Evaluation of IMET^{TM} Technology for Enhancement of Wastewater Sludge Digestion

by

Mevan C. Dissanayake

Submitted in Partial Fulfillment of the Requirements

for the degree of

Master of Science in Engineering

in the

Civil and Environmental Engineering Program

YOUNGSTOWN STATE UNIVERSITY

May, 2014

Evaluation of IMET™ Technology for Enhancement of Wastewater Sludge Digestion

Mevan C. Dissanayake

I hereby release this thesis to the public. I understand that this thesis will be made available from the OhioLINK ETD Center and the Maag Library Circulation Desk for public access. I also authorize the University or other individuals to make copies of this thesis as needed for scholarly research.

Signature: _____
Mevan C. Dissanayake, Student Date

Approvals: _____
Dr. Scott C. Martin, Thesis Advisor Date

_____
Dr. Suresh Sharma, Committee Member Date

_____
Dr. Douglas M. Price, Committee Member Date

_____
Dr. Salvatore A. Sanders, Associate Dean of Graduate Studies Date

ABSTRACT

This study evaluated the IMET™ technology for the enhancement of sludge digestion in comparison to the existing aerobic digesters at the Columbiana WWTP, where the study took place. This evaluation was based on changes in solids and organic matter, and the fate of nutrients, in an IMET pilot plant system. For a study period of eleven weeks, samples were collected from seven different locations in the IMET system, on a weekly basis, and were tested for various parameters included under the study's scope of work. The analysis of data focused on sludge digestion in three process tanks that contained IMET bioreactor modules, and the process of biosolids breakdown in the system's solubilization tank. The results of this study showed decreases of less than 2% of all solids and organic matter parameters in the IMET process tanks, which were considered statistically insignificant by the t-test for paired observations. Weak evidence was shown that the system's venturi and/or ozonation units had some impact on the solubilization of biosludge. Small decreases in nutrient concentrations (< 10.0%) were observed and deemed statistically plausible by the t-test for paired observations, thus, showing signs of biological activity in the IMET process tanks. A comparison between the IMET system and the aerobic digesters, at equivalent detention times, showed a slightly higher reduction of total COD and VSS in the IMET system. This difference was deemed statistically insignificant, after calculating confidence intervals for the mean values of IMET system's outflow concentrations, at confidence levels as low as 20%.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Scott Martin, for guiding me through this study and providing me with insurmountable amounts of support throughout the whole process. I would also like to extend my gratitude towards the committee members, Dr. Suresh Sharma and Dr. Douglas Price, for aiding this study with their invaluable suggestions.

This study would not have been possible without the tireless efforts of the IMET Corporation, and Columbiana County. Therefore, I would like to thank Dr. Mehmet Gencer and Kaan Gencer from IMET Corporation, for allowing me to do analysis on their technology and also for their helpfulness in all of my questions. Also, I would like to thank the staff of the Columbiana County Wastewater Treatment Plant, led by Brian Dicken, for being so accommodating to my research team throughout the entire study, and also for their assistance in laboratory analysis and sample collection.

I would like to thank my research partner, Sentel Rodgers, who bore half of the burden of all the hard work we did in the summer of 2013, and making possible all the results that were obtained. I would also like to thank Darshan Baral and Aashish Shrestha for their words of encouragement and guidance during this time.

Finally, I would like to express my appreciation towards my dear family and all of my friends who stood by me and provided me with immeasurable support throughout the past two years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Introduction

1.1 Description

This project focuses on the evaluation of an alternate sludge digestion technology developed by IMET Corporation and comparison with the existing aerobic digesters at Columbiana Wastewater Treatment Plant (WWTP). In this WWTP, the treated wastewater goes through a secondary clarifier, from which the sludge-free supernatant goes on towards filtration and ultraviolet (UV) light disinfection, while the sludge collected at the bottom of the clarifier arrives at the digesters. Sludge digestion is a vital component in the treatment process of wastewater, as it is necessary to reduce the organic matter and microorganisms contained in the waste streams from settling processes. The ultimate goal of this study was to determine whether the IMET system would be more effective than the existing digestion system in the reduction of produced sludge.

Columbiana WWTP treats an average of 2.35 million gallons a day (MGD) of wastewater from the local area and has the capability of providing secondary treatment to this influent (Brian Dicken, personal communication, 2013). The main components of this treatment plant are the oxidization ditch, secondary clarifiers, filtration units and aerobic sludge digesters. The plant has four separate digestion tanks that operate individually and are filled up and drained out as needed. After a digestion period of about two months, the digested sludge is conveyed into a building where it is fed into a dewatering unit that uses a belt press in order to squeeze the water out of the sludge. The dewatered sludge is then transferred to drying beds and given out to the farming communities of the area as fertilizer.

1.2 IMET System

The IMET system for sludge digestion is an experimental process of aerobic digestion with the goal of reduced sludge production. This system was run adjacent to the aerobic digesters in Columbiana WWTP during the analysis period of the project. A schematic diagram of the system is shown in Figure 1.1. Several photos of system components are presented in Appendix C.

Sludge was first pumped from a single existing aerobic digestion tank into the primary and secondary feed tanks before being fed to the solubilization tank, where sludge was continuously recirculated through a venturi unit. The venturi effect was expected to cause the cell walls of the microorganisms within the wastewater to rupture, releasing the cytoplasm held inside them and accelerating the digestion process.

The most unique aspect of this treatment process is the use of proprietary IMET bioreactors within three process tanks. In order to increase the rate of cell decomposition within these process tanks, the IMET bioreactors were used to consume the organic matter in the cytoplasm away from the reactor environment. The cylindrical IMET bioreactors contain support media and bio-film which help them perform this process. Within the main IMET system, there were four process tanks in a series arrangement. While the first and second tanks had four bioreactors in each of them, the third tank had two bioreactors, and there were none in the fourth and final tank. These bioreactors also had air pumps running continuously to deliver compressed air through the center of each

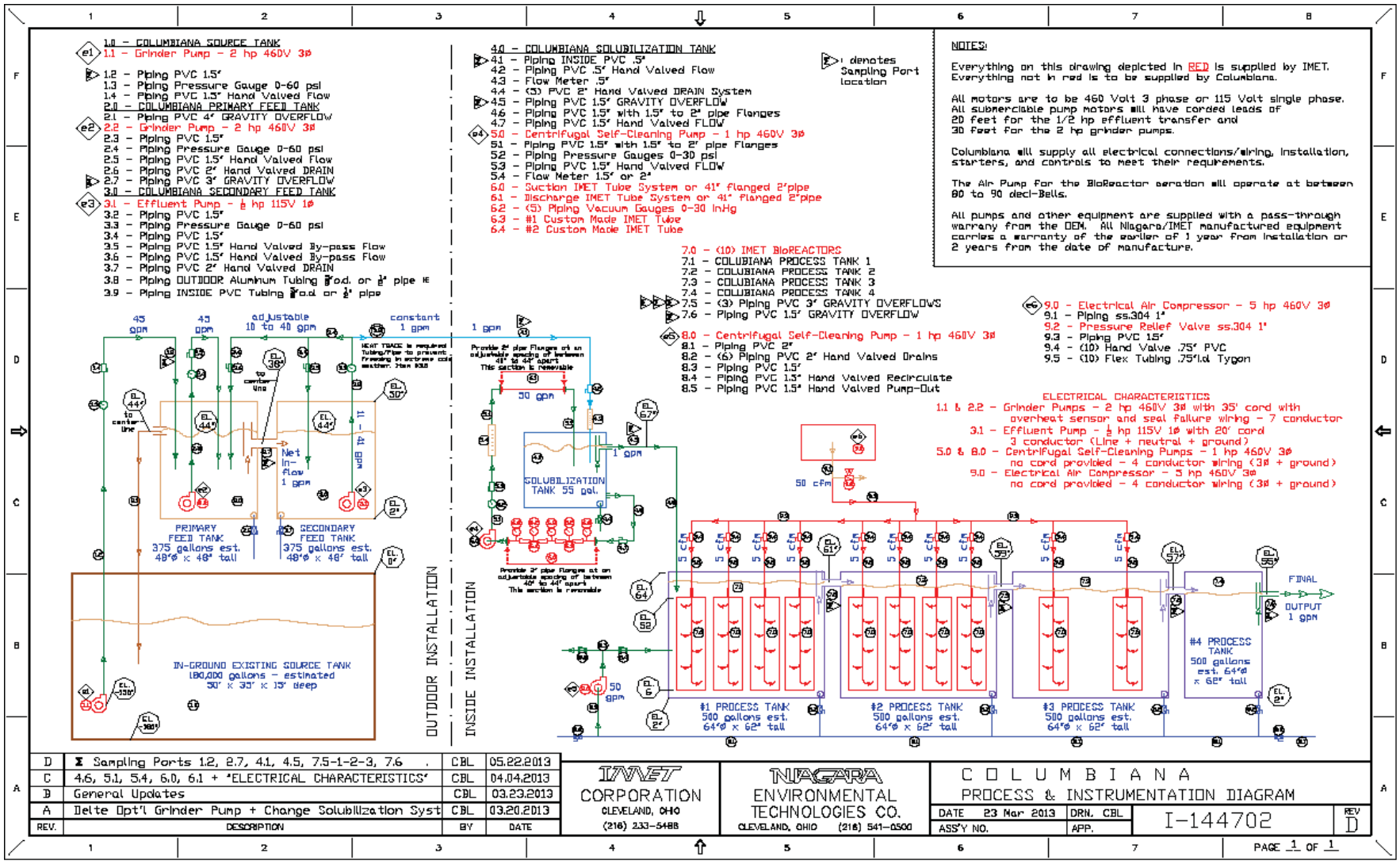

Figure 1.1: Schematic diagram of IMET system (IMET Corporation, 2013).

of them, providing constant aeration to the three tanks. The fourth tank was used primarily as a settling tank before the water was finally discharged.

1.3 Study Objectives

The scope of work for this study can be categorized into two important parts - the digestion of solids and organic matter and the fate of phosphorous and nitrogen. The primary objectives of this study were to collect background data on solids and sludge production at the WWTP, and to measure the changes in solids and organic matter as sludge flows through the IMET system. In addition, since the microorganisms in wastewater treatment are dependent on nutrients such as phosphorous and nitrogen, and effluent limits are imposed for some of these substances, it is also important to keep track of the amounts available within each digestion system at the WWTP. Therefore, this study also evaluated the nutrient cycling within the IMET reactors. This was designed to provide an accurate picture of the state of biological processes within each digestion system, and to allow estimation of the loading of nutrients that would be added back to the head works of the plant via dewatered supernatant from the sludge press.

CHAPTER 2

Literature Review

2.1 Overview of Wastewater Treatment

The importance of proper sewage (wastewater) disposal has been recognized as a necessary element of a growing infrastructure since the time of the ancient Mesopotamian civilizations. However, the primitive sewage collection systems were not improved upon into proper wastewater treatment mechanisms until the nineteenth century, when the surge of industrialization struck the western world. With the advances of technology in urbanized towns and industrial facilities that manufacture a variety of products through chemical and artificial processes, wastewater treatment has become a service of utmost priority in the modern world.

In order to protect human health and the environment, municipal wastewater treatment facilities must be capable of converting any constituent that they receive in their influent into effluent that is safe enough to be discharged back into natural waterways. Generally, three levels of treatment are considered. Primary treatment refers to the processes involved in physically removing solid constituents from wastewater. This entails preliminary processes such as screening for large objects such as sticks and cloths, and to grinding up smaller waste solids that will be filtered later. The most important aspect of primary treatment is the settling and disposal of the suspended solid particles in the wastewater stream. However, the root of the harmful consequences of wastewater lies in the dissolved and particulate organic constituents, pathogens, and nutrients that cannot be removed by gravity settling. It is due to this that secondary treatment is implemented in treatment plants in order to biologically remove organic matter from the influent, and

make it safe for discharge into the environment. In many cases, the governing bodies that determine the standards for discharging treated wastewater require the wastewater to undergo further tertiary treatment, which can consist of nutrient removal, filtration, and/or disinfection methods such as chlorination and UV treatment (Vesilind *et al*., 2004).

2.2 Biological Wastewater Treatment

The primary objective of biologically treating domestic wastewater is to transform dissolved and particulate constituents into acceptable end products, by capturing and incorporating suspended and non-settleable colloidal solids into a biological floc or biofilm, while also removing nutrients such as nitrogen and phosphorous from the influent (Metcalf & Eddy, 2003). This type of treatment is designed to achieve acceptable levels of organic materials as measured by biochemical oxygen demand (BOD) or chemical oxygen demand (COD). Microorganisms are usually maintained in an aerated environment that provides them with the factors needed to consume organic matter in the influent.

Biological treatment processes can be categorized in two ways – suspended growth and attached growth processes. These processes are principally distinguished by the type of media utilized in each process. In suspended growth processes, microorganisms are maintained in a liquid suspension while being provided with mixing. These processes can be performed in both aerobic (positive dissolved oxygen) and anaerobic (no oxygen present) conditions. Attached growth processes require a form of solid packing media for the microorganisms to grow on. This attached growth is known as a biofilm. The wastewater, along with its organic material and nutrients, is applied

externally onto the biofilm. With adequate aeration, the microorganisms are capable of consuming organic matter from the applied wastewater (Metcalf & Eddy, 2003).

Any living organism can be categorized as either prokaryotic or eukaryotic cells based on genetic functionality and cell structure. Prokaryotes have a simple cell structure and are commonly seen in bacteria and blue-green algae, while eukaryotes are single-celled and more complex and are typically found in fungi, protozoa and other multi-celled plant and animal organisms. A wide variety of microorganisms such as bacteria, fungi, algae, viruses, and protozoa can be found in wastewater. While some of these organisms can be harmless, others (pathogenic organisms) are capable of spreading infectious diseases to humans and other animals alike. Most of these organisms originate from the excrement of humans and other animals which is largely abundant in the influent to a wastewater treatment plant (Metcalf & Eddy, 2003).

Figure 2.1 shows the typical cell components of prokaryotic and eukaryotic cells. This figure illustrates that the cell structure of eukaryotes is more complex than that of prokaryotes. All cells are encapsulated by a cell wall and the internal components are contained within a cytoplasmic media. Cytoplasm is formed by an aggregate of ribose nucleic acid (RNA), volutin granules (polysulphates, sulfur), and storage products (glycogen, lipids) (Metcalf & Eddy, 2003).

The basic model of a domestic wastewater treatment plant would include primary, secondary and tertiary treatment components. Figure 2.2 shows a schematic diagram of a typical plant.

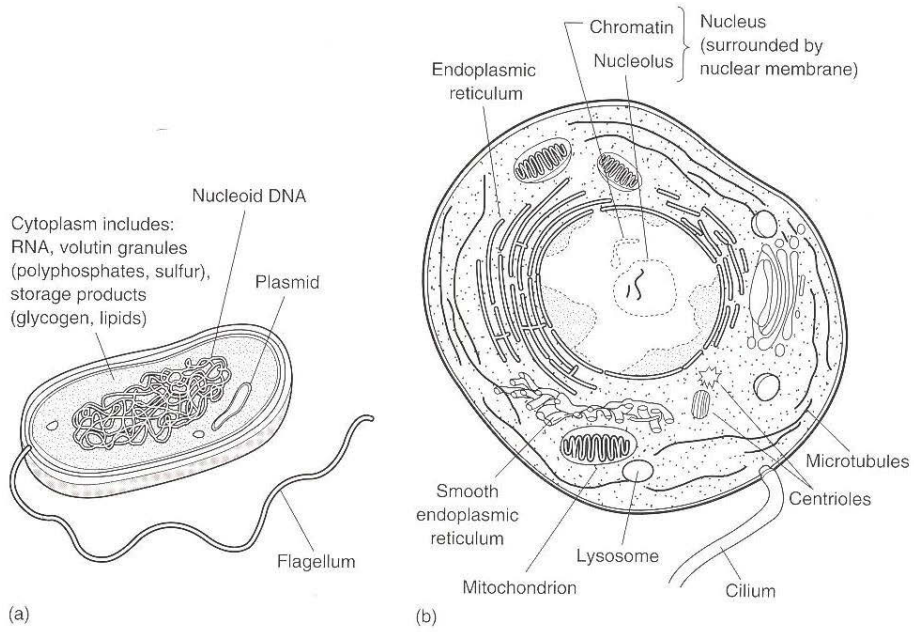

Figure 2.1: Typical cell structure; (a) prokaryotic cell, (b) eukaryotic cell (Metcalf & Eddy, 2003)

