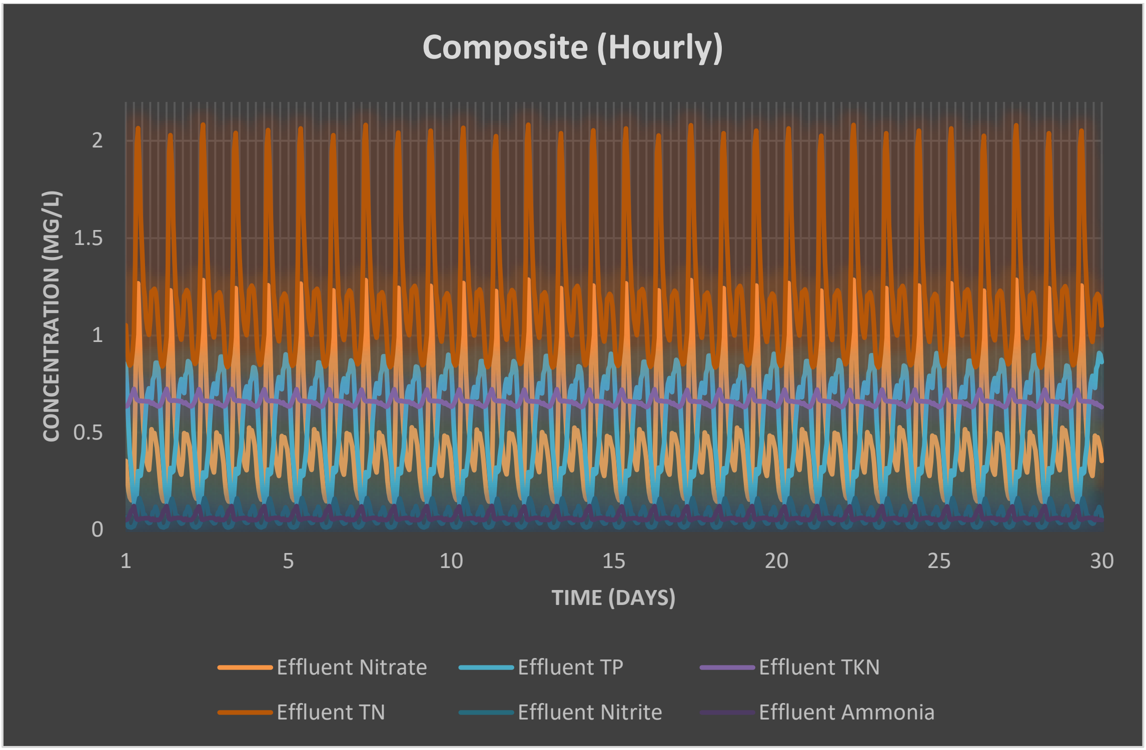

Figure 6-4 Hourly Average of Effluent Parameter Concentration vs Time

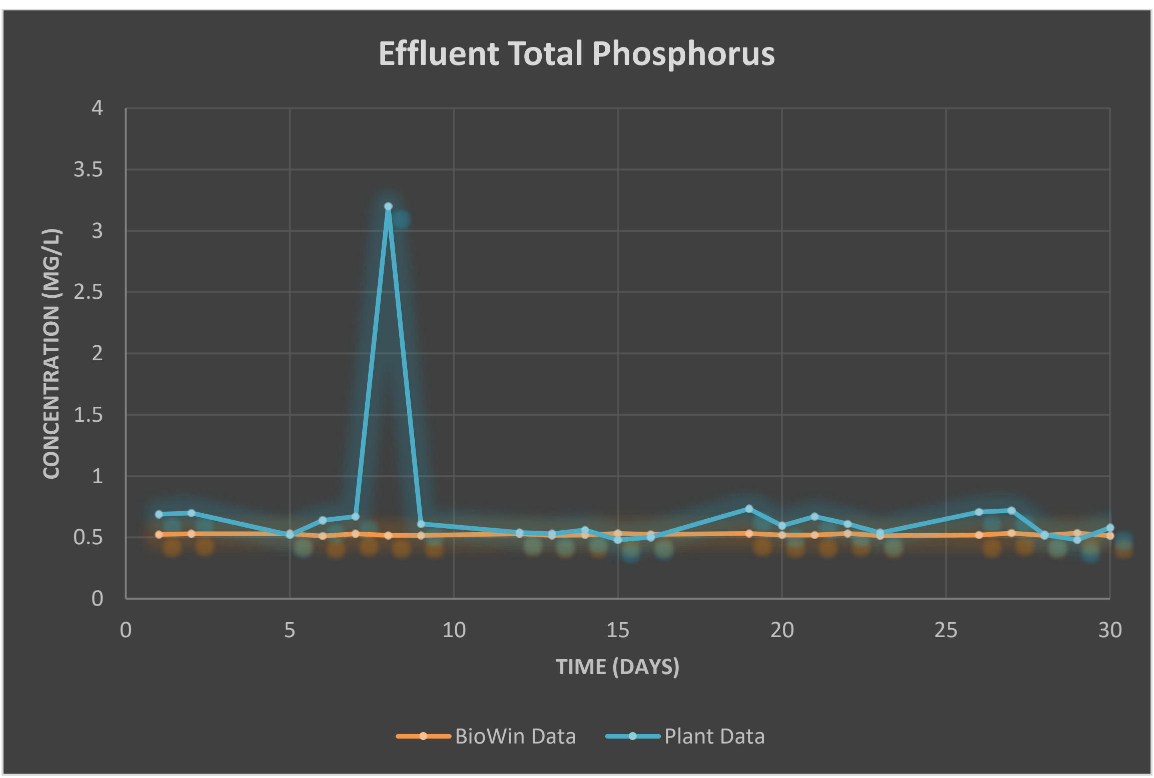

Figure 6-5 Effluent Total Phosphorus Concentration vs Time

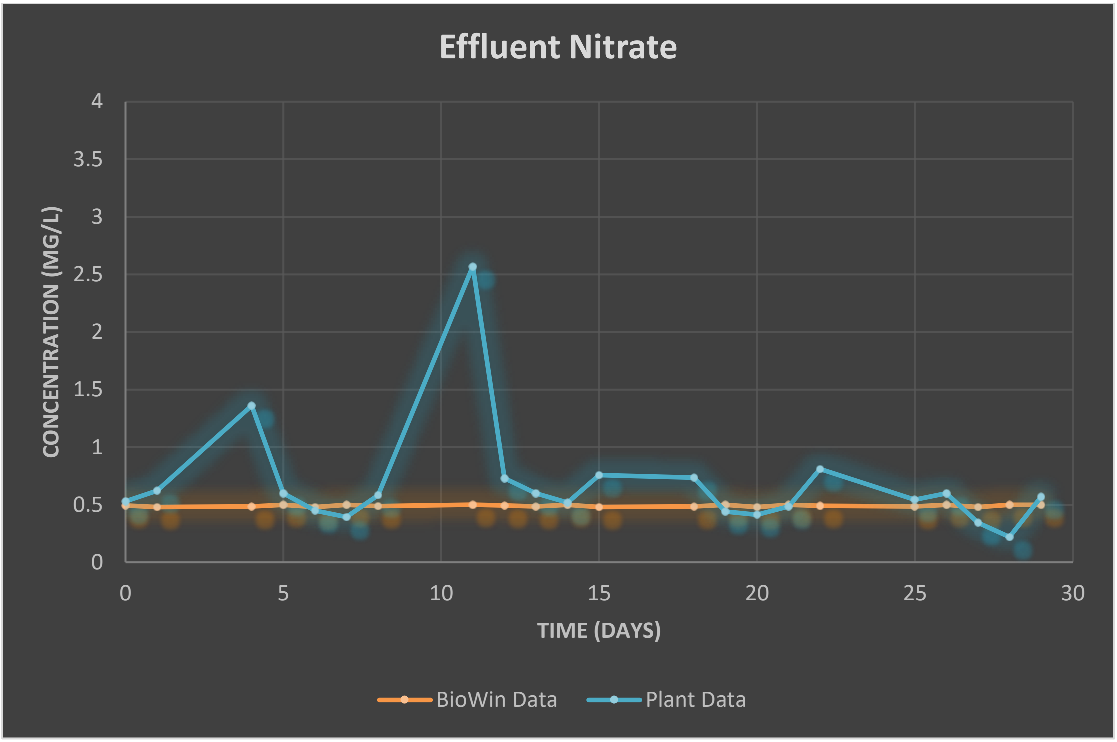

Figure 6-6 Effluent Nitrate Concentration vs Time

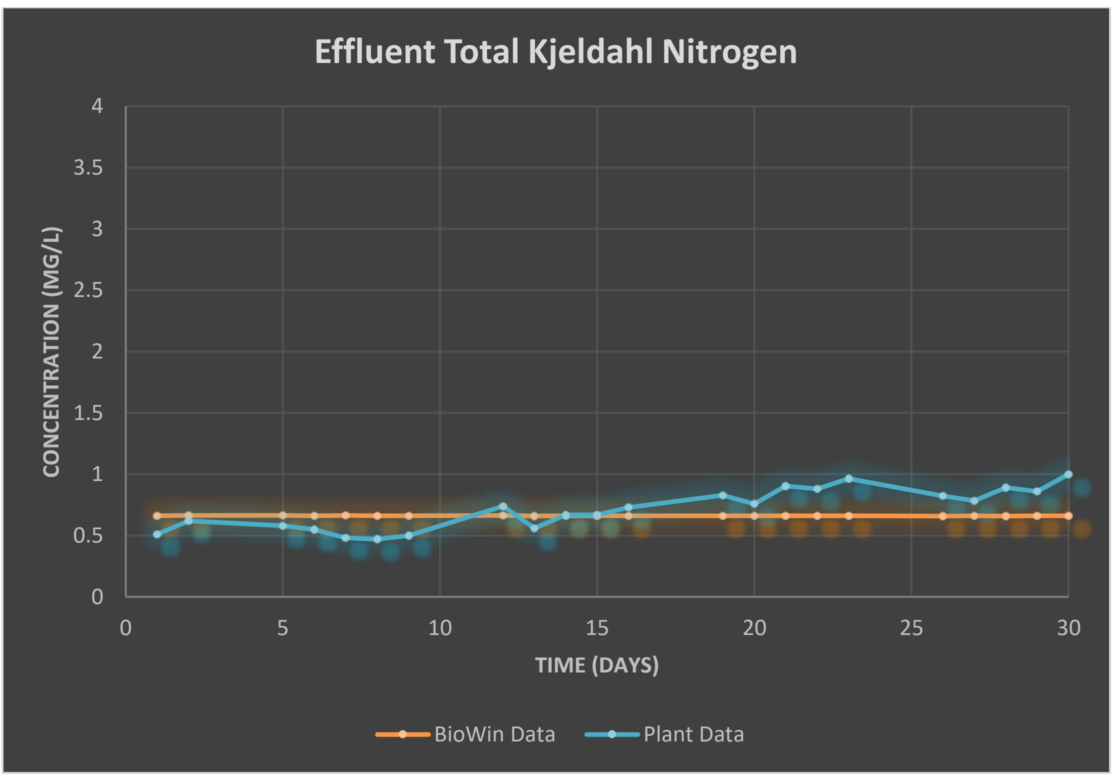

Figure 6-7 Effluent Total Kjeldahl Nitrogen Concentration vs Time