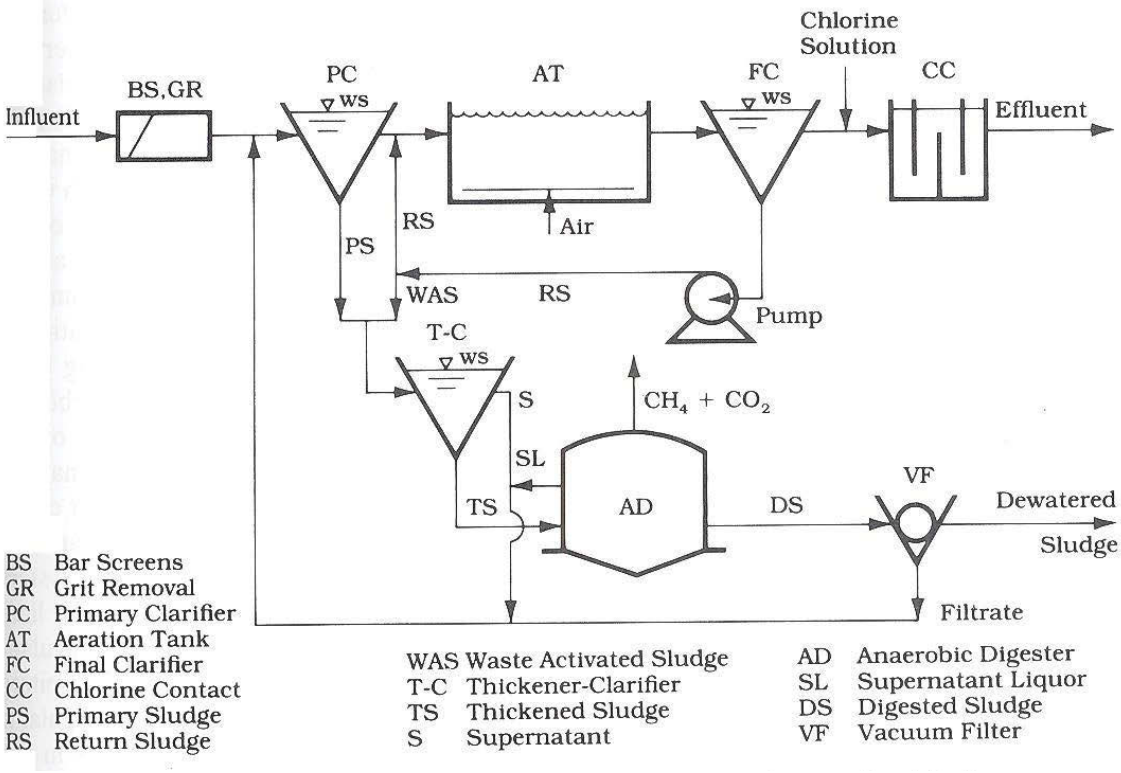

Figure 2.2: Activated Sludge plant for domestic wastewater (Reynolds and Richards, 1996)

First, the influent would go through bar screening and grit removal mechanisms in order to eliminate most of the coarse solids and sand/silt, respectively. Next, the primary clarifier would remove a substantial amount of suspended solids through settling, while conveying the remainder of the wastewater into the subsequent aeration tanks, where the aforementioned biological processes take place. These tanks are well aerated in order to ensure the microorganisms digest the organic matter to the best of their abilities. Alternatively, an attached growth biological process may be used. Biological treatment is followed by a final clarifier that performs further settling to remove the biomass from the wastewater. The minimal amount of tertiary treatment shown in this basic treatment system illustrates how the mixed liquor is conveyed through a chlorine contact unit before finally being discharged into natural water bodies. The amount of tertiary treatment processes could be increased based on the needs of the plant (Reynolds and Richards, 1996). Differences between this basic treatment system and the Columbiana WWTP, along with the exact specifics of its treatment units, are discussed later in this chapter.

2.3 Activated Sludge Process

The activated sludge process utilizes a mixed growth of microorganisms contained within a fluidized media under aerobic conditions to consume the organic material within wastewater as a food source, thereby eliminating it through the process of microbial respiration. The mixture of wastewater and the activated sludge process fluids are known as mixed liquor, and the suspended solids found within them as mixed liquor suspended solids (Reynolds and Richards, 1996).

In the early 1880's, Dr. Angus Smith studied the effects of increased aeration of wastewater and its correlation with organic matter, and this is considered to be the precursor to the modern activated sludge process that is used in biological treatment plants all around the world. Further research in the early 1900's led to better understanding of the importance of sludge within aerated tanks (Metcalf & Eddy, 2003).

There are three important components to the activated sludge process – a reactor containing the aerated and suspended microorganisms; a sedimentation tank for solids separation; and a recycling pump to return the solids removed from the liquid-solid separation processes to the reactor. Figure 2.3 illustrates how the activated sludge process works using these individual components.

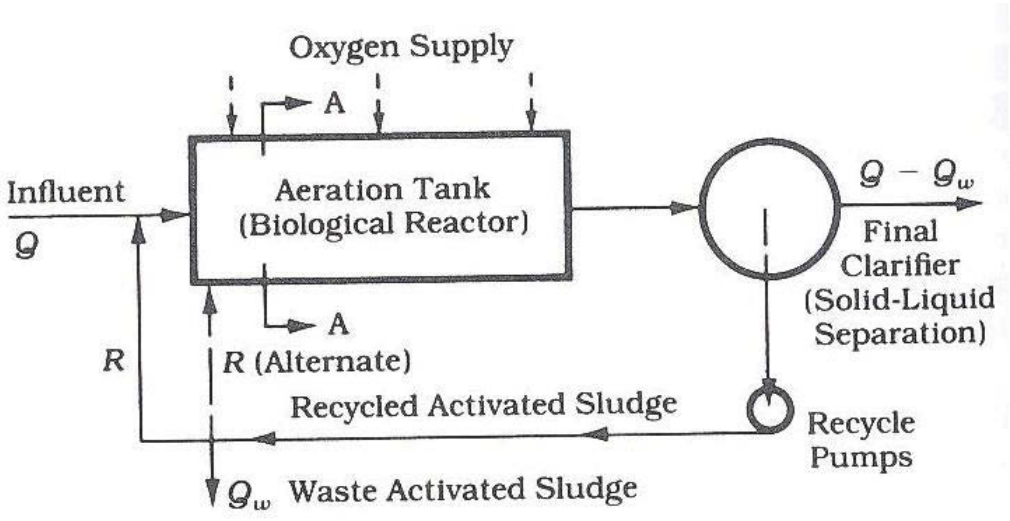

Figure 2.3: Activated Sludge process flowsheet (Reynolds and Richards, 1996)

The influent from the primary clarifier enters the biological reactor and the "mixed liquor" (i.e. mixture of microorganisms and wastewater) is provided with ample

aeration for the digestion of organic matter by microorganisms. The mixed liquor then moves to the final clarifier for sedimentation, resulting in the sludge particles settling at the bottom of the clarifier. The settled sludge from the final clarifiers is subject to a division between wasting and reuse. Some of the settled sludge is recycled back to the aeration tank to increase the concentration of microorganisms in the tank, while the rest is pumped to a separate unit that handles the digestion of sludge. The recirculation ratio is selected to achieve the desired balance of food (organic matter) and microorganisms in the biological process tank. The waste sludge usually undergoes a digestion process prior to dewatering and disposal. Due to the recurring use of microorganisms in the sludge, this process is known as the activated sludge process (Reynolds and Richards, 1996).

While biological treatment is effective in removing soluble, colloidal, and particulate organic substances, nitrification and denitrification, and phosphorous removal, the most efficient removal of settleable solids occurs through primary clarification. However, in smaller wastewater treatment plants (such as the Columbiana WWTP), this step may be omitted, and the system designed in a manner such that the biological treatment and the secondary clarification are capable of adequately treating the influent without primary sedimentation (Metcalf & Eddy, 2003).

2.4 Attached Growth Processes

Attached growth processes can be categorized into non-submerged attached growth processes, suspended growth processes with fixed-film packing and submerged attached growth processes. These processes can be executed in both aerobic and anaerobic settings. In modern days, the packing media is typically made out of plastic or some other synthetic material. However, when the technology was initially being

pioneered in the early 1900's, materials such as rock, gravel, sand, slag, and redwood were used (Metcalf & Eddy, 2003).

The most common non-submerged attached growth process is the trickling filter, a method that has been used since the early 1900's. A trickling filter can be described as a non-submerged fixed-film packing unit over which wastewater is distributed. The surface of the filter is covered in a biofilm, and as the liquid is "trickled" onto its surface, the treatment occurs. Modern plastic media provides a porous structure that allows minimum clogging, and maximum air circulation and surface area to volume ratio, ensuring a high rate of BOD removal. In typical non-submerged attached growth treatment systems, a rotary distributor is used to spray the wastewater onto the media bed, as shown in Figure 2.4.

Figure 2.4: Typical distributors with rotary arms, used to apply wastewater to trickling filter packing (Kusters Water, 2014)

In the case of suspended growth processes with fixed-film packing, packing material is placed in aeration tanks where the activated sludge process takes place in order to enhance this process. Usually, the packing material is internally fixed to the aeration tank. The addition of media increases the treatment capacity and sludge settleability while reducing the production of sludge and solid loadings in the final clarifier, hence also reducing the cost of operation. This design substantially reduces the size of the operation basin, and improves nitrification and denitrification processes within the system (Metcalf & Eddy, 2003).

Submerged attached growth processes refer to methods that are a relatively new form of aerobic treatment. These are compact units of packed-bed and fluidized-bed reactors that do not require secondary clarification and save a great deal of area due to its reduced size. Apart from BOD removal, these reactors have the ability to be used for purposes of nitrification and denitrification in a smaller scale (Metcalf & Eddy, 2003).

The IMET system for sludge digestion utilized in this study is essentially a suspended growth processes with fixed-film packing. Instead of being fixed to the aeration tank, the media is contained in cylindrical modules suspended in the tank, each with its own supply of diffused aeration. Figure 2.5 shows an example of a suspended growth process with modules similar to the IMET system.

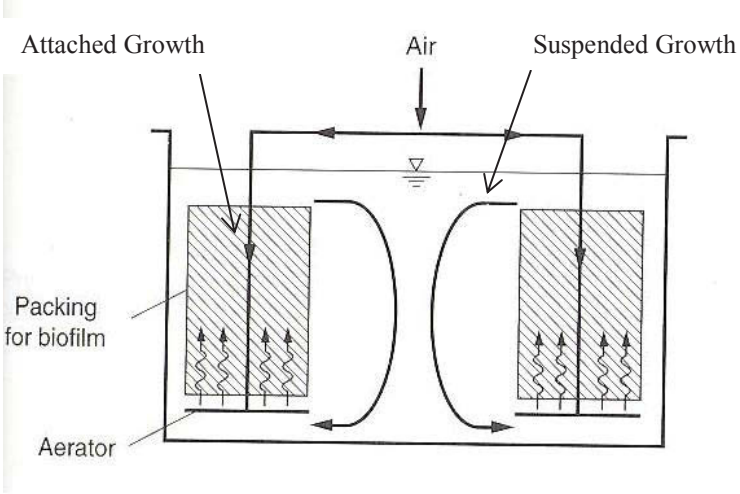

Figure 2.5: Schematic of typical Internal Fixed-Packing Attached Growth process (Metcalf & Eddy, 2003)

2.5 Sludge Production and Processing

Sludge can be defined broadly as the solids and bio-solid constituents collected in wastewater treatment processes that are typically found in liquid or semi-liquid form. Primary, waste-activated, and secondary sludge are some types of sludge that originate from different processes in wastewater treatment, and they all have their own unique characteristics. Of all the constituents that are removed in these processes, including preliminary constituents such as grit and scum, sludge is the constituent of the largest volume and this gives major importance to the processes of its disposal. In order to avoid adverse effects to public health and environmental welfare, the U.S. Environmental Protection Agency (USEPA) enforces strict regulations relating to the proper methods of processing, reusing and disposing of all solids (Metcalf & Eddy, 2003). Table 2.1 shows some typical physical characteristics of sludge produced from various wastewater treatment operations.

Table 2.1: Typical solids quantities and concentrations of sludge produced from various wastewater treatment operations and processes (Metcalf & Eddy, 2003)

Treatment Operation or Process	Dry Solids kg/10^3 m^3		Solids Concentration % Dry Solids	
	Range	Typical	Range	Typical
Primary Sedimentation	110-170	150	5-9	6
Waste Activated Sludge	70-100	80	0.5-1.5	0.8
Gravity Thickening	60-100	70	2-8	4
Extended Aeration	80-120	100	1.5-4	2.5

While preliminary operations such as grinding, screening, degritting, and blending will take care of the solids at the head of the plant, there are specific processes required for the disposal of sludge produced from biological treatment. The disposal of sludge is a costly process that needs to be done in an environmentally friendly manner. Therefore, it is in the best interest of wastewater treatment plants (and the governmental agencies that fund them) to stabilize and reduce the amount of sludge that is required to be disposed.

Sludge thickening is a common practice used in wastewater treatment plants to reduce sludge volume. Thickening is done by increasing the solids content of sludge via partial removal of the liquid fraction, usually by means of physical mechanisms. Gravity settling and air flotation are commonly used for thickening of primary sludge. However, for waste activated sludge, the use of machines such as centrifuges, gravity belts, and rotary drums is common. Depending on the type of sludge, thickening can reduce the volume by up to a fivefold decrease (Metcalf & Eddy, 2003).

One of the oldest and most common methods of stabilizing concentrated sludge is through anaerobic digestion, where organic and inorganic matter is digested without oxygen. There are three main types of chemical and biochemical reactions that occur in an anaerobic digestion process – hydrolysis, acidogenesis (creation of soluble organic compounds and short-chain organic acids), and methanogenesis (transformation of organic acids to methane and carbon dioxide by bacteria). In designing anaerobic

digesters it is important to allow adequate solid and hydraulic retention times, as they are directly related to the extent of the aforementioned reactions. The temperatures within these digesters are also an important factor of the microbial activities that take place within it. Digesters may be designed to operate in mesophilic temperatures (30 to 38°C), thermophilic temperatures (50 to 57°C), or a combination of both. The anaerobic digestion process produces the basic compound of ammonium bicarbonate during the protein breakdown of the raw sludge feed. Therefore, alkalinity concentrations are known to be great indicators of solid feed concentrations. Generally, the concentration of alkalinity ranges between 2000 to 5000 mg/L as $CaCO_3$ (Metcalf & Eddy, 2003).

Aerobic digestion is a popular method of treating waste activated sludge in smaller scale treatment plants, but recently there have been cases where it has been implemented for treatment plants that receive up to 50 MGD (million gallons per day). Even though the reduction of volatile solids in aerobic digesters is approximately the same compared to anaerobic digesters, the BOD concentrations, odor, fertilizer value of sludge, complexity of operation, and capital cost are greatly improved. Normally, the temperature at which these digesters operate is between 15 to 20°C, and up to 60 days of solids retention time is required in order to meet the regulation for pathogenic reduction rate. Tank volume, feed solids concentration, solids reduction, and oxygen requirements are important factors in the design of aerobic digesters (Metcalf & Eddy, 2003).

Aerobic digestion can be considered as an extension of the activated sludge process, as the similar concept of microorganisms consuming the available substrate takes place within these digesters as well. However, there is no recycling of return sludge, and no external food source, causing the microorganism population to consume

its own cytoplasm, a process known as endogenous respiration. The continuation of this process for extended periods of time results in the maximum possible digestion of the solid sludge content. Of the cell mass within the sludge content, approximately 20 to 25% is composed of organic compounds incapable of being biodegraded. The organic matter is oxidized aerobically into carbon dioxide, water, and ammonia, and the ammonia is converted to nitrate through nitrification during the digestion process. The oxidizable cell mass of the sludge content can be represented by $C_5H_7NO_2$, in the following equations which describe the aforementioned processes (Metcalf & Eddy, 2003).

Biomass destruction:

$$C_5H_7NO_2 + 5\ O_2 \rightarrow 4CO_2 + H_2O + NH_4HCO_3 \qquad (2.1)$$

Nitrification of ammonia nitrogen:

$$NH_4^+ + 2O_2 \rightarrow NO_3 + 2H^+ + H_2O \qquad (2.2)$$

Overall equation with complete nitrification:

$$C_5H_7NO_2 + 7O_2 \rightarrow 5CO_2 + 3H_2O + HNO_3 \qquad (2.3)$$

After digestion, the proper disposal of sludge is imperative for wastewater treatment plants. In order for this to be done, the final sludge must be dewatered. Reducing the water content of sludge through dewatering processes will result in a less costly disposal procedure, due to substantially lower volumes of the final product. Furthermore, it is easier to handle dewatered sludge as it is being conveyed to other facilities. There is a wide variety of methods for dewatering sludge that are currently being used. For smaller scale plants that have sufficient area, drying beds and lagoons that utilize natural evaporation or percolation are generally used. For plants with limited area available, mechanical methods such as centrifugation (centrifuges), filtration

(industrial vacuum filters), compaction (belt presses), capillary action, and squeezing are used (Metcalf & Eddy, 2003). Table 2.2 shows the typical solids content values after dewatering processes.

Table 2.2: Typical solids content data for types of dewatered sludge (Metcalf & Eddy, 2003)

Type of Sludge	**Cake Solids %**	
	Range	**Typical**
Total Anaerobically Digested	20-25	22
Total Aerobically Digested	12-25	18

Finally, the dewatered sludge is dumped in landfills, incinerated or applied to land in an environmentally safe manner. Incineration is a commonly used disposal method as it results in significant volume reduction and also destroys pathogenic and toxic organic compounds completely. Landfilling requires compliance with many regulations prior to being considered as an option, although it is often the most cost-effective of the three choices. There are many known environmental advantages of land application. By applying biosolids onto designated lands, with the proper amount of sunlight and soil microorganisms provided, the elimination of pathogenic and toxic substances can be achieved. It is also a common practice to distribute land applied sludge to farming communities in the area as a form of fertilizer (Metcalf & Eddy, 2003).

2.6 Nutrients in Wastewater

In consideration of wastewater influents, nitrogen and phosphorous are two nutrients most commonly monitored due to their importance in the growth of microorganisms and potential impact on aquatic ecosystems. Treatment plants are often required to monitor their concentration levels as they are discharged from the treatment facility and also when they are being recycled back within the facility in individual

treatment processes (Metcalf & Eddy, 2003). Table 2.3 shows typical concentration values of some nutrients and important constituents contained in wastewater influent and their concentrations following the removal processes throughout the plant.

Table 2.3: Solids concentration data of wastewater constituents at different stages of treatment (all units are mg/L) (Metcalf & Eddy, 2003)

Wastewater Constituent	Raw Concentration Range	Primary Effluent		Secondary Effluent	
		Conc.	Removal %	Conc.	Removal %
Total Solids (TS)	390-1230	1322	9	1183	10
Total Suspended Solids (TSS)	120-400	131	40	9.8	55
Total Organic Carbon (TOC)	80-260	72	21	14	64
Ammonia-N	12-45	21	5	9.5	52
Nitrate-N	0	0.1	0	1.4	0
Total Kjeldahl Nitrogen (TKN)	20-70	30.6	3	13.9	53
Phosphorous-P	4-12	5.1	16	3.4	28

Nitrogen is an element found abundantly in the atmosphere, albeit mostly inaccessible to organisms in its most common form of dinitrogen gas (N_2). Throughout the course of becoming a nutrient readily available for biological processes, and finally leaving the treatment plant, nitrogen undergoes several chemical transformation processes such as nitrification and denitrification. The nitrification process converts the ammonia, which is abundantly found in wastewater influent, into nitrite (NO_2^-), and the nitrite into nitrate (NO_3^-). The nitrification process utilizes prokaryotic microorganisms in order to oxidize these elements into their subsequent forms, while simultaneously supplying the microorganisms with nutrition in their aerated state (Bernhard, 2010).

Phosphorous is also an important element for the growth of biological organisms, that is abundantly found on earth, but in low concentrations in water (MPCA, 2007). When it is found in wastewater, it is in compounds of phosphate such as orthophosphate (inorganic P), polyphosphate, and organic phosphate. Approximately 20 to 30% of inorganic P is removed from wastewater in a typical treatment plant, because this element

is relatively insoluble, and therefore readily adsorbed into the settled solid particles in biological treatment (Lusk *et al.*, 2011)

While nitrogen is largely found in waterways due to agricultural processes, mainly from industrially manufactured fertilizers, the contributions of nitrogen to municipal wastewater treatment facilities are primarily from human waste (Dr. Scott Martin, personal communication, 2014). One third of the total nitrogen in domestic wastewaters is typically in organic form, mainly as urea (Lennetech, 2014). Since the enforcement of heavy regulations on laundry and kitchen cleaning chemicals productions in the 1970's, the most common contributor of phosphorous in wastewater is human waste. Phosphorous concentrations in natural waters are usually low, unless affected by fertilizer runoff, sewage discharge or animal waste (Dr. Scott Martin, personal communication, 2014).

In the environment outside the wastewater treatment plant, excessive concentrations of nutrients in the discharged effluent may cause severe water quality problems. Phosphorous in excess can stimulate the growth of plankton and plant species that can subsequently decay and consume large quantities of dissolved oxygen and disrupt the equilibrium of the environment (Enger *et al*., 2002). Similarly, large amounts of nitrate in a waterbody can cause a eutrophic growth of algae that is detrimental to the sustainability of the ecosystem (Lennetech, 2014). Due to these reasons, biological treatment plants may have tertiary processes catered towards removing these elements from the effluent before being discharged (Metcalf & Eddy, 2003).

2.7 Columbiana WWTP

The Columbiana WWTP was constructed in 1931, originally consisting only of an Imhoff tank and six slow sand filters. Since then the plant has gone numerous changes and upgrades in order to meet the requirements imposed by Ohio Environmental Protection Agency (EPA) and also the developing urban infrastructure of the municipality (ARCADIS, 2006). In order to maintain the standards of water quality, the US government created the federally mandated National Pollutant Discharge Elimination System (NPDES) permit as part of the Clean Water Act of 1972, and is enforced by the EPA as a limiting device to the discharges made by any entity into water bodies (USEPA, 2014). This law requires entities, such as the Columbiana WWTP, that discharges significant amounts of wastewater to water bodies, to obtain individual permits establishing limits for the plant's discharge of carbonaceous biochemical oxygen demand (CBOD), pH, total suspended solids (TSS), fecal coliforms, oil and grease, toxicants (metals, volatile organics), and nutrients (phosphorous, ammonia) (United States EPA, 2002).

The Columbiana WWTP NPDES permit (3PD00041*GD) provides monitoring requirements and discharge limits that the plant must adhere to. These effluent limits are as shown in Table 2.4. There are no limitations imposed on the plant's phosphorous and nitrate loadings in the effluent. This permit also describes monitoring requirements and limits for the influent, receiving stream (Mill Creek), sanitary sewer overflow (SSO), and sludge loadings.

Table 2.4: Final effluent limitations of Columbiana WWTP. All units are in mg/L, unless specified otherwise (Ohio EPA NPDES, 2011).

Parameter	Discharge Limitations					Measuring Frequency	Sampling type	Monitoring Months
	Concentration			Loading * kg/day				
	Minimum	Weekly	Monthly	Weekly	Monthly			
Dissolved Oxygen	5.4	-	-	-	-	1/ day	Multiple grab	All
Total Suspended Solids	-	10.1	6.7	90.0	60.0	3/ week	24hr Composite	All
Ammonia-N	-	1.2	0.83	11.0	7.4	3/ week	24hr Composite	Summer
Ammonia-N	-	2.5	1.66	22.2	14.8	3/ week	24hr Composite	Winter

The Columbiana WWTP is required to provide the EPA with monthly monitoring reports on the influent and effluent. The data for January through May of 2013 are shown in Table 2.5 (influent) and Table 2.6 (effluent).

Table 2.5: Influent parameters for Columbiana WWTP from January – May, 2013. All units are in mg/L, unless specified otherwise (City of Columbiana, 2013).

Parameter	Minimum	Maximum	Average
pH (pH units)	6.93	9.58	7.79
TSS	50	659	250.30
CBOD 5 day	36.9	237.5	113.85

Table 2.6: Effluent parameters for Columbiana WWTP from January – May, 2013. All units are in mg/L, unless specified otherwise (City of Columbiana, 2013).

Parameter	Minimum	Maximum	Average
Dissolved Oxygen	8.5	11.4	10.06
pH (pH units)	7.18	8.43	8.06
TSS	1.0	3.65	1.77
Ammonia-N	0.02	0.27	0.053
CBOD 5 day	2.04	7.74	3.07
Phosphorous-P	0.5	3.4	1.78
Total Kjeldahl Nitrogen	0.769	1.01	0.88
Nitrite + Nitrate	6.7	15	9.54

CHAPTER 3

Methods & Procedures

3.1 Experimental Design

3.1.1 Rationale

In order to evaluate the performance of the IMET system, its results needed to be compared to those of the existing aerobic digestion system. The key objective for the success of the IMET system was to achieve a reduction in sludge production. The main parameters used to monitor the progress of sludge digestion were TSS and volatile suspended solids (VSS). These indicate the total mass and organic content of sludge solids, respectively. COD was also a key parameter used to measure the progress of sludge digestion. The main function of the IMET bioreactors was to consume the organic matter of the cytoplasm released from ruptured microorganism cells subject to the venturi effect of the system's solubilization tank. In order to monitor the dissolved organic matter that is a result of this process, soluble COD was determined in addition to total COD.

Nutrient loadings were also considered an important factor in the evaluation process of the IMET system. This is due to the fact that, in most thickening, dewatering, and digestion facilities (sludge processing) of a wastewater treatment plant, the liquid waste streams are often recycled back to the head of the plant at a point subsequent to the preliminary treatment facilities (Metcalf & Eddy, 2003). Higher concentrations in the inflow might affect the performance of treatment processes and cause discharge permit limits to be exceeded. In order to affirm that no such increase in loadings would occur as a result of the implementation of the IMET system, nutrient and organic matter concentrations were also monitored.

Based on the predicted functions of the IMET bioreactors, it was expected that a significant decrease in solids would occur as sludge passed through the process tanks of the system. In order for the IMET system to be considered successful, the reduction in TSS, VSS, and total COD should be greater than that of the existing aerobic digesters for the same detention time. In addition, soluble concentrations of COD, phosphorous, ammonia, and nitrate should not be excessively high.

3.1.2 Operational Changes

Throughout the course of the study, several modifications were applied to the system by the IMET Corporation employees with the intention of improving its performance and mitigating the operational problems that were encountered during the study. The main changes from the original design were the removal of the outflow valves from the process tanks, the addition of an inner tank to the 4th process tank, and the application of defoaming agents and ozonation to the process tanks. The details of these changes, including the reasoning behind their implementation, and all the other changes that were made to the system, will be discussed in the next chapter.

3.2 Sampling

The sludge samples were collected at the Columbiana WWTP, which is located approximately 20 miles south of Youngstown State University (YSU). These samples were collected on a weekly basis for a study period of 10 weeks, starting from the 2nd of July to the 17th of September, 2013. The containers used for collecting samples were 250 ml low-density polyethylene (LDPE) plastic bottles. Seven samples were collected on each date from seven different sampling points within the IMET system. Figure 3.1 shows where the points were located on the system components.

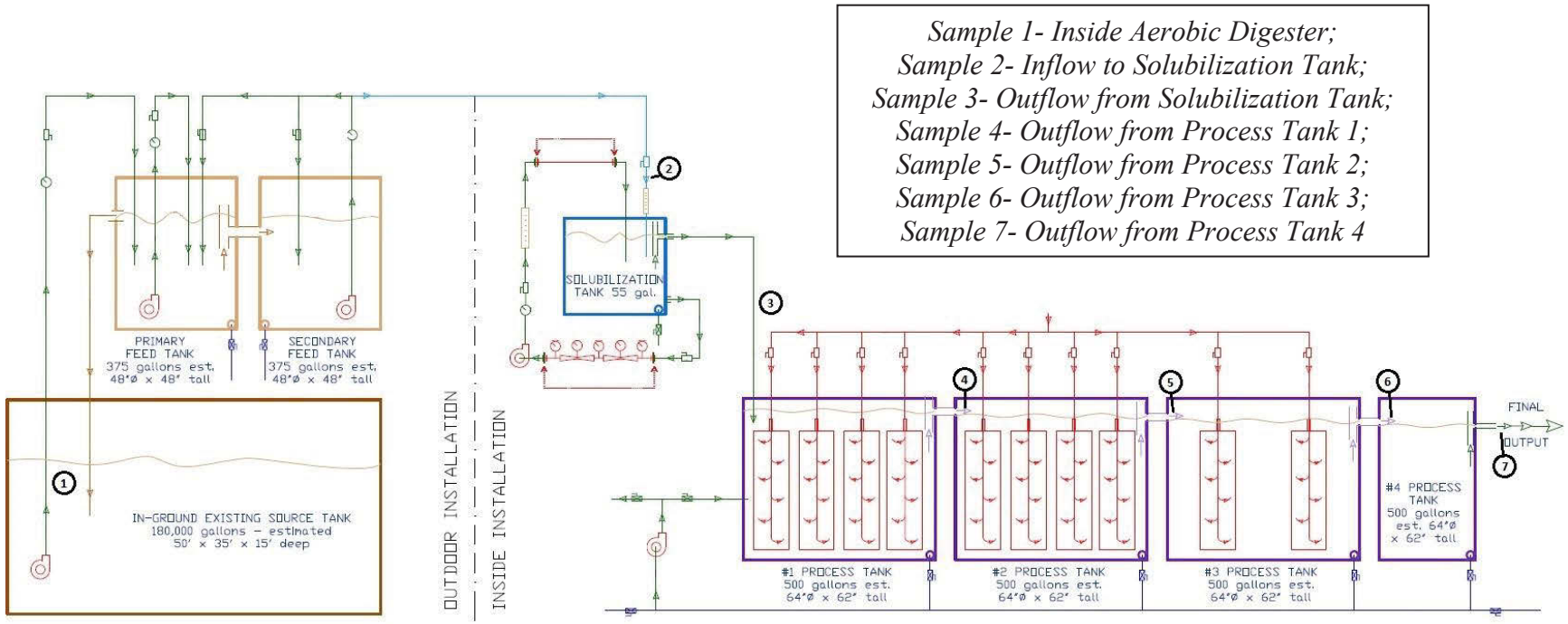

Figure 3.1: Sampling points on the IMET system (IMET Corp, 2013).

In order to extract Sample 1 from the aerobic digester, which contained sludge at a level of approximately 15 feet below the ground surface, an extension pole with a container affixed to the end of it was utilized. A turkey baster was used to extract the sludge from the outflow valves of the corresponding process tanks for Samples 4, 5, and 6. Samples 2 and 7 were collected by holding the sample bottles under the sampling points, out of which the sludge was flowing freely.

Besides the samples collected for laboratory analysis at YSU, there was another set of seven samples collected from the aforementioned points for the laboratory analyses of solid contents, pH, and DO, which were performed at Columbiana WWTP. In order to assist with the process of sample collection and to ensure the safety of the process, a WWTP employee was also present during sample collection. Furthermore, during each trip to the WWTP, field notes were recorded in order to document and assess any changes that may have occurred to the system over the course of the preceding week.

3.3 Laboratory Analysis

The scope of analysis for this study primarily focused on the changes in concentrations of solids and organic matter, and the fate of nutrients. In order to assess the solids and organic matter budgets and reactor conditions, tests were performed to find the values of TSS, VSS, total and soluble COD, pH and dissolved oxygen (DO). All of these tests except COD tests were performed at Columbiana WWTP by their personnel and the results were collected in the subsequent week. For the assessment of nutrients in the sludge samples, standard testing methods for finding total soluble phosphorous (TSP), soluble nitrate N and soluble ammonia N were performed. All of these tests were performed in the YSU Environmental Engineering Laboratory.

In order to accommodate the effective concentration ranges of the standard testing methods used for these measurements, the original samples had to be filtered and/or diluted from their original concentrations. For each sludge sample collected, a filtrate sample of approximately 50 ml was obtained by filtering through a Fisher G4 glass fiber filter, using a vacuum pump. Furthermore, 1 mL of each unfiltered sample was diluted up to 25 mL with deionized water in order to create a set of 25-fold diluted samples. The original, filtrate, and diluted samples were then stored in a refrigerator at about 5°C in order to minimize any degeneration of the solid, organic and nutrient values. The filtrate and diluted samples were stored in 125 mL LDPE plastic bottles.

For the COD test, both the diluted and filtered samples were used in order to determine total COD and soluble COD, respectively. The two tests were differentiated by the types of reagent used in the digestion of the samples. The chemical reagent used for the HACH total COD test has the capability of yielding results for COD concentrations in the range of 20-1500mg/L (High Range), which was the reasoning behind using samples diluted 25-fold for this test. The effective range for the chemical reagent used for the HACH soluble COD test is 3-150 mg/L (Low Range). Furthermore, both tests required a set of standard solutions with known COD concentration samples that were used to calibrate the values obtained for the samples. For the High Range samples a blank sample (0 mg/L) of deionized water and an Environmental Express 1000 mg/L COD Standard was used for calibration. For the Low Range samples, standards with COD concentrations of 50, 100, and 150 mg/L were used. 2 mL of each sample and standard was then added and mixed in with their respective reagent vials, and digested at 150°C for approximately 2 hours in a HACH COD reactor.

The soluble ammonia, soluble nitrate, and total soluble phosphorous tests were performed according to the procedures of Standard Methods for the Examination of Water and Wastewater, 21st edition (2005). The ammonia test was done using the Phenate Method (4500-NH_3,F), the nitrate test according to the Cadmium Reduction Method (4500- NO_3^-,E), and the TSP test by performing a persulfate digestion, followed by the Ascorbic Acid Method (4500-P,E) (WEF, 2005).

3.4 Data Processing

After the testing procedures were completed, the concentration values of the samples were determined by the use of a spectrophotometer. For the TSP, nitrate, and ammonia tests, a Bausch & Lomb Spectronic 1001 spectrophotometer was used. For the COD test, a Thermo Scientific GENESYS 20 spectrophotometer was used. Once calibrated to a wavelength specified for each particular test, the spectrophotometer provides a value of absorbance for the sample it is reading. In order to find the concentrations of the samples, the absorbances of the standards and the samples were first obtained from the spectrophotometer. Using the known values for the standards, a standard curve relating concentration to absorbance was created. The absorbances of the samples were then substituted into the equation of the trendline for this graph in order to find their respective concentrations. The exception to this procedure was for the total COD test, where the Thermo Scientific spectrophotometer was calibrated to read out the concentrations directly in units of mg/L. Figure 3.2 shows typical standard curves created for the TSP (a) and soluble COD (b) tests. Note that absorbance is inversely related to concentration in the soluble COD test.