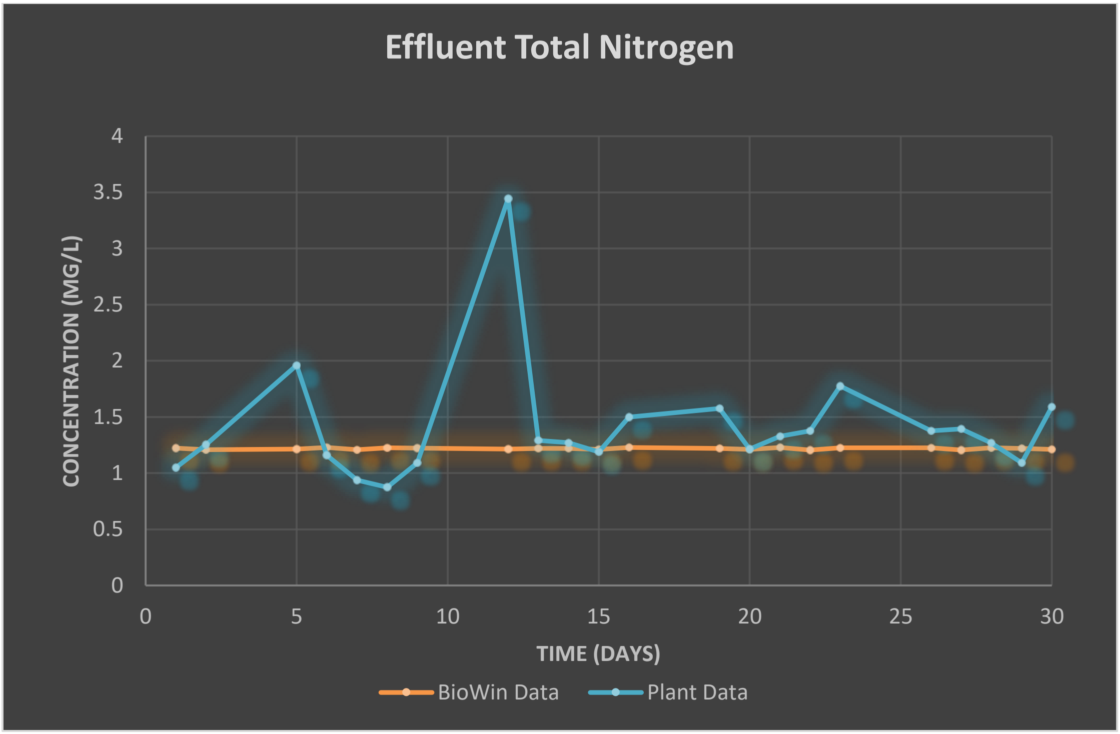

Figure 6-8 Effluent Total Nitrogen Concentration vs Time

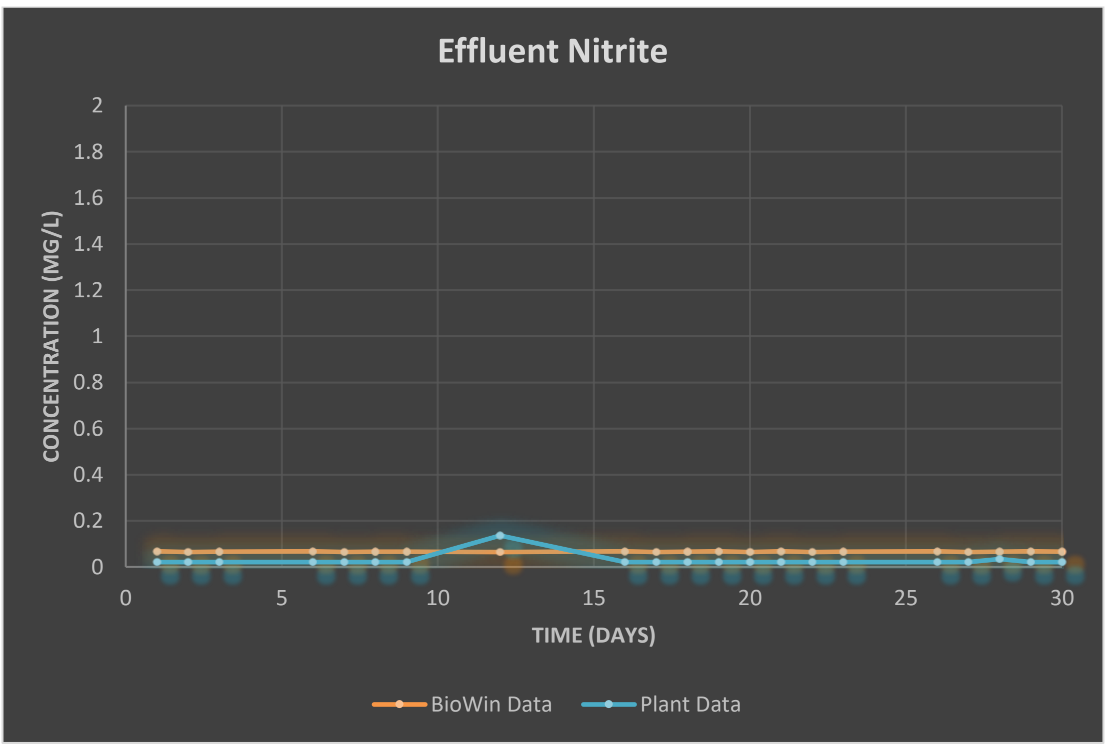

Figure 6-9 Effluent Nitrite Concentration vs Time

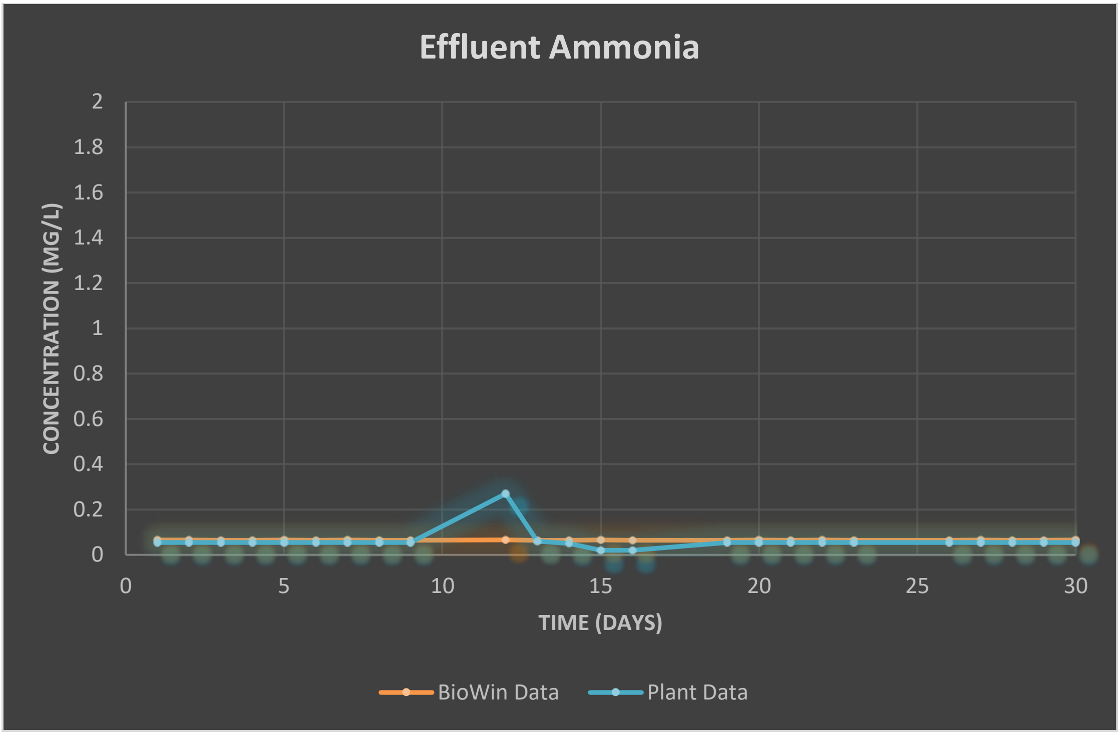

Figure 6-10 Effluent Ammonia Concentration vs Time

As you can see in figures 6-5 to 6-10, the county lab data accurately matches the BioWin data with few exceptions as there might be data gaps, human error or high influent concentration recorded in the plant data on that particular day. The effluent prediction from the model is similar to the effluent concentrations recorded at the plant. The parameters compared are effluent parameters and they all fall within the discharge limits required for the plant. Another 30-day simulation was run from 3/9/2018 to represent the current expected profiles of the plant and the results are show in appendix.