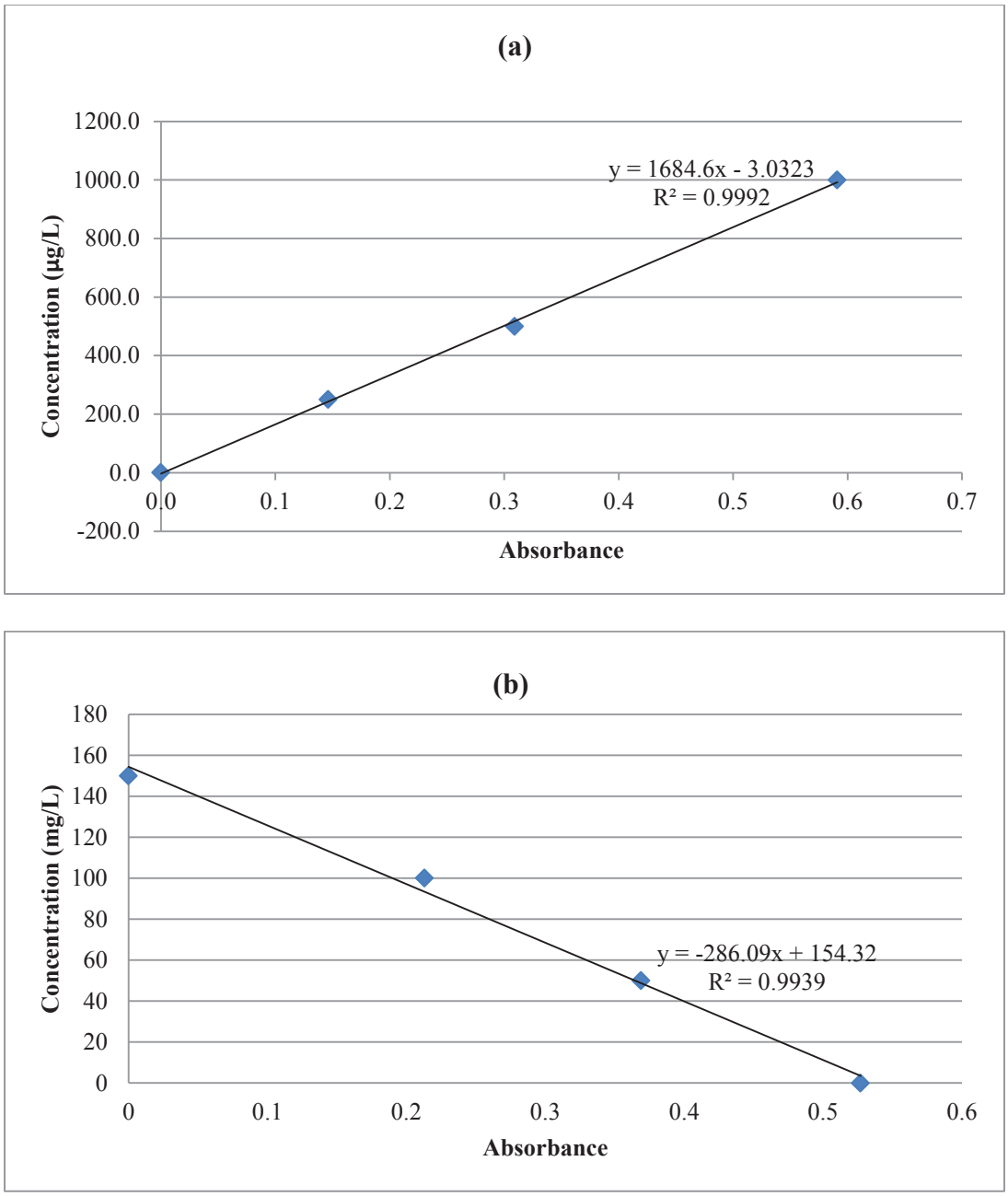

Figure 3.2: Typical standard curves for (a) TSP test, (b) soluble COD test.

The values that were obtained from the total COD, soluble COD, total phosphorous, ammonia, and nitrate tests were entered into an Excel file created specifically for the set of samples collected on each sampling date. When the data from the tests performed at YSU and the SS, VSS, pH, and DO data from the Columbiana

WWTP laboratory tests had been obtained for a given date, they were entered into another Excel database file containing all the data for the entire eleven week study period. For each parameter, the mean and standard deviation at every sample location were calculated and summarized in a separate table.

CHAPTER 4

Results & Discussion

4.1 Timeline

During the study period, starting on June 24 through September 17, samples were collected on a weekly basis. There were 11 sampling dates, with samples typically being collected between the times of 9 am – 11 am. Based on the sampling notes collected during each visit to the WWTP, a summary of the study timeline is presented below.

June 24th, 2013

The IMET system was launched. A volume of 90,400 gallons (342,200 liters) of sludge was drained from the secondary clarifier and added into the aerobic digester which feeds the IMET system. The TSS of this new batch of sludge was 3680 mg/L, and its VSS was 1683 mg/L. The process and solubilization tanks had been filled up with water, and as sludge was being drawn out of the aerobic digester, sludge flow through system commenced at the design flow rate of 1 gpm (3.79 L/min).

June 28th, 2013

According to Brian Dicken, plant Superintendent, excessive foaming had been gradually occurring and was causing operational problems to the system. The tanks were subsequently drained and refilled at a flow rate higher than 1 gpm, as the feed pump was clogging up when the system was running at the design flow rate.

July 2nd, 2013

The first set of samples was collected. The sludge that was being re-applied to the system as of the 28th of June had just reached the 4th process tanks at the time of sampling.

July 9th, 2013

Samples were collected. During the time of sampling, the IMET system had been shut down for approximately 1 hour due to troubleshooting of the system. Therefore, sample 3 was not collected. The excessive foaming made it difficult to retrieve samples 4, 5, and 6 from the outflow valves of the respective process tanks. Therefore, these samples were retrieved from the middle of the process tank instead. Furthermore, the air pumps running through the bioreactors had been shut off until a few minutes prior to the time of sample collection, as supports were being constructed above them to prevent displacement during the pumping of air due to upward thrust. There was no flow in the system, and consequently no exit flow leaving the system from the 4th process tank. Therefore, sample 7 was also not collected.

July 12th, 2013

The system was shut off again, due to excessive foaming that caused overflow in the solubilization tank. The foam was cleaned up and the 4th process tank was drained.

July 16th, 2013

Samples were collected. Since being turned off, the IMET system was turned back on approximately 1 hour before sample collection. The outflow valves of the first 3 process tanks were removed due to problems caused by foaming. Samples 4, 5, and 6 were collected from the middle of their respective process tanks. The solubilization tank was producing large amounts of foam. In order to prevent this, the water-based defoaming agent NALCO 7465 was being added to the solubilization tank. The 4th process tank was still drained and had no outflow from it. Therefore, Sample 7 was not collected. The

supernatant water from the sludge dewatering process was being circulated into the IMET system.

July 22nd, 2013

The IMET system was shut down, drained, and cleaned out due to excessive foaming. A smaller holding tank was suspended by cable supports inside the 4th process tank. The outflow from the 3rd process tank was routed directly into this tank. The stated purpose of this tank was to hold the suspended solids inside it and separated from the final outflow. The original outflow from the 4th process tank was shut off. An outflow pipe from the inner tank was used instead. An ozonation unit was added to the system at the solubilization tank with the goal of increasing the rate of digestion.

July 23rd, 2013

Samples were collected. Samples 4, 5, and 6 were collected from the middle of their respective process tanks. The air pumps had been turned off and were not turned on until just prior to sample collection. The solubilization tank was not completely filled and there was a wait of approximately 30 minutes before a sample could be collected from it. The system was still in the process of being flushed out due to foaming. Tap water was being applied to the 4th process tank, and the contents of the tank were drained into the aerobic digester that feeds the IMET system. The outflow from the 4th process tank was shut off. Therefore, sample 7 was not collected. The NALCO 7465 defoaming agent was being added continuously for 3 minutes at a rate of 260 ml/min for process tank 1, and at a rate of 70 ml/min for process tank 2, at 2 hour intervals. This dosing pattern was continued for the remaining duration of the study.

July 26th, 2013

49,300 gallons (186,600 liters) of new sludge was added to the aerobic digestion tank that feeds the IMET system. The new sludge had a solids content of 4.28%, of which 41.08% was VSS.

July 27th, 2013

The system was shut off after being run continuously since the 23rd of July.

July 29th, 2013

The system was turned back on.

July 30th, 2013

Samples were collected. Samples 4, 5, and 6 were collected from the middle of their respective process tanks. Sample 7 was collected from the outflow pipe from the inner tank. The system had been running continuously for 24 hours at the time of sampling. It was decided to add pH and DO to the list of parameters tested in laboratory analysis.

August 8th, 2013

Samples were not collected on this week. The system was turned on after being shut down for troubleshooting due to foaming problems.

August 13th, 2013

Samples were collected. Sample 7 was collected from the outflow pipe from the inner tank. The system had been running continuously for approximately 5 days. The foaming was still occurring but had reduced since the last sampling date. It was decided to add nitrate N to the list of parameters tested in laboratory analysis.

August 20th, 2013

Samples were collected. The system had been running continuously since the previous sampling date. Sample 7 was collected from the middle of process tank 4. The foaming levels were approximately the same as that of the previous sampling date

August 27th, 2013

Samples were collected. The system had been running continuously since the previous sampling date. Sample 7 was collected from the middle of process tank 4. The foaming levels had increased slightly since the previous sampling date. After this sample collection it was decided to discontinue the supply of ozone to the system.

September 3rd, 2013

Samples were collected. The system had been running continuously since the previous sampling date. Sampling point 7 had been modified so that the effluent was coming from outside the inner tank instead of from inside it. Therefore, sample 7 was collected from this point on this and every subsequent sampling date. The foaming levels had slightly increased since the previous sampling date. The solids content inside the 4th process tank appeared to have increased since the previous sampling date.

September 10th, 2013

Samples were collected. The system had been running continuously since the previous sampling date. The foaming levels had slightly increased since the previous sampling date. The solids content inside the 4th process tank appeared to have increased since the previous sampling date. Due to the level of solids in the 4th process tank, sample 7 was

collected from the outflow pipe from the inner tank. The sludge was cleaned out of process tank 4 after samples were collected.

September 17th, 2013

Samples were collected. The system had been running continuously since the previous sampling date. Sample 3 was collected from the middle of process tank 1, due to foaming.

Based on the field notes, it was observed that the IMET system had not reached steady-state during the first few weeks of sampling, due to the numerous operational problems that were faced. The IMET system was run continuously in what was believed to be steady-state after the sampling date of July 30th, 2013. The data from July 30 and all earlier dates were not considered to be representative of normal operating conditions. Only the data from the 6 sampling dates starting from the 13th of August were considered to be suitable for analysis and discussion for this study.

4.2 Analytical Data

All analytical data from the study are presented in Tables 4.1 through 4.9. At the bottom of the tables the collected data has been summarized by calculating the mean and standard deviation values for each sampling location. Since only the data after the 13th of August were considered suitable for analysis, the mean and standard deviations for the data before and after this date were also calculated separately.

Table 4.1: Summary of total COD in IMET system. All values are in mg/L

Date	Sample Location						
	1	**2**	**3**	**4**	**5**	**6**	**7**
7/2/2013	9,425	10,325	10,575	10,125	9,100	7,500	2,250
7/9/2013	8,675	11,050	N/A	10,025	9,475	9,550	N/A
7/16/2013	7975	8,950	7,875	6,875	6,550	6,050	N/A
7/23/2013	7,775	7,250	7,850	6,800	6,475	7,950	N/A
7/30/2013	10,825	10,225	11,700	9,525	8,625	7,600	7,600
8/13/2013	11,050	11,850	11,775	10,550	10,325	10,450	9,300
8/20/2013	10,775	10,750	9,700	10,250	10,425	10,450	9,750
8/27/2013	9,225	9,150	9,375	9,425	9,125	9,475	10,025
9/3/2013	8,575	8,000	8,375	8,750	7,950	7,875	125
9/10/2013	8025	8,250	8,275	8,375	8,175	7,975	7,400
9/17/2013	6,950	6,975	7,350	7,200	7,550	7,650	50
Before 8/13:							
Mean	8,935.0	9,560.0	9,500.0	8,670.0	8,045.0	7,730.0	4,925.0
St Dev	1,239.7	1,496.3	1,945.8	1,688.4	1,431.3	1,250.3	3,783.0
After 8/13:							
Mean	9,100.0	9,162.5	9,141.7	9,091.7	8,925.0	8,979.2	6,108.3
St Dev	1,592.3	1,828.2	1,539.5	1,248.1	1,237.2	1,309.0	4,753.1
All Data:							
Mean	9,025.0	9,343.2	9,285.0	8,900.0	8,525.0	8,411.4	5,812.5
St Dev	1,374.7	1,615.5	1,616.5	1,402.7	1,340.1	1,381.1	4,299.0

Table 4.2: Summary of soluble COD in IMET system. All values are in mg/L

Date	Sample Location						
	1	**2**	**3**	**4**	**5**	**6**	**7**
7/2/2013	43.6	47.9	43.3	50.0	46.1	46.5	47.5
7/9/2013	48.9	65.6	N/A	46.5	50.7	45.7	N/A
7/16/2013	*	41.1	136.2	91.1	73.8	63.5	N/A
7/23/2013	48.9	56.0	113.5	136.2	94.7	71.3	N/A
7/30/2013	37.3	40.5	138.6	125.7	106.8	100.3	101.4
8/13/2013	27.9	16.1	28.7	27.0	29.0	29.6	27.6
8/20/2013	32.5	36.2	33.9	33.0	30.2	36.2	35.6
8/27/2013	39.0	39.3	40.5	39.3	39.3	37.6	43.6
9/3/2013	43.3	47.4	53.3	48.3	49.6	47.7	55.2
9/10/2013	44.6	48.3	41.4	45.5	50.8	44.3	44.6
9/17/2013	41.4	37.4	44.6	38.6	47.4	42.7	50.2
Before 8/13:							
Mean	44.7	50.2	107.9	89.9	74.4	65.4	74.4
St Dev	5.5	10.6	44.5	41.5	26.6	22.3	38.1
After 8/13:							
Mean	38.1	37.5	40.4	38.6	41.0	39.7	42.8
St Dev	6.6	11.6	8.5	7.9	9.7	6.5	10.0
All Data:							
Mean	40.7	43.3	67.4	61.9	56.2	51.4	50.7
St Dev	6.8	12.5	43.8	37.9	25.2	20.1	22.2

*Negative values were received for these samples, and were neglected in analysis.

Table 4.3: Summary of ammonia N in IMET system. All values are in mg/L

Date	Sample Location						
	1	**2**	**3**	**4**	**5**	**6**	**7**
7/2/2013	1,322.0	1,441.0	1,402.0	846.3	409.9	469.4	6,876.0
7/9/2013	196.94	1,439.0	N/A	590.8	256.9	462.4	N/A
7/16/2013	336.3	327.0	2,541.0	9,987.0	7,193.0	5,755.0	N/A
7/23/2013	168.9	225.1	326.5	709.2	101.3	281.4	N/A
7/30/2013	176.5	411.7	2,588	1,059.0	441.1	176.5	215.7
8/13/2013	514.8	918.6	1,393.0	514.8	787.4	827.8	898.4
8/20/2013	127.9	195.2	363.6	276.0	289.5	451.1	511.7
8/27/2013	122.8	89.6	136.1	269.0	362.1	355.4	13,970.0
9/3/2013	347.3	625.2	*	389.0	479.3	264.0	11,630.0
9/10/2013	185.7	218.9	86.24	106.1	99.50	106.1	46.43
9/17/2013	81.46	183.3	*	*	*	*	2199.0
Before 8/13:							
Mean	440.2	768.7	1,714.3	2,638.3	1,680.5	1,428.9	3,545.8
St Dev	497.8	616.2	1,075.6	4,111.5	3,084.7	2,421.4	4,709.5
After 8/13:							
Mean	230.0	371.8	494.7	311.0	403.5	334.1	4,876.4
St Dev	167.8	326.5	610.9	152.1	255.1	292.0	6,224.6
All Data:							
Mean	325.5	552.2	1,104.5	1,474.7	1,042.0	831.7	4,543.7
St Dev	353.9	498.2	1,039.6	3,004.6	2,170.5	1,647.7	5,587.8

*Negative values were received for these samples, and were neglected in analysis.