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

The dynamic model for the Valrico Advanced Wastewater Treatment Plant was developed in BioWin. The model was designed and tuned based on the plant data. The model predictions accurately match the plant data. This chapter provides the concluding remarks based on this study as well as the recommendations for future work.

7.1 Conclusion

After data collection and several trips to the Valrico AWWTP, a working BioWin model exactly mimicking the plant was created. A previous model for the plant called the lumped model was developed by the BEST group in which all the oxidation ditches and clarifiers were lumped into one. The lumped model was helpful in providing the initial guess and design settings for the plant but since the equipment were lumped, the model was not the most accurate representation of the plant and there was no scope for individual control settings for each equipment. The expanded model had all four oxidation ditches and six clarifiers with their respective volumes and operating conditions. A scheduled pattern for aeration as it is used in the plant was also implemented in the model. Since, the operations at Valrico AWWTP maintains an MLSS concentration of 4500 mg/L, a control scheme was added to the BioWin model to make sure that the MLSS concentration does not become excessively high or low. The influent flow in the model closely represents the diurnal flow pattern of the plant. The influent data was collected from the SCADA system of the plant and some previously done influent testing results were used to validate the flow pattern. The 24-hour flow pattern was then used in BioWin to run the simulations.

The BioWin model was run for different number of days to make sure that it was working correctly. To validate the BioWin model, the effluent data from the model was compared with the effluent data collected from the testing laboratory of the Valrico AWWTP. Since, the data available from the plant was for the year of 2016 and was in the form of daily averages, a simulation was run for 30 days starting from April 4th, 2016 and the results were converted to daily averages before they were compared to the plant data for the month of April 2016. The parameters studied for the effluent were TP, TKN, TN, ammonia, nitrate and nitrite. The effluent results match the plant data and both the plant and the BioWin model meets the discharge limits set by the NPDES. Since the model predictions accurately match the plant data, the model can be used for predicting effluent behavior and taking control actions in advance. The model is also helpful in developing new control strategies for the plant.

Another 30-day simulation was run from February to March 2018 to predict the current and the future effluent behavior of the plant. The effluent concentrations still seem to be under the permit limits and the results are shown in the appendix.

7.2 Recommendations and Future Work

Other than meeting the NPDES discharge limits, wastewater treatment plants also strive for cost efficiency. To reduce the cost of operation, the plant operations can focus on some of the areas such as, aeration control, wasting control, recycling control, solids retention time, etc. All these parameters have a direct effect on the operating costs of the plant. An effective way to start decreasing these costs is by making sure that these certain parameters are only utilized as much as they are needed. It would be very helpful to have controllers for these parameters which would automatically switch off when not required.

In future, a sample testing campaign can be conducted to validate the influent data that has been fed in the model currently. Although, available influent data has been used in the model, it would be very helpful to get the effluent data in order to be able to develop model-based control strategies. If wastewater sample analysis is done for both influent and effluent, a more accurate data will be available to compare the results with the model. This data can also be used to tune the kinetic parameters of the model and help increase the plant performance. The operations at the Valrico Plant are modified according to the season and the influent coming in. A control system can be developed in the BW controller which mimics the operation log at the plant. This will keep the BioWin model updated with the plant operating conditions and hence provide better predictions for the future.

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APPENDIX A: LIST OF NOMENCLATURE

AAO: Anaerobic-Anoxic-Oxic Parameters

AOB: Ammonia Oxidizing Bacteria

ASM: Activated Sludge Modeling

AWWTP: Advanced Wastewater Treatment Plant

BOD: Biological Oxygen Demand

BNR: Biological Nutrient Removal

BW: BioWin

COD: Chemical Oxygen Demand

cBOD: Carbonaceous Biological Oxygen Demand

CSTR: Continuously Stirred Tank Reactor

DO: Dissolved Oxygen

EPA: Environmental Protection Agency

F/M: Food to Microorganisms Ratio

HRT: Hydraulic Retention Time

IAWPRC: International Association on Water Pollution Research Control

MGD: Million Gallons Per Day

MLSS: Mixed Liquor Suspended Solids

MLVSS: Mixed Liquor Volatile Suspended Solids

NOB: Nitrite Oxidizing Bacteria

NPDES: National Pollutant Discharge Elimination System

O&M: Operating and Maintenance

OHO: Ordinary Heterotrophic Organisms

PAO: Phosphorus Accumulating Organisms

PHA: Polyhydroxyalkanoic Acids

RAS: Return Activated Sludge

rbCOD: readily biodegradable Chemical Oxygen Demand

SBNR: Simultaneous Biological Nutrient Removal

SCADA: Supervisory Control And Data Acquisition

SND: Simultaneous Nitrification Denitrification

SRT: Solids Retention Time

TKN: Total Kjeldahl Nitrogen

TP: Total Phosphorus

TSS: Total Suspended Solids

UCT: University of Cape Town

UV: Ultra Violet

VFA: Volatile Fatty Acids

VSS: Volatile Suspended Solids

WAS: Waste Activated Sludge

WWTP: Wastewater Treatment Plant

APPENDIX B: BIOWIN TUNING

GUIDE

- Enter measured lab data in column on left (**BOLD**)
  (If data is missing, estimate. May need to repeat after Step 2)
- Check resulting fractions (**BOLD**)