Table 4.4: Summary of TSP in IMET system. All values are in mg/L

Date	Sample Location						
	1	**2**	**3**	**4**	**5**	**6**	**7**
7/2/2013	27.02	38.67	39.17	38.03	38.03	37.10	38.46
7/9/2013	52.82	52.68	N/A	54.11	53.82	50.96	N/A
7/16/2013	60.36	59.36	59.44	28.92	31.34	41.76	N/A
7/23/2013	62.59	62.51	62.59	58.29	35.52	17.64	N/A
7/30/2013	51.40	51.31	52.58	44.91	37.50	38.00	38.76
8/13/2013	41.43	39.84	39.00	38.24	37.90	37.65	38.49
8/20/2013	57.18	58.52	58.85	57.68	56.26	56.34	56.43
8/27/2013	74.00	74.00	73.59	66.10	68.79	66.34	45.00
9/3/2013	62.26	63.00	61.85	61.19	61.93	62.43	55.37
9/10/2013	65.75	64.92	65.81	65.81	65.24	65.89	67.51
9/17/2013	63.91	65.18	65.10	64.70	63.51	62.87	61.76
Before 8/13:							
Mean	50.8	52.9	53.4	44.9	39.2	37.1	38.6
St Dev	14.1	9.2	10.4	11.9	8.6	12.2	0.2
After 8/13:							
Mean	60.8	60.9	60.7	59.0	58.9	58.6	54.1
St Dev	10.9	11.5	11.7	10.6	11.1	10.9	10.7
All Data:							
Mean	56.2	57.3	57.8	52.5	50.0	48.8	50.2
St Dev	12.9	10.8	11.2	12.9	14.0	15.6	11.5

Table 4.5: Summary of nitrate N in IMET system. All values are in mg/L

Date	Sample Location						
	1	**2**	**3**	**4**	**5**	**6**	**7**
7/2/2013							
7/9/2013							
7/16/2013							
7/23/2013							
7/30/2013							
8/13/2013	124.3	130.7	126.3	155.2	122.9	122.4	129.2
8/20/2013	182.1	180.6	184.6	235.0	182.1	178.2	176.7
8/27/2013	233.8	246.6	245.0	250.8	217.1	215.7	60.5
9/3/2013	295.0	293.2	280.4	270.0	264.5	252.0	157.2
9/10/2013	283.5	295.6	287.2	279.8	280.8	252.7	278.0
9/17/2013	305.1	314.7	329.7	300.0	317.4	294.6	266.3
Before 8/13:							
Mean							
St Dev							
After 8/13:							
Mean	237.3	243.6	242.5	248.5	230.8	219.3	178.0
St Dev	72.0	73.4	74.7	51.0	71.2	61.6	83.0
All Data:							
Mean	237.3	243.6	242.5	248.5	230.8	219.3	178.0
St Dev	72.0	73.4	74.7	51.0	71.2	61.6	83.0

Table 4.6: Summary of TSS in IMET system. All values are in mg/L

Date	Sample Location						
	1	**2**	**3**	**4**	**5**	**6**	**7**
7/2/2013	17,556	17,512	18,132	17,900	15,812	14,216	4,300
7/9/2013	14,528	17,828	N/A	17,368	16,288	16,792	N/A
7/16/2013	14,624	16,600	11,792	12,824	11,916	10,972	N/A
7/23/2013	14,320	13,076	13,424	12,208	12,152	14,928	N/A
7/30/2013	19,612	18,608	20,436	18,196	15,840	14,540	14,160
8/13/2013	18,852	18,224	17,680	17,728	18,148	18,088	15,492
8/20/2013	16,552	17,448	17,916	17,612	17,652	17,568	17,136
8/27/2013	16,956	17,660	16,488	16,540	16,976	16,340	8,800
9/3/2013	16,740	16,664	17,176	16,912	16,187	15,708	2,416
9/10/2013	15,584	15,096	15,632	16,644	14,424	16,044	15,964
Before 8/13:							
Mean	16,128	16,725	15,946	15,699	14,402	14,290	9,230
St Dev	2,360	2,163	4,023	2,929	2,171	2,106	6,972
After 8/13:							
Mean	16,937	17,018	16,978	17,087	16,677	16,750	11,962
St Dev	1,192	1,212	931	551	1,459	1,026	6,252
All Data:							
Mean	16,532	16,872	16,520	16,393	15,540	15,520	11,181
St Dev	1,813	1,660	2,607	2,117	2,117	2,030	5,995

Table 4.7: Summary of VSS in IMET system. All values are in mg/L

Date	Sample Location						
	1	**2**	**3**	**4**	**5**	**6**	**7**
7/2/2013	10,744	10,844	11,196	11,000	9,680	8,788	2,536
7/9/2013	9,092	11,220	N/A	10,888	10,040	10,428	N/A
7/16/2013	9,128	10,436	7,628	8,300	7,636	7,004	N/A
7/23/2013	9,048	8,132	8,528	7,712	7,824	9,680	N/A
7/30/2013	12,308	11,564	12,528	11,300	9,808	9,044	8,952
8/13/2013	11,720	11,424	10,996	11,024	11,324	11,252	9,548
8/20/2013	10,400	10,840	11,396	11,200	11,352	11,212	10,796
8/27/2013	11,060	11,444	10,640	10,652	10,800	10,444	5,576
9/3/2013	10,800	10,680	10,820	10,768	10,344	10,116	1,496
9/10/2013	10,112	9,648	10,100	10,680	9,176	10,452	10,316
Before 8/13:							
Mean	10,064	10,439	9,970	9,840	8,998	8,989	5,744
St Dev	1,445	1,357	2,281	1,694	1,166	1,278	4,537
After 8/13:							
Mean	10,818	10,807	10,790	10,865	10,599	10,695	7,546
St Dev	622	733	477	238	898	509	3,960
All Data:							
Mean	10,441	10,623	10,426	10,352	9,798	9,842	7,031
St Dev	1,121	1,046	1,501	1,262	1,294	1,284	3,829

Table 4.8: Summary of pH in IMET system.

Date	Sample Location						
	1	**2**	**3**	**4**	**5**	**6**	**7**
7/2/2013							
7/9/2013							
7/16/2013							
7/23/2013							
7/30/2013	5.73	5.72	5.54	5.92	6.33	6.50	6.54
8/13/2013	5.78	5.91	5.92	5.98	5.96	6.01	6.02
8/20/2013	5.72	5.75	5.76	5.89	5.90	5.91	5.95
8/27/2013	5.55	5.51	5.55	5.77	5.71	5.76	6.65
9/3/2013	5.51	5.51	5.55	5.67	5.61	5.59	6.68
9/10/2013	5.45	5.54	5.58	5.64	5.71	5.70	5.70
Before 8/13:							
Mean	5.7	5.7	5.5	5.9	6.3	6.5	6.5
St Dev							
After 8/13:							
Mean	5.6	5.6	5.7	5.8	5.8	5.8	6.2
St Dev	0.1	0.2	0.2	0.1	0.1	0.2	0.4
All Data:							
Mean	5.6	5.7	5.7	5.8	5.9	5.9	6.3
St Dev	0.1	0.2	0.2	0.1	0.3	0.3	0.4

Table 4.9: Summary of DO in IMET system. All values are in mg/L.

Date	Sample Location						
	1	**2**	**3**	**4**	**5**	**6**	**7**
7/2/2013							
7/9/2013							
7/16/2013							
7/23/2013							
7/30/2013	2.67	1.79	1.48	0.90	2.95	3.61	3.71
8/13/2013	3.14	0.90	0.66	0.98	0.90	0.92	1.11
8/20/2013	4.41	2.62	1.84	2.67	2.65	3.02	1.70
8/27/2013	4.73	3.75	1.07	2.16	3.45	3.95	2.52
9/3/2013	7.29	6.49	1.50	3.14	5.58	5.92	5.14
9/10/2013	7.65	6.42	3.85	4.02	5.42	5.29	4.86
Before 8/13:							
Mean	2.7	1.8	1.5	0.9	3.0	3.6	3.7
St Dev							
After 8/13:							
Mean	5.4	4.0	1.8	2.6	3.6	3.8	3.1
St Dev	1.9	2.4	1.2	1.1	2.0	2.0	1.8
All Data:							
Mean	5.0	3.7	1.7	2.3	3.5	3.8	3.2
St Dev	2.1	2.4	1.1	1.2	1.8	1.8	1.7

After August 13th, most concentrations were relatively consistent from week to week, so mean concentrations for the period of August 13 to September 17 were calculated at each sampling point. Results are presented in Table 4.10.

Table 4.10: Summary of parameter trends from 8/13/2013 to 9/17/2013 in IMET system.

Sample Location	Mean concentrations								
	Tot COD (mg/L)	**Sol COD (mg/L)**	**TSS (mg/L)**	**VSS (mg/L)**	**TSP (mg/L)**	**Ammonia N (mg/L)**	**Nitrate N (mg/L)**	**DO (mg/L)**	**pH Units**
1	9,100	38.11	16,937	10,818	60.76	230.0	237.3	5.44	5.60
2	9,163	37.45	17,018	10,807	60.91	371.8	243.6	4.04	5.64
3	9,142	40.40	16,978	10,790	60.70	494.7	242.5	1.78	5.67
4	9,092	38.64	17,087	10,865	58.95	311.0	248.5	2.59	5.79
5	8,925	41.05	16,677	10,599	58.94	403.5	230.8	3.60	5.78
6	8,979	39.67	16,750	10,695	58.59	334.1	219.3	3.82	5.79
7	6,108	42.79	11,962	7,546	54.09	4876.4	178.0	3.07	6.20

Trends in each parameter through the IMET system are shown graphically in Figures 4.1 through 4.9.

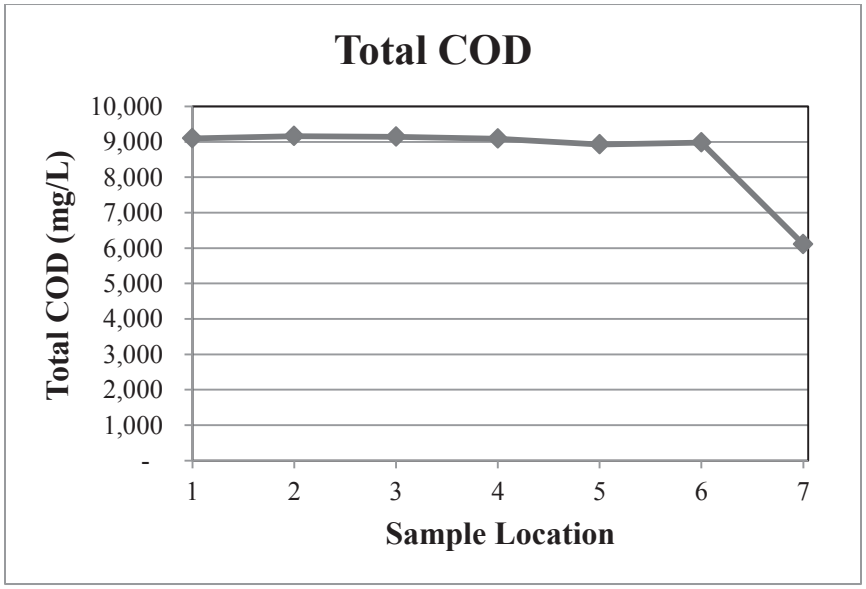

Figure 4.1: Summary of total COD trend from 8/13/2013 to 9/17/2013 in IMET system.

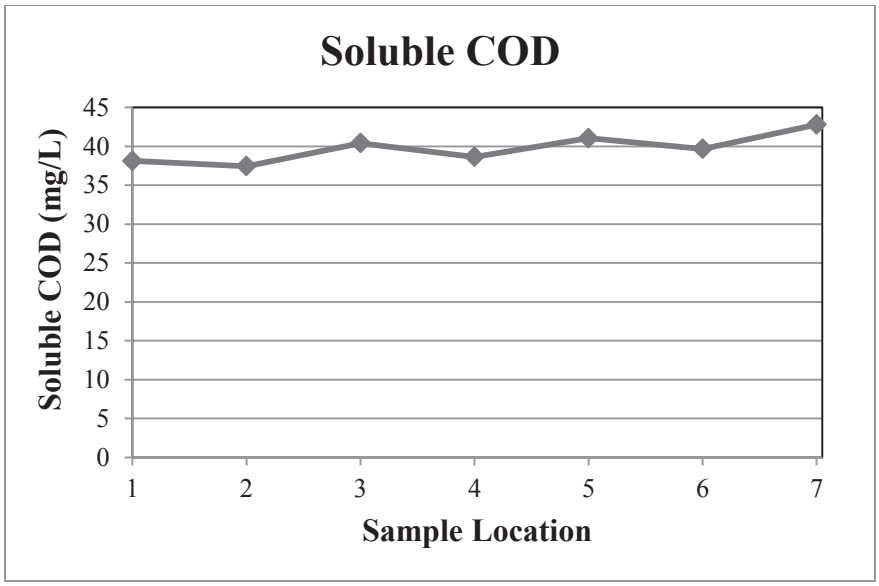

Figure 4.2: Summary of soluble COD trend from 8/13/2013 to 9/17/2013 in IMET system.

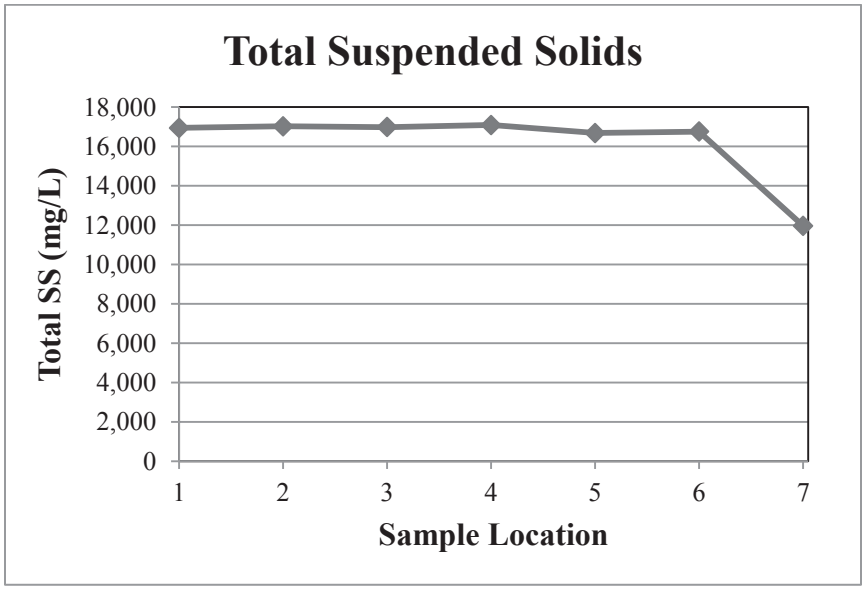

Figure 4.3: Summary of TSS trend from 8/13/2013 to 9/17/2013 in IMET system.

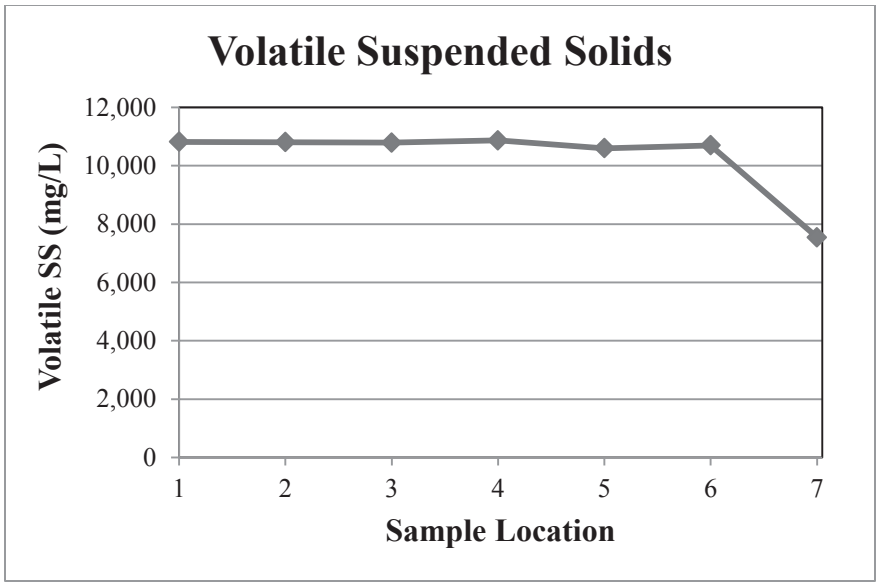

Figure 4.4: Summary of VSS trend from 8/13/2013 to 9/17/2013 in IMET system.

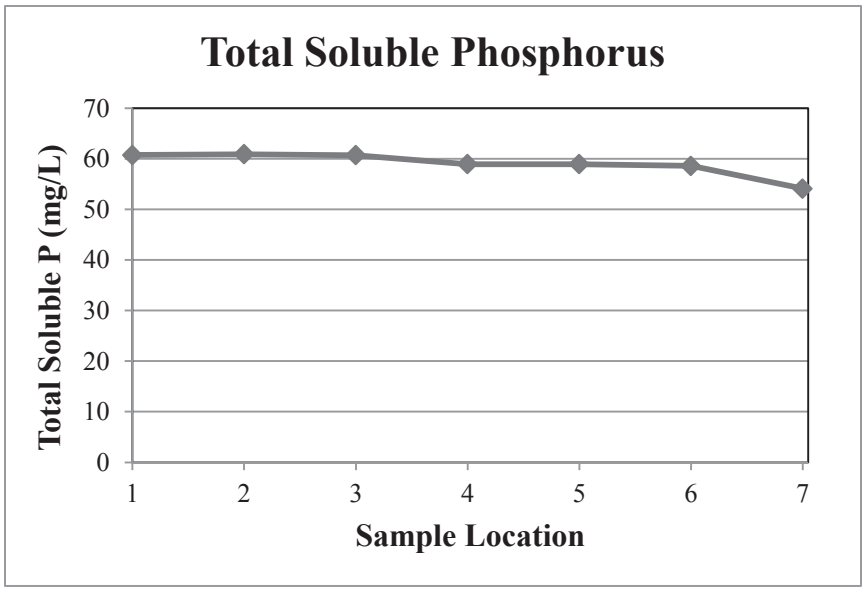

Figure 4.5: Summary of TSP trend from 8/13/2013 to 9/17/2013 in IMET system.

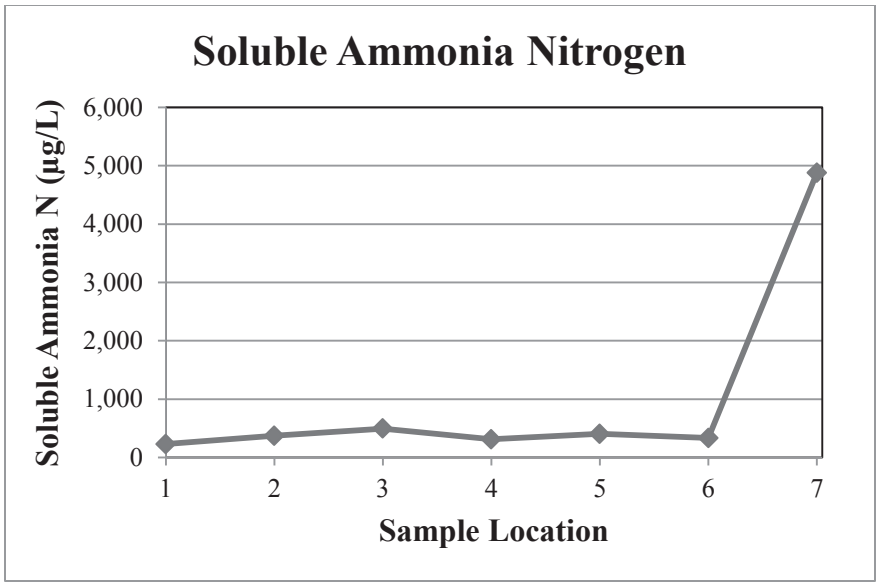

Figure 4.6: Summary of ammonia N trend from 8/13/2013 to 9/17/2013 in IMET system.

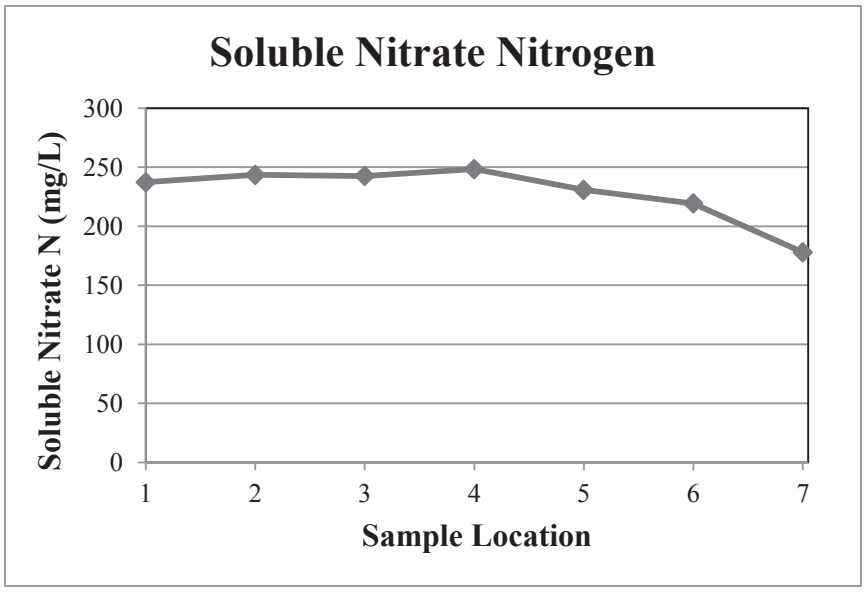

Figure 4.7: Summary of nitrate N trend from 8/13/2013 to 9/17/2013 in IMET system.

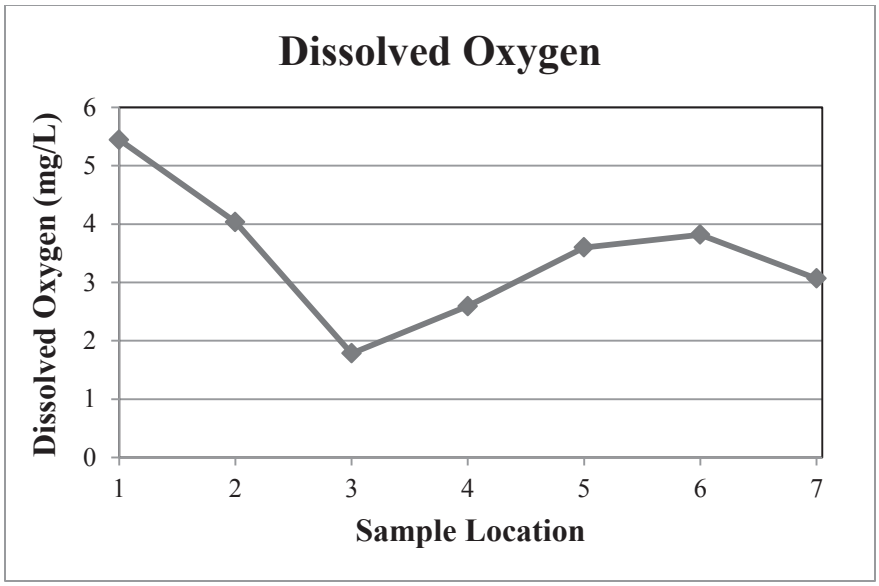

Figure 4.8: Summary of DO trend from 8/13/2013 to 9/17/2013 in IMET system.

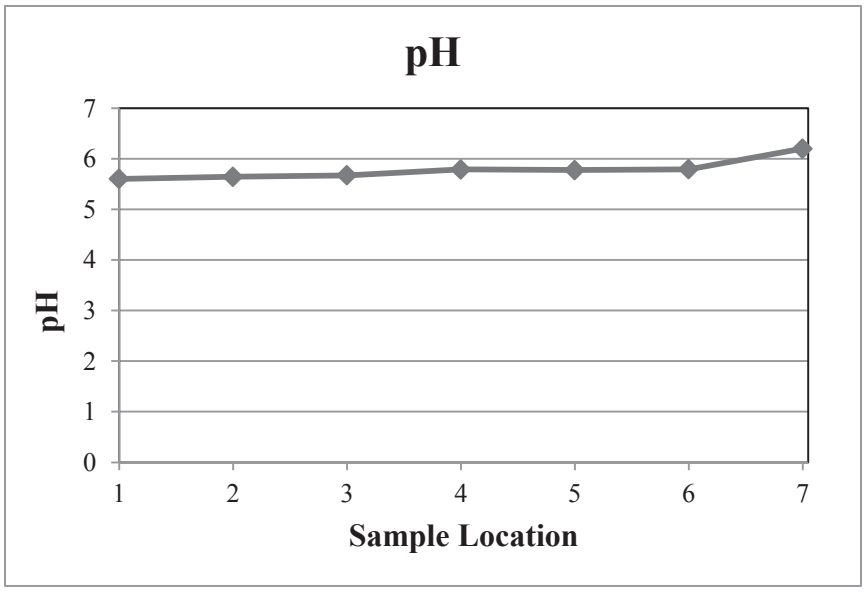

Figure 4.9: Summary of pH trend from 8/13/2013 to 9/17/2013 in IMET system.

4.3 Discussion

The summary trends for each parameter tested in the IMET system, shown in Figures 4.1 through 4.9, can be used to make general observations of how the system performed under normal operating conditions from August 13 to September 17. It must be noted that the values represented in these graphs are mean values from the aforementioned study period. Also, since the 4th process tank (Sample location 7) had no IMET modules and only performed settling of solid matter, it is not considered as part of the IMET system's process and was disregarded in this analysis.

In this analysis, the trends of data between sample locations 2 and 3 and between samples locations 3 and 6 were considered significant. This is due to the fact that Samples 2 and 3 are the inflow and outflow to the solubilization tank, respectively, and reflect the performance of the venturi in accelerating the breakdown of biosolids in the sludge. Correspondingly, Sample 3 is also the inflow to the 1st IMET process tank, with Sample 6 being the outflow from the 3rd IMET process tank. Thus, these points are representative of the starting and ending points for the sludge digestion process performed by the IMET bioreactors.

The total COD trend throughout the study period shows no significant decrease within the IMET system. It was hypothesized that the design of the IMET process tanks created a digestion process that would substantially decrease total COD, however, the mean decrease within the system was only 1.3%. Furthermore, the weekly data for these sample locations often showed erratic behavior from week to week.

The trend for soluble COD appeared to show more variability between each sample locations, but ultimately, showed an increase of 4.2% through the system (from

location 3 to location 6). It was expected that the solubilization tank of the IMET system would increase the soluble COD significantly, through its venturi process; however, from sample location 2 to 3, an increase of only 7.7% was seen in the mean values. Also, it must be noted that this increase occurred when the venturi process was paired with the addition of ozonation, which possibly helped the solubilization of biosludge due to cell lysis.

The trends for TSS and VSS appear to behave similarly, with no significant deviation throughout the IMET portion of the system. There are substantial decreases observed in both parameters at the final sampling point, but as it is likely that this decrease was caused due to settling and not due to a mechanism of the IMET bioreactors, this is not considered important.

The trend of TSP shows a decrease of 3.6% through the IMET reactors. The trend for soluble ammonia shows no considerable decrease within the system, while the trend for soluble nitrate shows a decrease of 7.6%. While none of these changes are substantial, the results indicate that some biological activity occurred within the IMET tanks. Within the first IMET process tank, a decrease in ammonia and an increase in nitrate was observed, thus showing evidence of nitrification. However, in the subsequent tanks these trends were reversed. This could be due to nutrient uptake by biofilm in the IMET reactors.

The trend for dissolved oxygen shows a rapid decrease in DO in the solubilization tank, most likely due to a pressure decrease in the venturi, then an increase as the sludge enters the IMET process tanks. This is due to the vigorous aeration in the IMET reactors. The DO levels within the process tanks were still substantially lower than that of the

aerobic digester, which suggests that the aeration within the IMET system may be less efficient.

The pH values remained constant for most of the study period and experienced a slight increase throughout the system, while still being typical of pH values in aerobic digesters. The pH values were also outside the optimal range for bacterial growth (typically 6.5 to 7.5) and may have slightly hindered the metabolism in the IMET reactors.

Due to the limited number of sampling dates and erratic nature of the data acquired, a t-test for paired observations was performed on the data set to confirm validity of the observed increases and decreases. The t-test for paired observations is a statistical method that sets up a null hypothesis, which states that the two sets of paired observations have the same means, and then evaluates the probability of the null hypothesis being a true statement. In order to do find this probability (p), the differences (d_i) between two sets of paired data are first calculated, and the mean ($\bar{x}$) and standard deviation (s_d) of all the differences are used to derive a corresponding t-value. The t-value equation is as follows.

$$t = \frac{\bar{d}}{s_d/\sqrt{N}} \qquad (4.1)$$

Here, t is the t-value, $\bar{d}$ is the mean difference, s_d is the standard deviation of differences, and N is the number of observations (Walpole and Myers, 1993). In order to derive the probability of no difference occurring between sample locations, the corresponding t-value along with the degrees of freedom (N-1) was entered into the Probability value t-test calculation tool at www.easycalculation.com. The sample location pairings for this analysis were Samples 2 and 3 (performance of solubilization tank), and Samples 3 and 6

(performance of three IMET reactors). The results of this analysis are shown in Table 4.11. This table shows the increase or decrease in mean parameter concentrations between sampling locations, as well as the probability that there is actually no statistical difference between the two locations.

Table 4.11: Percentage change of mean concentrations, and probability of no difference between measured concentrations, based on t-test for paired observations.

Parameter	Location 3 vs. Location 2		Location 6 vs. Location 3	
	Percentage Change	Probability of no difference	Percentage Change	Probability of no difference
Total COD	-0.23%	92.79%	-1.78%	60.47%
Soluble COD	+7.73%	35.11%	-1.73%	60.67%
TSS	-0.24%	91.42%	-1.35%	54.28%
VSS	-0.16%	95.17%	-0.88%	64.26%
TSP	-0.33%	52.83%	-3.46%	12.37%
Ammonia-N	+33.06%	35.56%	-32.46%	75.38%
Nitrate-N	-0.45%	80.57%	-9.57%	1.04%
DO	-55.00%	11.97%	+111.11%	5.16%
pH	+1.79	1.89%	+1.75%	1.29%

For total COD, TSS and VSS, the probability of no difference was found to be relatively high (over 50% for both 3 vs. 2 and 6 vs. 3), rendering the observed percentage changes in mean concentrations insignificant. This could be interpreted as an indication that the IMET system did not significantly enhance the digestion of solid and organic matter in the sludge. However, the 7.73% increase in mean soluble COD concentration between Sample 2 and 3 can be deemed significant due to the relatively low probability (35.1%) of no difference. This provides weak evidence that of the IMET system's venturi and/or ozonation units had some impact on the solubilization of biosludge.

For the nutrient parameters, observed decreases in TSP and nitrate through the three IMET process tanks are apparently real (p of 12.4% and 1.0%, respectively). Ammonia also showed an observed decrease through the process tanks; however, there is

a 75.4% probability that this is due to variability in the data. While this suggests that some biological activity occurred within the IMET process tanks, the expected inverse relationship between ammonia and nitrate in nitrification was not observed.

Since the existing aerobic digesters at the Columbiana WWTP operate in batch mode, with sludge being digested within the tanks for approximately 60 days before being replaced with a new batch of sludge, as opposed to the continuous-flow model of the IMET system, it is not possible to do a direct comparison of the sludge digestion rates between the two systems. Therefore, a first-order kinetic reaction rate was determined for the aerobic digester using the weekly data for Sample 1 starting from the 26th of July, which is the last day a new batch of sludge was added to the aerobic digester. The first-order reaction model for sludge digestion is as follows:

$$C = C_0 e^{-kt} \qquad (4.2)$$

Here, C is the concentration at time t (mg/L), C_0 is the initial concentration (mg/L), k is the rate constant (d^{-1}), and t is elapsed time in days (Vesilind *et al*., 2004). By plotting the weekly concentrations in the aerobic digester versus time, it was possible to create an exponential trendline in the form of the first-order reaction's equation, and using this to find a value for C_0. Then, equation 4.2 was rearranged in the form of equation 4.3, which makes it possible to create a plot with a linear slope that represents the rate constant for the aerobic digester.

$$-\ln\frac{C}{C_0} = kt \qquad (4.3)$$

This method was used to generate rate constants for total COD and VSS, which are considered the best parameters to monitor the progress of sludge digestion. The derived

rate constants for total COD and VSS are 0.0097 d^{-1} and 0.0042 d^{-1}, respectively. Figure 4.10 shows the graphs used to find the rate constants for both parameters.