Measurements	Value	Unit		Parameter	Value	Unit	Typical range
Main influent concentrations							
Flow	0.0	mgd or m3/d					
Total COD	980.0	mgCOD/L					
Total Kjeldahl Nitrogen	70.0	mgN/L					
Total P	11.7	mgP/L					
Other influent concentrations							
Nitrate N	0.0	mgN/L					
pH	7.3						
Alkalinity (CaCO3 equivalent)	325.0	mgCaCO3/L	→	**Alkalinity (molar)**	6.5	meq/L	2 - 6
Calcium	147.0	mg/L					
Magnesium	32.0	mg/L					
Dissolved oxygen	0.3	mgO2/L					
Other measurements							
Effluent filtered COD	26.5	mgCOD/L	→	**Fus**	0.03	-	0.03 - 0.08
Influent filtered COD (GFC)	392.0	mgCOD/L	→	**CODp**	588.0	mgCOD/L	
Influent FF COD	235.2	mgCOD/L	→	**Fbs**	0.21	-	0.12 - 0.25
Influent acetate	30.0	mgCOD/L	→	**Fac**	0.14	-	0.0 - 0.3
Influent ammonia	48.6	mgN/L	→	**Fna**	0.69	-	0.5 - 0.8
Influent ortho-phosphate	7.0	mgP/L	→	**Fpo4**	0.60	-	0.3 - 0.6
Influent carbonaceous BOD5	490.0	mgO2/L	→	**COD/BOD5**	2.00	-	1.9 - 2.2
Influent filtered cBOD5 (GFC)	245.0	mgO2/L					
Influent VSS	437.0	mgVSS/L	→	**Fcv**	1.35	mgCODp/mgVSS	1.5 - 1.7
Influent TSS	525.0	mgTSS/L	→	**ISS**	88.0	mgISS/L	15 - 45

Figure B-1 BioWin Influent Specifier Input

Influent COD fractions	Default	Estimate	Notes
Fbs	0.160	0.214	*from Step 1*
Fus	0.050	0.026	*from Step 1*
Fup	0.130	**0.157**	*affects BOD, VSS*
Fzbh	0.020	**0.080**	*from separate method*
Fxs	0.640	0.523	*by difference (must be > 0!!)*
Fxsp	0.750	**0.716**	*affects VSS, scale: 0 to 1*

GUIDE

- Change COD fractions **(BOLD)** until match is achieved

Suggestion:

Inhibited cBOD5 = 0.84 x "true" cBOD5

Influent values	Measured (From Step 1)	Calculated (Based on fractions above)	Match Status
CODt	980		
Soluble COD (GFC)	392	381	***Acceptable***
FF COD	235	235	***Excellent***
cBOD5	490	490	***Excellent***
fcBOD5 (GFC)	245	252	***Acceptable***
VSS	437	442	***Acceptable***
TSS	525	530	***Excellent***

Important fractions	(can be used as a check)	
Fraction	Value	Typical range
COD/cBOD5	2.00	1.9-2.2
Sol. COD fraction	0.39	0.3-0.5
VSS/TSS	0.83	0.75-0.85

dif	ss
124.4670913	231.34
0	
3.27553E-08	
52.03905999	
27.41640839	
27.41640839	

Calculated concentrations (from CODt & fractions)		
Sus	25	
Xi	154	
Sbs (Sbsc + Sbsa)	210	
Sbsc	180	
Sbsa	30	
Xs (c+p)	513	
Zbh	78	
Xsc	146	Added to Ss for BOD calcs
Xsp	367	