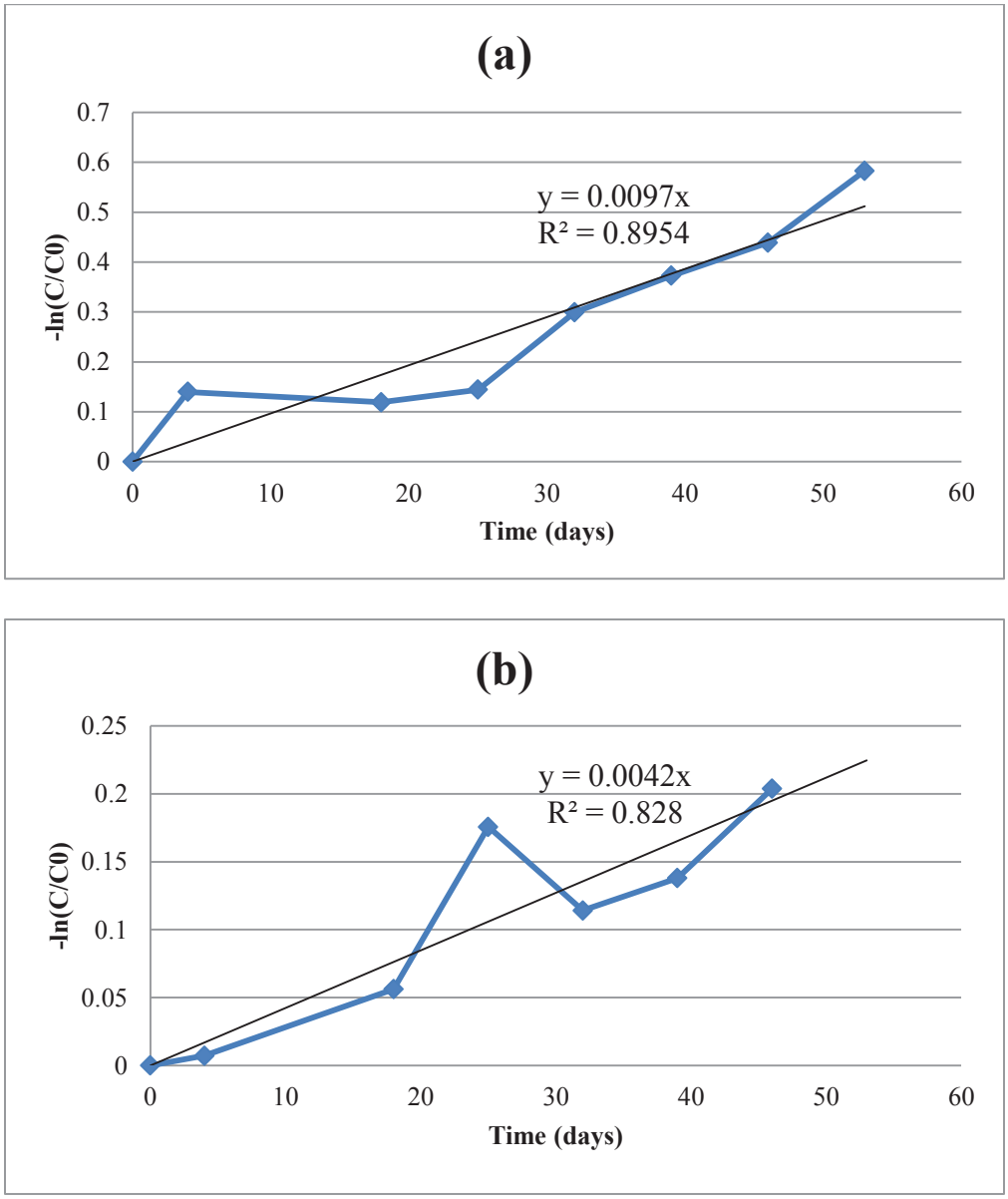

Figure 4.10: First-order reaction curve in aerobic digester for (a) total COD, (b) VSS.

These reaction rates were subsequently substituted into the first-order reaction equation, and using the mean concentration values for Sample 3 as C_0, a theoretical final concentration for the aerobic digester, for the same detention time as the IMET system,

was calculated. This value was then compared with the actual mean concentrations of the 3rd IMET process tank (Sample 6), thus giving a meaningful comparison for the IMET system and the existing aerobic digesters.

The IMET process tanks each have a capacity of 500 gallons, and it is assumed that the volume at any given time within each tank is 480 gallons. Given the 1 gpm design flow rate, for 3 tanks with a volume of 480 gallons, the detention time for the IMET system was calculated to be 1 day (3 tanks * 480 gallons/tank / 1 gallon/minute = 1440 minutes = 1 day). Using the aforementioned information, theoretical concentrations after one additional day of aerobic digestion were calculated and are shown in Table 4.12. These represent the concentrations that would be expected in the outflow from process tank 3 (sample location 6) if aerobic digestion continued with no IMET modules present.

Table 4.12: Comparison of IMET systems concentrations vs. theoretical concentrations of aerobic digesters. All values are in units of mg/L.

Parameter	**C_0**	**C**	
		IMET	**Aerobic Digester**
Total COD	9,141	8,979	9,053
VSS	10,790	10,695	10,745

Upon initial review of the information shown in Table 4.12, the IMET system appears to yield a greater reduction of total COD and VSS levels in comparison to the aerobic digesters at the WWTP. This could be evidence supporting a theory that the IMET system has superior sludge digestion capabilities. However, before that conclusion is made, the statistical plausibility of this observation must be assessed. In order to do this, a confidence interval for the true mean value of the IMET final concentration must be developed. After determining whether the calculated value of the outflow

concentration with aerobic digestion alone lies within this confidence interval, a more valid assessment can be made on the IMET system's sludge digestion capability.

The confidence interval for true mean value (μ) was calculated using the following equation.

$$\mu = \bar{x} \pm \frac{ts}{\sqrt{n}} \qquad where\ t = f(\alpha, v) \tag{4.4}$$

Here, $\bar{x}$ is the mean concentration, t is the t-value, s is the standard deviation, and n is the number of observations. The t-value for this equation is derived from a t-distribution table, based on values of α and υ, and the desired confidence level. The following equations show how these values are calculated (Walpole an Myers, 1993).

$$\alpha = \frac{\left(1-\frac{\%\ Confidence}{100}\right)}{2} \tag{4.5}$$

$$v = n - 1 \tag{4.6}$$

Using this method, confidence intervals were calculated, for true mean values of total COD and VSS in the IMET reactor outflow, and are shown in Table 4.13.

Table 4.13: Confidence intervals for true mean values of IMET system outflow concentrations at different confidence levels. All values are in units of mg/L.

Parameter	**μ**		
	90% Confidence	**60% Confidence**	**20% Confidence**
Total COD	8,979.2±1,076.8	8,979.2±491.6	8,979.2±142.7
VSS	10,695.2±484.9	10,695.2±214.0	10,695.2±61.6

The results of Table 4.13 show that, even for the lowest confidence level of 20%, the aerobic digester's calculated concentration values for both total COD and VSS, which were 9,053.5 and 10,745.2 respectively, are within the confidence intervals of the corresponding IMET system's true mean values. Therefore, it is likely that the reductions in total COD and VSS observed in the IMET system are not statistically significant.

CHAPTER 5

Conclusion & Recommendations

5.1 Summary and Conclusions

The goal of this study was to evaluate the IMET^{TM} technology for the enhancement of sludge digestion and compare its performance against the aerobic digesters at the Columbiana WWTP. Concentrations of solids and organic matter were monitored in order to determine the rates of sludge digestion within an IMET pilot plant system. The study also evaluated the fate of nutrients within the system, in order to ensure that no inadvertent increases in nutrient loadings would occur due to the IMET system.

Sludge samples were collected from seven different locations in the IMET system during an eleven-week study period, and analyzed for total COD, soluble COD, TSS, VSS, soluble ammonia N, soluble nitrate N, TSP, and DO concentrations as well as the pH. The focal points of the study, in terms of processes within the IMET system, were on the digestion of sludge within three process tanks equipped with IMET fixed-film bioreactor modules, and the breakdown of biosolids by the solubilization tank equipped with recirculating venturi units and ozonation.

The results obtained by this study showed no significant reduction (< 2.0% for total COD, TSS, and VSS) of solid or organic matter by the IMET process tanks. Furthermore, the minor reductions observed in the results were considered statistically insignificant by the t-test for paired observations. The increase of 7.7% in soluble COD within the solubilization tank showed weak evidence that the IMET system's venturi and/or ozonation units had some impact on the solubilization of biosludge. The results

also showed that there was a slight decrease in TSP and nitrate N concentrations (3.5% and 9.6%, respectively) through the IMET process tanks, and the t-test for paired observations suggests that these decreases were statistically significant. There was no evidence suggesting that the IMET system would cause any increases of TSP, ammonia N, or nitrate N loadings.

In order to create a comparison between the IMET system's three process tanks and the aerobic digesters at Columbiana WWTP, first-order kinetic reaction rates of 0.0097 d^{-1} and 0.0042 d^{-1} were determined for total COD and VSS, respectively, in the aerobic digester. A slightly higher reduction (< 1.0%) of total COD and VSS was observed in the IMET system than expected in the same detention time without IMET modules. However, this minor difference was deemed statistically insignificant after an evaluation of confidence intervals for mean concentrations of total COD and VSS, in the IMET system's outflow. The theoretical outflow concentrations of the aerobic digesters remained within this confidence interval even at confidence levels as low as 20%.

5.2 Recommendations

Based on the data collected in this study, the IMET technology cannot be recommended for enhancement of aerobic sludge digestion. The evaluation of the IMET technology was based on a pilot-scale system that ran well for a period of only six weeks. If further studies like this are performed, some changes should be made to yield more conclusive results. The greatest improvement that could be made to the study is extending its time period, thus making more data available for analysis. While the data collection frequency of one week was acceptable, as long as the system was at steady-state

throughout that week, more weekly data would most likely result in smaller standard deviation for all parameters, and consequently, more statistically significant conclusions.

The addition of ozonation, defoaming agents, and a recirculating venturi unit created additional factors that were outside the original scope of project, and may have added changes to the results that were not due to the IMET technology. Future testing must be done in a manner that yields results directly originating from the proprietary IMET bioreactors.

The most interesting finding from this study came from the total COD and VSS comparison between the IMET system's mean concentrations and the theoretical concentrations of the aerobic digesters. This analysis initially suggested that the IMET system might be capable of yielding greater reductions of the aforementioned concentrations, but – the reductions were not found to be statistically significant. It is possible that a higher detention time within the IMET system would result in a greater, and more statistically significant, reduction in solids and organic matter. This is one possible area for future research.

Throughout the course of this study, the fourth IMET process tank was neglected, due to its lack of functionality within the system. The initial idea of including this tank was to be a visual aid to show how well the system's digestion processes work. However, large quantities of solid sludge were building up inside this tank and it had to be cleaned out frequently. Based on the results of the study, the tank could have been better used to study the effective removal of solids after treatment by the IMET system. This is essential in order for this system to be considered practical in a larger scale.

REFERENCES

- ARCADIS. (2006). City of Columbiana Wastewater Treatment Plant Improvements 2003-2005 Pamphlet.
- Bernhard, A. (2010). The Nitrogen Cycle: Processes, Players, and Human Impact. *Nature Education Knowledge* 3(10):25.
- City of Columbiana (2013). Columbiana WWTP Monitoring Report. *MS Excel* document. Emailed to Rodgers S.
- Cornell University Nutrient Management Spear Program (2005). *Agronomy Fact Sheet #12.* [Internet]. Cited 01/15/2014. Available from: http://nmsp.cals.cornell.edu/publications/factsheets/factsheet12.pdf.
- Enger, E. D., & Smith, B. (2002). *Environmental Science: A study of Interrelationships.* Boston, CT: McGraw-Hill.
- IMET Corporation (2013). Columbiana PID rev D.pdf. *Adobe Acrobat* document. Emailed to Martin, S. C.
- Jia, H., Jia, Y., Gencer, M., Zakriski, P. (2012). Bio-sludge reduction using IMET System at Ishii Wastewater Treatment Plant, Guangzhou, China Presentation. *Adobe Acrobat* document. Emailed to Dissanayake, M. C.
- Kusters Water [Internet]. Cited 03/25/2014. Available from: http://kusterszima.com/kusters-water/products/biological/trickling-filter-rotary-distributors/.
- Lennetech. [Internet]. Cited 01/15/2014. Available from: http://www.lennetech.com/periodic/water/nitrogen/nitrogen-and-water.htm.

- Lusk, M., Gurpal, S. T., & Obreza, T. (2011). Onsite Sewage Treatment and Disposal Systems: Phosphorous. *University of Florida IFAS Extension.* Publication #SL349.
- Metcalf & Eddy (2003). *Wastewater Engineering: Treatment and Reuse* (4th ed.). Boston, MA: McGraw-Hill.
- Minnesota Pollution Control Agency (MPCA), 2007. [Internet]. Cited 1/15/2014. Available from: http://www.pca.state.mn.us/index.php/view-document.html?gid=8547.
- Ohio Environmental Protection Agency. National Pollutant Discharge Elimination System permit for City of Columbiana. Issued 04/11/2011. Permit No. 3PD00041*GD.
- Probability (P) Value T test Calculator. [Internet]. Accessed 04/21/2014. Available from: http://www.easycalculation.com/statistics/p-value-t-test.php.
- Reynolds, T. D., & Richards, P. A. (1996). *Unit Operations and Processes in Environmental Engineering* (2nd ed.). Stamford, CT: Cengage Learning.
- United States Environmental Protection Agency. Federal Water Pollution Control Act. As Amended Through P.L. 107–303, November 27, 2002.
- United States Environmental Protection Agency [Internet]. Accessed 04/17/2014. Available from: http://www2.epa.gov/laws-regulations/history-clean-water-act.
- Vesilind, P. A., & Morgan, S. M. (2004). Introduction to *Environmental Engineering* (3rd ed.). Stamford, CT: Cengage Learning.
- Walpole, R. E., & Myers, R. H. (1993). *Probability and Statistics for Engineers and Scientists* (5th ed.). New York, NY: Macmillan.

- Water Environment Federation (2005). *Standard Methods for the Examination of Water and Wastewater* (21st ed.). Linthicum, MD. Cadmus Professional Communications.

APPENDIX A

Field Sampling Notes

Columbiana WWTP IMET Project
Notes on Sampling and WWTP Operations

June 24, 2013

- Project meeting held at WWTP to launch the treatment study. Reactors had been filled and the flow of sludge was started.
- Brian Dicken explained sludge management procedures at the WWTP:
  - Settled sludge is drawn from the bottom of the secondary clarifier about once a week and pumped to one of four aerobic digesters.
  - Sludge is placed in one digester tank until it is full; then they will start filling another tank.
  - Once a digester is full and the sludge has been adequately digested, the digested sludge will be sent to a belt filter press for dewatering. This is done at 2-3 month intervals, so maybe 5 times per year.
  - After dewatering, the sludge is placed on drying beds on the WWTP site to dry further and await transport to land application sites (local farm fields).
  - They are not allowed by OEPA to land apply sludge from December to March, since the ground may be frozen and sludge cannot be incorporated into the soil, causing a risk of surface runoff into streams.

July 2, 2013

- Collected samples beginning at 9:00 AM from seven locations – inside digester #1; inflow to solubilization tank; outflow from solubilization tank; outflow from tanks 1, 2, 3, and 4.
- Dan from the WWTP staff collected samples at the same time for analysis of TSS and VSS.
- There was a lot of foam on the sludge; this was causing operational problems with the IMET system. All the tanks had been drained on Friday (6/28) and were being refilled at a higher than normal flow rate. The 4th tank was just filling up when we arrived. Brian Dicken said that the feed pump was clogging up when it was run at the design flow rate of 1 gpm.
- The sludge currently in aerobic digester #1 was placed there on June 24. A volume of 90,400 gal was drained from the secondary clarifier. TSS was measured at 3,680 mg/L toward the beginning of the withdrawal; this value is probably higher than the average TSS of the batch. Volatile solids were 45.74% of TSS.
- Brian Dicken showed us the files they use to record monitoring results for OEPA and said that we are welcome to copy them onto a flash drive. He also gave us a copy of a handwritten data sheet on sludge production for the first six months of 2013. A total of 98.06 dry tons was produced.

July 9, 2013

- Samples were collected at Columbiana WWTP at 10:30am. The IMET system had been shut down for approximately 1 hour as the IMET team was analyzing the system.
- Samples were collected from; inside digester, inflow to solubilization tank, and middle of process tanks 1, 2, and 3. First 2 samples were from representative

conditions of the operational system, however the samples from the process tanks are not representative, as there was no flow in the system, no exit flow from the 4th process tank, and the bioreactor air pumps had been shut off until a few minutes prior to the collection of samples.

- It was noted that supports had been constructed above the bioreactors in the process tanks in order to secure them and prevent their displacement due to upward thrust from their air pumps.
- Dan from the WWTP staff collected samples at the same time for analysis of TSS and VSS.
- Files with records of OEPA results for January-May 2013 were obtained from Brian Dicken.

July 16, 2013

- Samples were collected at Columbiana WWTP at 11am. The IMET system had been shut off on the previous Friday (7/12) and was turned back on this morning approximately 1 hour before sample collection. This was due to excessive foaming that caused overflow in the solubilization and process tanks. The foam was cleaned up and the 4th process tank had been drained.
- Samples were collected from; inside digester, inflow to solubilization tank, outflow from solubilization tank, and middle of process tanks 1, 2, and 3. The first 3 samples were representative of normal operational conditions, however the outflow from the solubilization tank was producing a large amount of foaming and caused minor inconveniences in collecting sample. The outflow valve(?) of all the process tanks had been removed due to foaming, therefore, samples from process tanks were collected from the middle of the tanks. The 4th tank had been drained and had no outflow, therefore a sample was not collected at this location.
- Brian Dicken mentioned that after the system had been shut off and the foaming cleaned up, the system was rebooted with treated discharge water from the aerobic digesters mixed in and circulated within the system. New pipes had been built into the process tanks to aid the circulation of water within them. Also some chemical agent was being added to the solubilization tank with the goal being, the prevention of the excessive foaming.

July 23, 2013

- Samples were collected at Columbiana WWTP at 10am. The air pumps had been turned off upon arrival and were started prior to collection. It was noted that the sludge in the digesters entering were the same as last weeks'.
- Samples were collected from; inside digester, inflow to solubilization tank, outflow from solubilization tank, and middle of process tanks 1, 2, and 3. System is still in the state of troubleshooting and some draining and cleaning of the tanks had to be performed in the night before due to excessive foaming. There was a wait of approximately 30 minutes before a sample could be collected from the outflow of the solubilization tank due to it not being adequately filled up at that point.
- New additions to the system included a holding tank suspended inside the 4th process tank. The outflow of the 3rd tank was routed directly into this tank, which had holes in approximately ¾ of the way down on the side of its body in order to separate the

water, which escapes out to the process tank, from the floating solids that would remain on the inside. Dr. Gencer stated that this was placed there in order to visually emphasize how the final outflow water would be clearer than it appears. In addition to the venturi pipes at the solubilization tank there was also another system that had been installed a few days prior to our arrival to help the tanks' processes. It was referred to as 'Ozone technology' by Dr. Gencer and he explained that it adds Dissolved Oxygen to the system and helps improve the venturi effect by making the microorganism cells more prone to rupture.

- In order to prevent problems from foaming Dr. Gencer stated that he plans on adding the water-based defoaming agent (NALCO 7465) into some process tanks periodically, as is done to the solubilization tank. However he had not done so yet. He provided us with product information for this defoaming agent, which he obtained from the products' website, and also of the silicone-based agent NALCO 7468 which he planned to use in the future in case the first one is not as successful.
- The entire system was being flushed out of its foam and Dr. Gencer said that he predicts the system would be flushed out and ready to be operational within 24 hours. Clean water was being applied to the 4th tank in order to flush out the settled and some floating solids. The contents of this tank were being discharged back into the digester while the outflow from the 4th tank to the drain was shut off.

July 30, 2013

- Samples were collected at Columbiana WWTP at 10am. The system had been running continuously since the last sampling date, except over the weekends when it was turned off and turned back on Monday (7/29).
- Samples were collected from; inside digester, inflow to solubilization tank, outflow from solubilization tank, middle of process tanks 1, 2, 3, and outflow from process tank 4. Outflow from 4th tank is connected directly to the inner settling tank within and it was recommended that a sample also be collected from the outside of this inner tank.
- According to Dr. Gencer defoaming agents have been continuously applied to process tanks 1 and 2, since last Tuesday (7/23) after samples were collected. Defoaming agent is applied every 2 hours at a rate of 260ml/min for tank 1, and 70ml/min for tank 2, for a 3 minute period (total: {260+70}*3= 990ml per application). Defoaming apparatus was also installed on tank 3 but was deemed unnecessary and has not been used so far. At the time of sample collection some foaming was still evident, more so in tank 1 than in tank 2, hence the higher dosage of defoaming agent for the 1st tank. According to Dr. Gencer, the current problems with foaming were attributed to some issues with the venturi pipe.
- According to Brian Dicken, 49.3 gallons of new sludge was added to the digester on Friday (7/26). Sludge had 4.28% solids content and 41.08 VS. By Dr. Gencer's recommendation, Dan from the WWTP staff was told to calculate DO and pH for the day's samples.
- It was also noted that the sludge press was running during the duration of sampling. However, it was drawing sludge from the 4th digester tank (furthest from the IMET tank) and had no apparent effect on sampling.

August 13, 2013

- Samples were collected at Columbiana WWTP at 10am. The system had been running continuously since the last Thursday (8/08).
- Samples were collected from; inside digester, inflow to solubilization tank, outflow from solubilization tank, outflows of process tanks 1, 2, 3, and 4.
- There was less foaming in the first process tank compared to the last sampling date, however the second tank still had a considerable amount of foaming in its surface. Brain Dicken said that he applied some foaming agent to the tanks in the morning prior to sampling.
- Samples were collected from the outflow pipes of the process tanks, as originally intended, instead of from the middle of the process tanks. Some stoppages of flow to and from the solubilization tank (sample points 2 and 3) were notices as the flow seemed to be stopping and starting erratically within several periods of time.

August 20, 2013

- Samples were collected at Columbiana WWTP at 10:30am. The system had been running continuously as it was on the previous sampling date (8/13).
- Samples were collected from; inside digester, inflow to solubilization tank, outflow from solubilization tank, outflows of process tanks 1, 2, 3, and middle of process tank 4.
- The foaming levels were noted to be approximately the same as in the last sampling.
- The outflow from the 4^{th} process tank (sample 7) had been changed such that the outflow is from outside the inner tank unlike previously where it was from inside it.

August 27, 2013

- Samples were collected at Columbiana WWTP at 10am. The system had been running continuously as it was on the previous sampling date (8/20).
- Samples were collected from; inside digester, inflow to solubilization tank, outflow from solubilization tank, outflows of process tanks 1, 2, 3, and middle of process tank 4.
- Foaming levels seemed higher than the last sampling date upon visual observation. According to the staff at the WWTP some light rain was experienced approximately an hour before the time of sampling.
- The modified outflow of the 4^{th} process tank which provided the discharge from outside of the inner tank was not working due to a low level of volume. The pipe discharging to the outside drain where the 7^{th} sample is usually collected was from the inner tank. Therefore, the 7^{th} sample was collected using a turkey baster from the middle of the process tank.

September 3, 2013

- Samples were collected at Columbiana WWTP at 10am. The system had been running continuously as it was on the previous sampling date (8/27).
- Samples were collected from; inside digester, inflow to solubilization tank, outflow from solubilization tank, outflows of process tanks 1, 2, 3, and 4.
- Foaming levels seemed higher than the last sampling date upon visual observation.

- There was only a slight discharge of effluent from the outflow of process tank 4, while the old discharge pipe from tank 4 was also open discharging effluent at a faster rate. The old discharge pipe had to be closed before the 7th sample was collected in order to increase the discharge rate from the other pipe.
- The solids content in the 4th process tank appeared to be high inside the inner tank and outside of it also. Upon inserting a wooden pole into the contents and attempting to swirl it, it was evident that there was a heavy buildup of sludge in this water.

<u>September 10, 2013</u>

- Samples were collected at Columbiana WWTP at 10am. The system had been running continuously as it was on the previous sampling date (9/3).
- Samples were collected from; inside digester, inflow to solubilization tank, outflow from solubilization tank, outflows of process tanks 1, 2, 3, and 4.
- Foaming levels seemed higher than the last sampling date upon visual observation.
- Sample 7 from the 4th process tank could not be collected from its designated pipe as the solid content was too thick in the tank to have an outflow from that pipe, and had worsened since last week. Sample was collected instead from the old pipe. Brian Dicken stated that he plans on draining out the sludge from this tank after the collection of sample and predicted that this would need to be done once a week in the future.

<u>September 17, 2013</u>

- Samples were collected at Columbiana WWTP at 10am. The system had been running continuously as it was on the previous sampling date (9/10).
- Samples were collected from; inside digester, inflow to solubilization tank, outflow from solubilization tank, middle of process tank 1, outflows of process tanks 2, 3, and 4.
- The foaming levels in process tank 1 (sampling point 3) was too high at the point where the turkey baster would have been inserted in the pipe, therefore the sample was simply collected from the middle of the tank.
- The process tank had been cleared of most sludge content therefore no problems were faced in collecting the last sample. Brian Dicken stated that he would be cleaning this tank out every day following the collecting of samples.

APPENDIX B

Tables

Table B.1: T-test for paired observations of all parameters

Total COD

Date	Location 2	Location 3	Difference
8/13/2013	11,850	11,775	-75
8/20/2013	10,750	9,700	-1,050
8/27/2013	9,150	9,375	225
9/3/2013	8,000	8,375	375
9/10/2013	8,250	8,275	25
9/17/2013	6,975	7,350	375
		Mean	-20.83
N		Std. Dev.	536.29
6		t	-0.0952
		P (no diff.)	0.9279

Location 3	Location 6	Difference
11,775	10,450	-1,325
9,700	10,450	750
9,375	9,475	100
8,375	7,875	-500
8,275	7,975	-300
7,350	7,650	300
	Mean	-162.50
	Std. Dev.	721.07
	t	-0.5520
	P (no diff.)	0.6047

Soluble COD

Date	Location 2	Location 3	Difference
8/13/2013	16.14	28.73	12.59
8/20/2013	36.16	33.88	-2.28
8/27/2013	39.31	40.46	1.15
9/3/2013	47.39	53.33	5.94
9/10/2013	48.33	41.44	-6.89
9/17/2013	37.37	44.57	7.20
		Mean	2.9517
N		Std. Dev.	7.0335
6		t	1.0280
		P (no diff.)	0.3511

Location 3	Location 6	Difference
28.73	29.58	0.85
33.88	36.16	2.28
40.46	37.60	-2.86
53.33	47.70	-5.63
41.44	44.26	2.82
44.57	42.69	-1.88
	Mean	-0.7367
	Std. Dev.	3.2872
	t	-0.5489
	P (no diff.)	0.6067

TSS

Date	Location 2	Location 3	Difference
8/13/2013	18,224	17,680	-544
8/20/2013	17,448	17,916	468
8/27/2013	17,660	16,488	-1,172
9/3/2013	16,664	17,176	512
9/10/2013	15,096	15,632	536
		Mean	-40.00
N		Std. Dev.	779.42
5		t	-0.1148
		P (no diff.)	0.9142

Location 3	Location 6	Difference
17,680	18,088	408
17,916	17,568	-348
16,488	16,340	-148
17,176	15,708	-1,468
15,632	16,044	412
	Mean	-228.80
	Std. Dev.	770.14
	t	-0.6643
	P (no diff.)	0.5428

VSS

Date	Location 2	Location 3	Difference
8/13/2013	11,424	10,996	-428.00
8/20/2013	10,840	11,396	556.00
8/27/2013	11,444	10,640	-804.00
9/3/2013	10,680	10,820	140.00
9/10/2013	9,648	10,100	452.00
		Mean	-16.800
N		Std. Dev.	583.358
5		t	-0.0644
		P (no diff.)	0.9517

Location 3	Location 6	Difference
28.73	29.58	0.85
33.88	36.16	2.28
40.46	37.60	-2.86
53.33	47.70	-5.63
41.44	44.26	2.82
44.57	42.69	-1.88
	Mean	-0.737
	Std. Dev.	3.287
	t	-0.5011
	P (no diff.)	0.6426

Ammonia

Date	Location 2	Location 3	Difference
8/13/2013	918.60	1,393.04	474.44
8/20/2013	195.24	363.56	168.32
8/27/2013	89.55	136.07	46.52
9/3/2013	625.19	(83.36)	-708.55
9/10/2013	218.91	86.24	-132.67
9/17/2013	183.28	(54.30)	-237.58
		Mean	139.15
N		Std. Dev.	255.43
4		t	1.0896
		P (no diff.)	0.3556

Location 3	Location 6	Difference
1,393.04	827.75	-565.29
363.56	451.08	87.52
136.07	355.41	219.34
(83.36)	263.97	347.33
86.24	106.14	19.90
(54.30)	-	54.30
	Mean	-59.63
	Std. Dev.	347.13
	t	-0.3436
	P (no diff.)	0.7538

Nitrate

Date	Location 2	Location 3	Difference
8/13/2013	130.70	126.30	-4.40
8/20/2013	180.63	184.55	3.92
8/27/2013	246.63	246.98	0.35
9/3/2013	293.23	280.42	-12.81
9/10/2013	295.56	287.23	-8.32
9/17/2013	314.69	329.69	15.00
		Mean	-1.045
N		Std. Dev.	9.8660
6		t	-0.2594
		P (no diff.)	0.8057

Location 3	Location 6	Difference
126.30	122.38	-3.92
184.55	178.18	-6.37
246.98	215.73	-31.26
280.42	252.03	-28.39
287.23	252.70	-34.53
329.69	294.57	-35.11
	Mean	-23.264
	Std. Dev.	14.2627
	t	-3.9953
	P (no diff.)	0.0104

TSP

Date	Location 2	Location 3	Difference
8/13/2013	39.84	39.00	-0.84
8/20/2013	58.52	58.85	0.33
8/27/2013	74.00	73.59	-0.41
9/3/2013	63.00	61.85	-1.15
9/10/2013	64.92	65.81	0.89
9/17/2013	65.18	65.10	-0.08
		Mean	-0.21
N		Std. Dev.	0.75
6		t	-0.6773
		P (no diff.)	0.5283

Location 3	Location 6	Difference
39.00	37.65	-1.34
58.85	56.34	-2.51
73.59	66.34	-7.25
61.85	62.43	0.57
65.81	65.89	0.08
65.10	62.87	-2.23
	Mean	-2.11
	Std. Dev.	2.80
	t	-1.8487
	P (no diff.)	0.1237

DO

Date	Location 2	Location 3	Difference
8/13/2013	1.79	1.48	-0.31
8/20/2013	0.90	0.66	-0.24
8/27/2013	2.62	1.84	-0.78
9/3/2013	3.75	1.07	-2.68
9/10/2013	6.49	1.50	-4.99
		Mean	-1.8000
N		Std. Dev.	2.0399
5		t	-1.9731
		P (no diff.)	0.1197

Location 3	Location 6	Difference
1.48	0.92	-0.56
0.66	3.02	2.36
1.84	3.95	2.11
1.07	5.92	4.85
1.50	5.29	3.79
	Mean	2.5100
	Std. Dev.	2.0446
	t	2.7451
	P (no diff.)	0.0516

pH

Date	Location 2	Location 3	Difference
8/13/2013	5.91	5.92	0.01
8/20/2013	5.75	5.76	0.01
8/27/2013	5.51	5.55	0.04
9/3/2013	5.51	5.55	0.04
9/10/2013	5.54	5.58	0.04
		Mean	0.0280
N		Std. Dev.	0.0164
5		t	3.8103
		P (no diff.)	0.0189

Location 3	Location 6	Difference
5.92	6.01	0.09
5.76	5.91	0.15
5.55	5.76	0.21
5.55	5.59	0.04
5.58	5.70	0.12
	Mean	0.1220
	Std. Dev.	0.0638
	t	4.2761
	P (no diff.)	0.0129

APPENDIX C

Photographs

Figure C.1: Aerobic digesters at Columbiana WWTP

Figure C.2: Primary and secondary holding tanks

Figure C.3: Venturi units

Figure C.4: Solubilization tank

Figure C.5: IMET bioreactor modules

Figure C.6: IMET Process tank 1

Figure C.7: IMET Process tank 2

Figure C.8: IMET Process tank 3

Figure C.9: IMET Process tank 4 and inner tank

Figure C.10: IMET Process tank 4, side view of inner tank

Figure C.11: Layout of IMET Process tanks

Figure C.12: Foaming in process tank 1

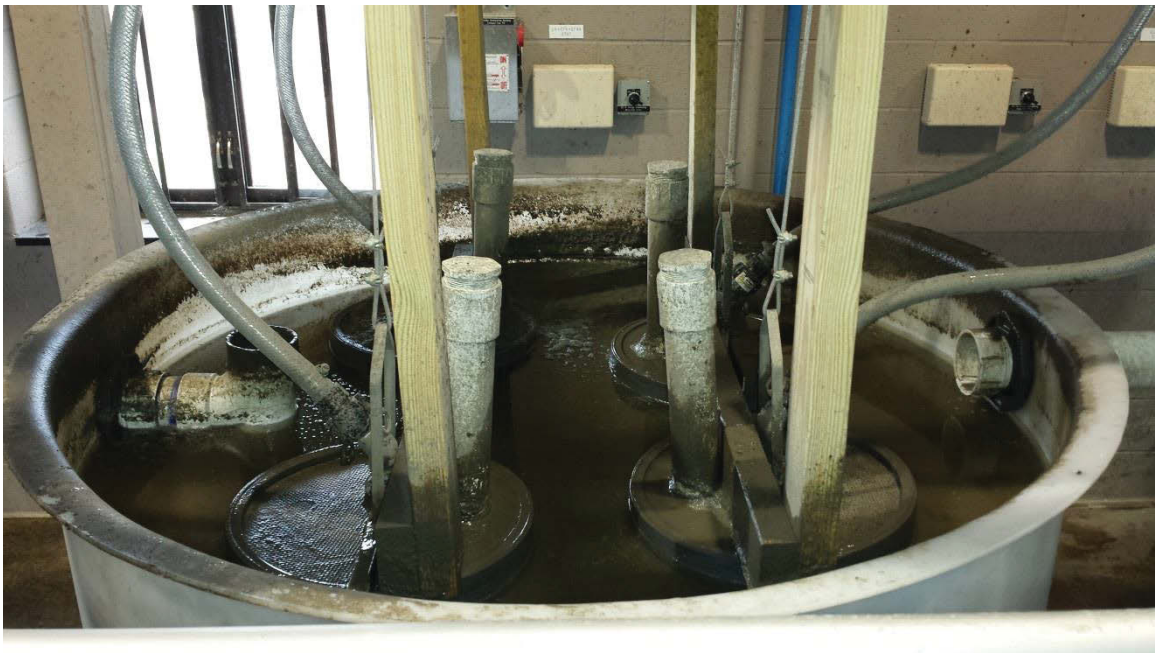

Figure C.13: Process tank 2 in steady-state

Figure C.14: Process tank 3 in steady-state

Figure C.15: Ozonation unit

Figure C.16: Defoaming agent application units