Figure B-2 BioWin Influent Specifier Solver

APPENDIX C: BIOWIN SIMULATION RESULTS

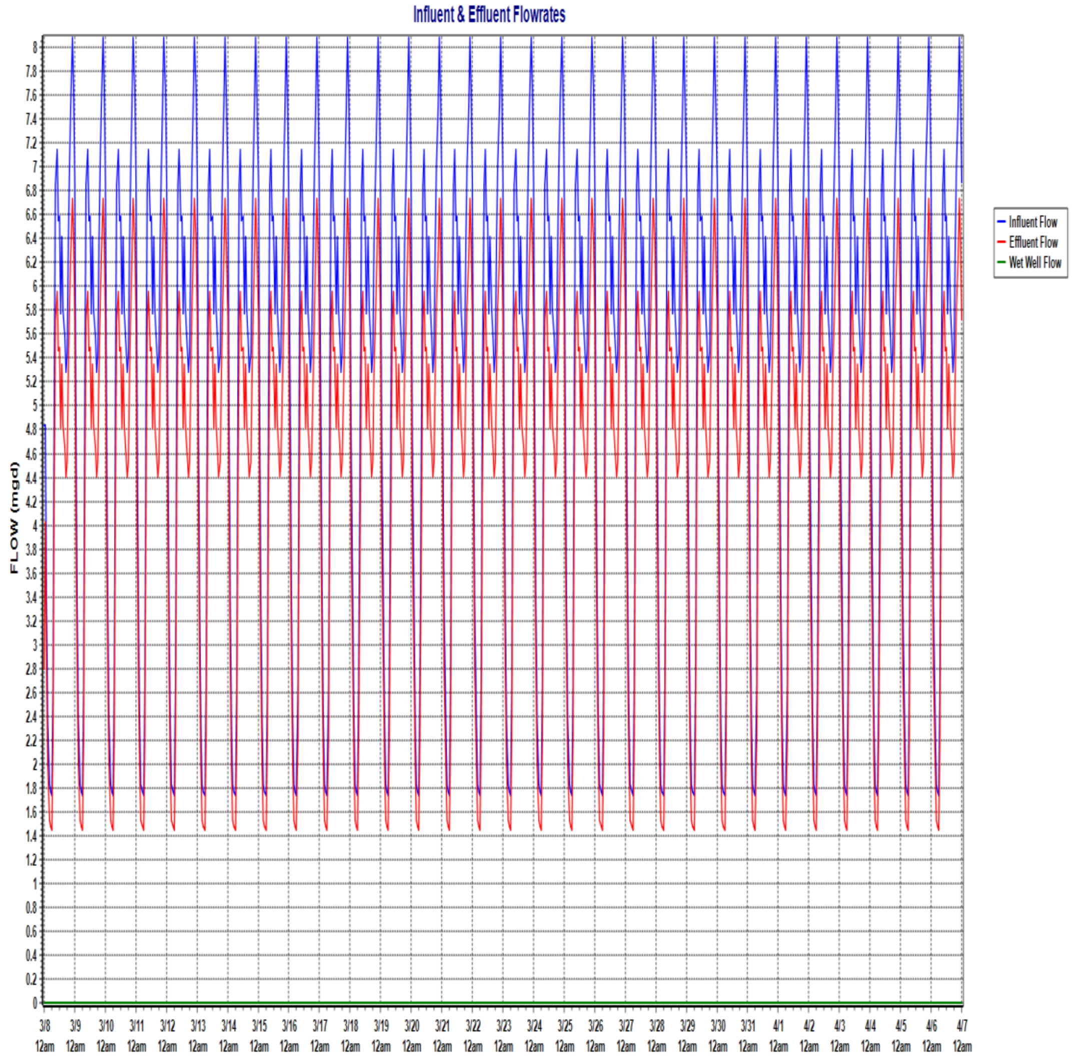

Figure C-1 30-day Influent and Effluent Flowrate Profile

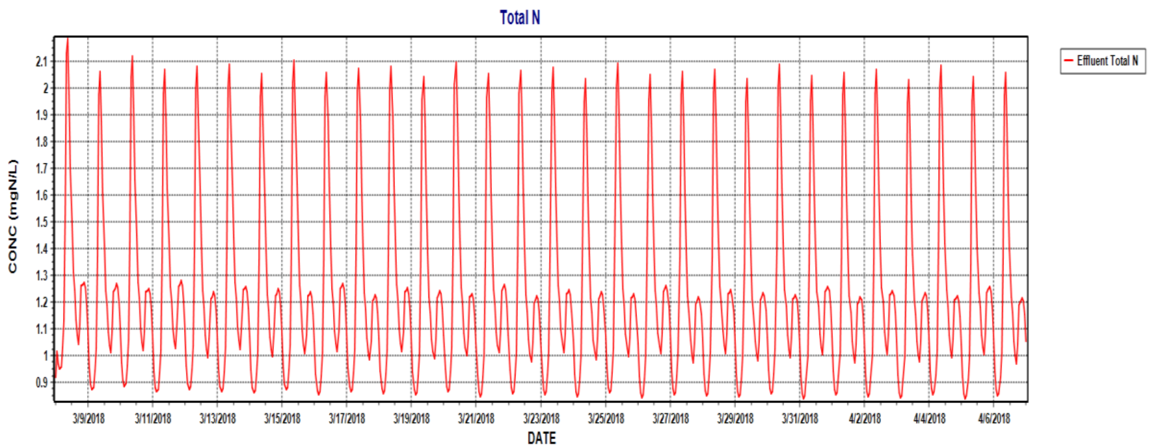

Figure C-2 30-day Effluent Total Nitrogen Concentration Profile

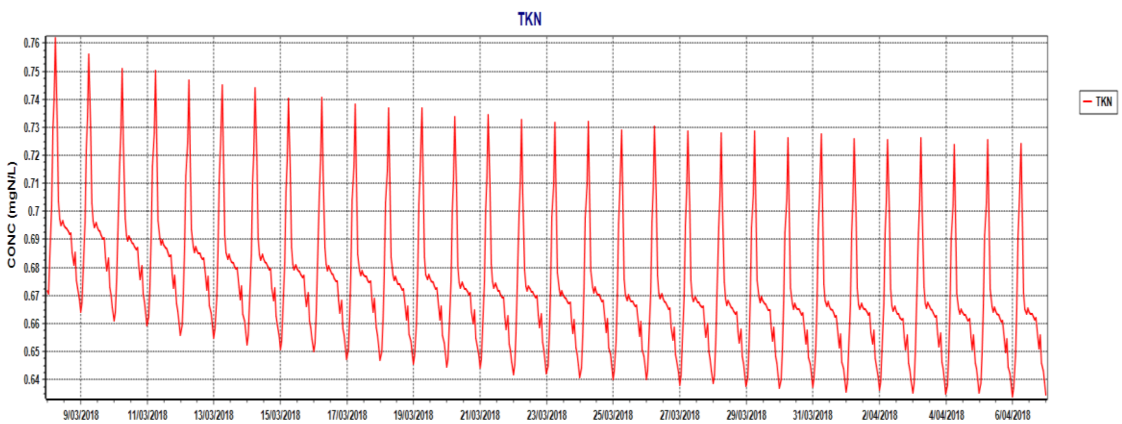

Figure C-3 30-day Effluent Total Kjeldahl Nitrogen Concentration Profile

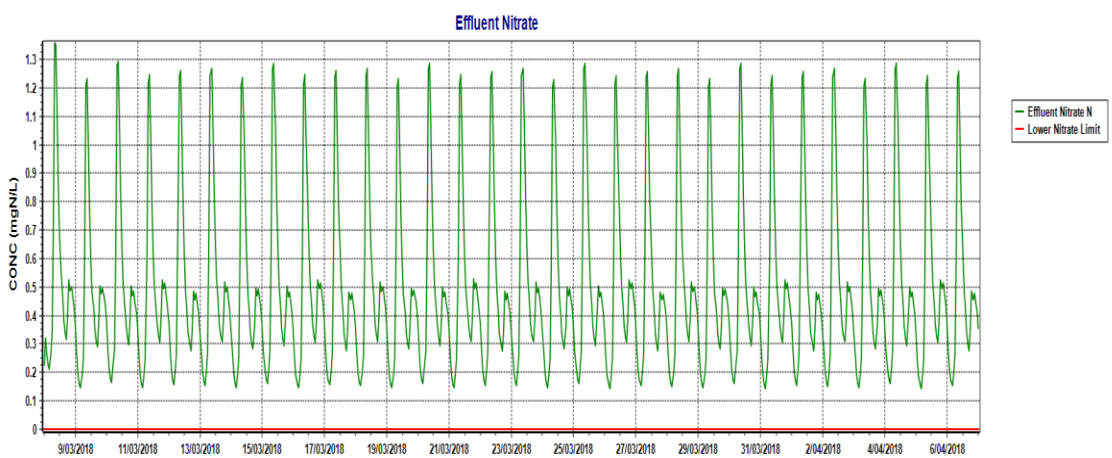

Figure C-4 30-day Effluent Nitrate Concentration Profile

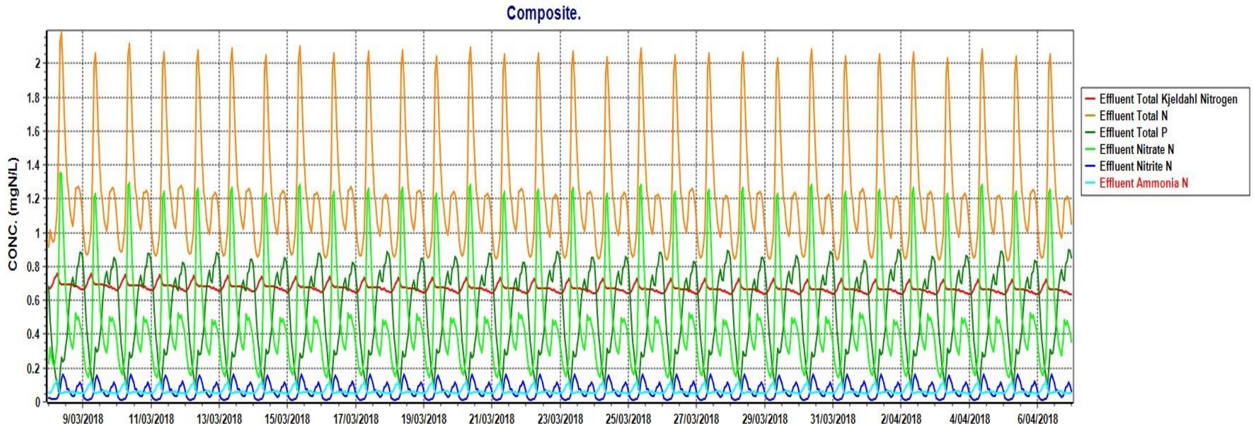

Figure C-5 30-day Effluent Composite Concentration Profile

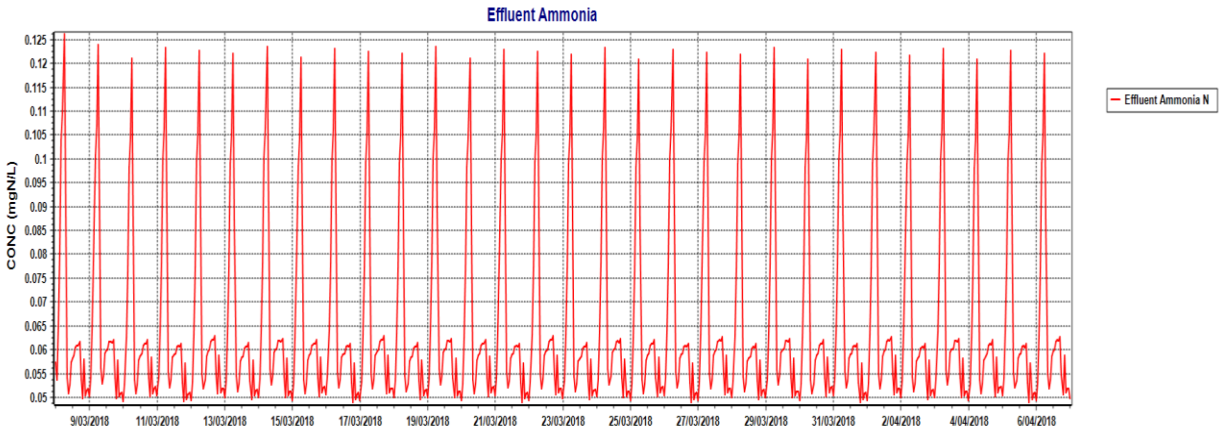

Figure C-6 30-day Effluent Ammonia Concentration Profile

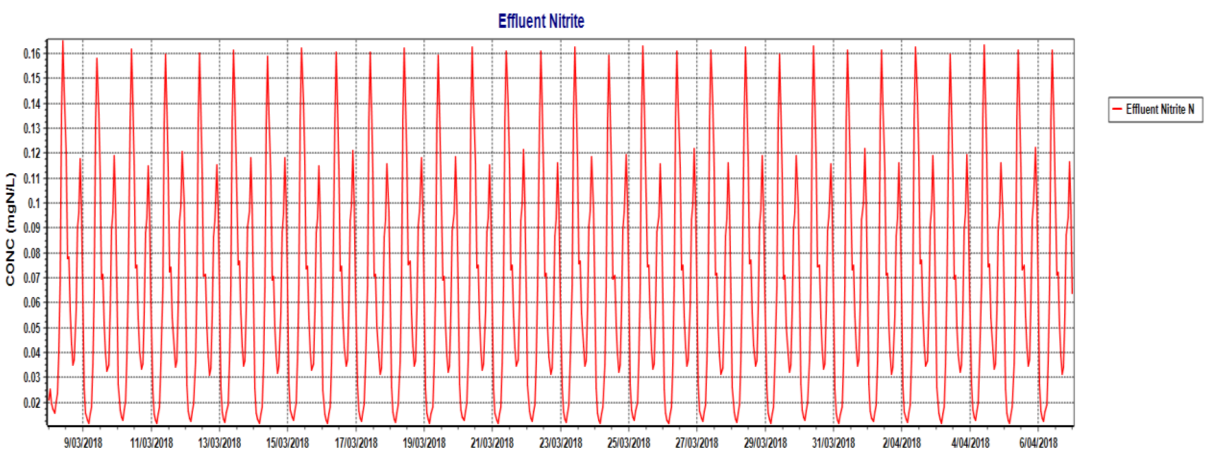

Figure C-7 30-day Effluent Nitrite Concentration Profile

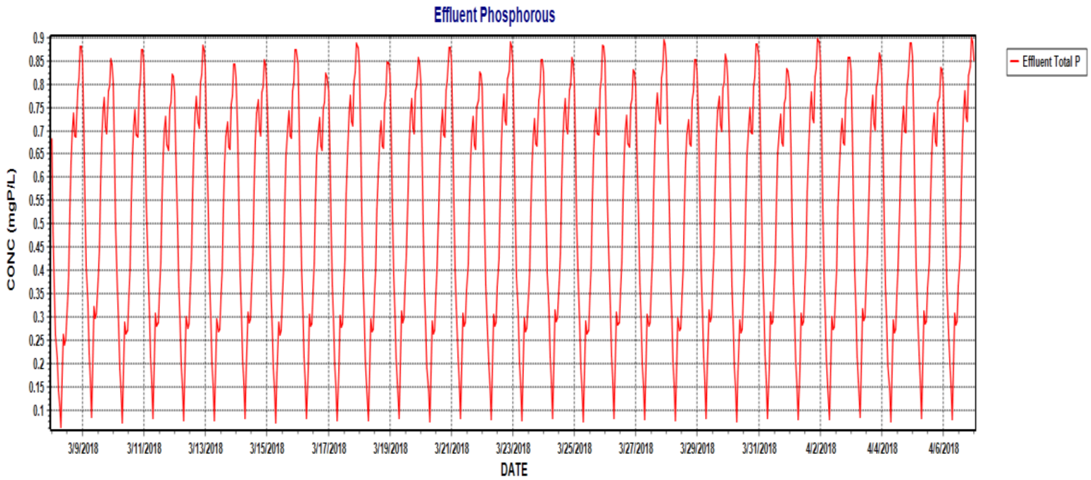

Figure C-8 30-day Effluent Total Phosphorus Concentration Profile

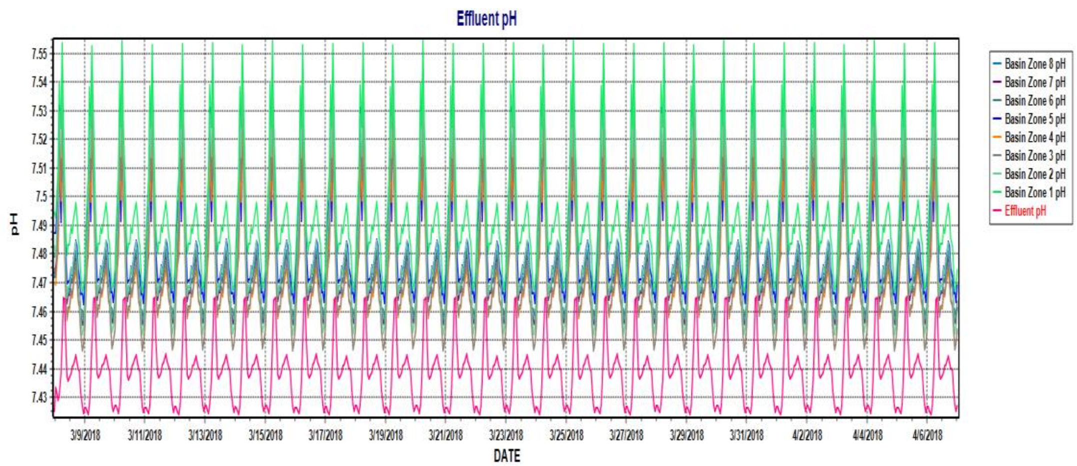

Figure C-9 30-day pH Concentration Profile

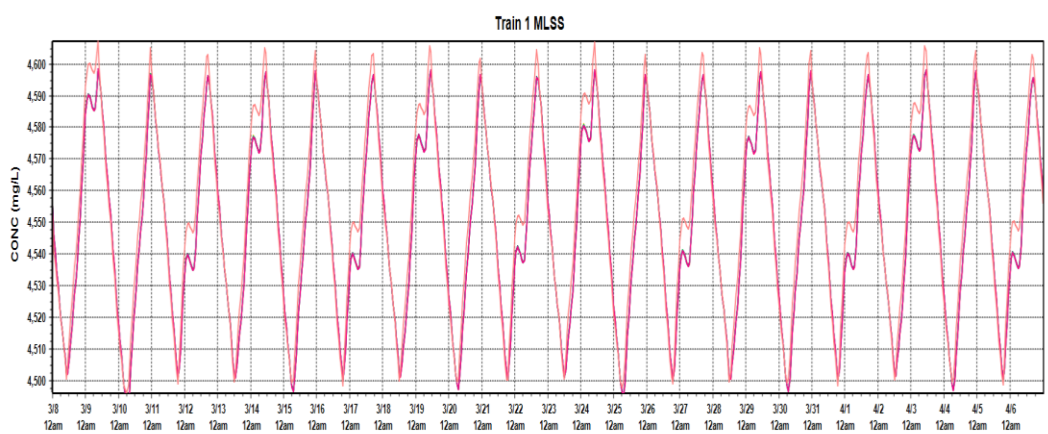

Figure C-10 30-day Mixed Liquor Suspended Solids Profile in the Oxidation Ditch

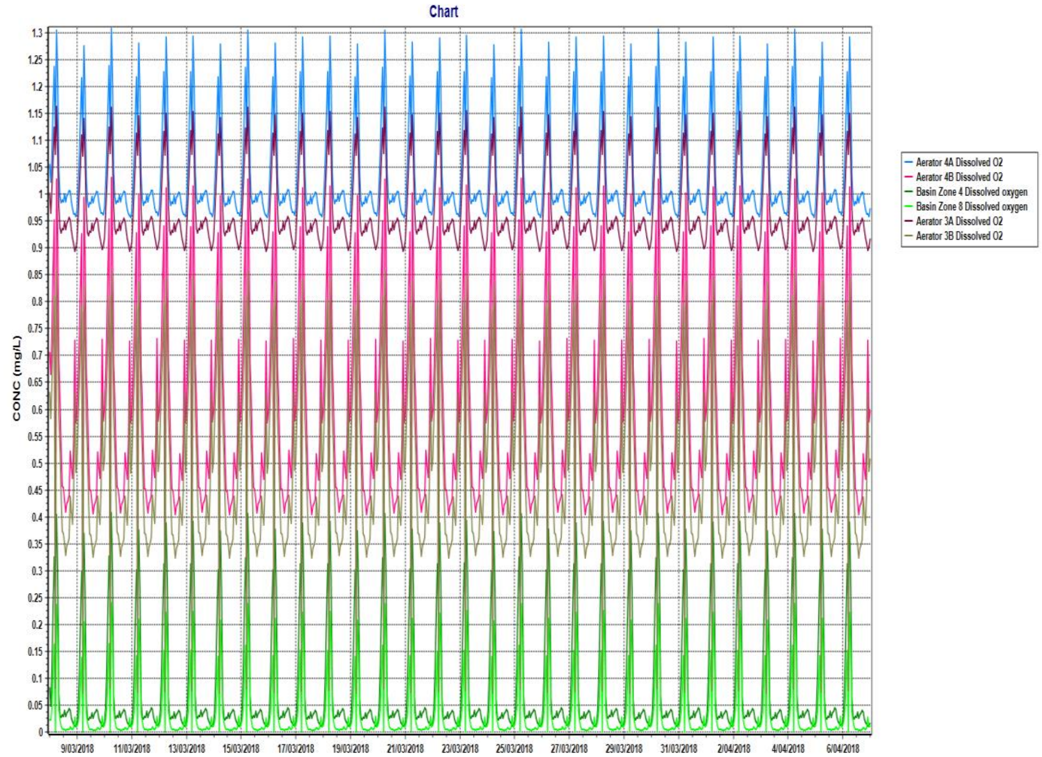

Figure C-11 30-day Dissolved Oxygen Profile