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A Comparative Study of the Effects of External Selection on Settleability and Formation of Aerobic Granular Sludge

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A COMPARATIVE STUDY OF THE EFFECTS OF EXTERNAL SELECTION ON SETTLEABILITY AND FORMATION OF AEROBIC GRANULAR SLUDGE

by

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ABSTRACT

A COMPARATIVE STUDY OF THE EFFECTS OF EXTERNAL SELECTION ON SETTLEABILITY AND FORMATION OF AEROBIC GRANULAR SLUDGE

Tyler A Brickles
Old Dominion University, 2017
Director: Dr. Gary Schafran

Aerobic granular sludge (AGS) has shown much promise in the advancement of the wastewater treatment industry. AGS has been studied intensely since the early 1990's due to highly desirable characteristics of nutrient removal efficiency, low footprint, and abnormally faster settling rates than conventional activated sludge. With the exception of a few on-going research projects, all AGS systems have been studied and implemented through the use of sequencing batch reactors (SBR). Recently, a novel approach to developing AGS and improving settling characteristics of activated sludge within conventional activated sludge (CAS) processes has being attempted through the use of external selection.

Activated sludge was fed to a hydrocyclone for approximately 374 days to select for denser material that would improve settling and potentially cultivate AGS. The effect of the hydrocyclone on the activated sludge was directly compared to the settling characteristics of an identical parallel treatment train that did not utilize the external selector. Data suggests that with the correct nozzle and operating pressure, much of the faster settling sludge and ballast material for the cultivation of AGS can be selected for, retained, and returned to the activated sludge process. During the warmer months, while the wastewater temperature was consistently >19°C, the hydrocyclone improved settling rates in the activated sludge by up to 15-20x the settling rates of the activated sludge in the parallel train.

While a shift to granulation did not occur, further research and optimization could potentially lead to the cultivation of AGS and the further improvement of settling characteristics of activated sludge. The settling performance imparted on the activated sludge by the hydrocyclone shows that it is feasible to improve the overall settleability of activated sludge in a suspended growth process through external selection.

Key Words: Aerobic granular sludge, External selection, Hydrocyclone, Settling velocity

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NOMENCLATURE

ACFM	Actual Cubic Feet per Minute
AGS	Aerobic Granular Sludge
AnGS	Anaerobic Granular Sludge
AOB	Ammonia Oxidizing Bacteria
BNR	Biological Nutrient Removal
CAS	Conventional Activated Sludge
CFM	Cubic Feet per Minute
dGAO	Denitrifying Glycogen Accumulating Organism
DO	Dissolved Oxygen
dPAO	Denitrifying Phosphate Accumulating Organism
GPM	Gallons per Minute
HP	Horsepower
HRSD	Hampton Roads Sanitation District
IMLR	Internal Mixed Liquor Recycle
ISC	Intrinsic Settling Classification
JR WWTP	James River Wastewater Treatment Plant
MGD	Million Gallons per Day
ML	Mixed Liquor
MLSS	Mixed Liquor Suspended Solids
NOB	Nitrite Oxidizing Bacteria
PAO	Phosphate Accumulating Bacteria
PSI	Pounds per Square Inch
RAS	Return Activated Sludge
RWI	Raw Water Influent
SBAR	Sequencing Batch Airlift Reactor
SBR	Sequencing Batch Reactor
SFA	Solids Flux Analysis
SIP	Stock Isotonic Percoll
SND	Simultaneous Nitrification-Denitrification
SOR	Surface Overflow Rate
SRT	Solids Retention Time
SVI	Sludge Volume Index (5, 10, 30 minute)
TDH	Total Dynamic Head
TOF	Threshold Of Floccution
TSS	Total Suspended Solids
UB WWTP	Urbanna Wastewater Treatment Plant
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WWTP	Wastewater Treatment Plant
ZSV	Zone Settling Velocity

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CHAPTER 1

1.0 Introduction

Activated sludge is one of the oldest and most widely practiced wastewater treatment technologies (Jones and Schuler 2010) due in part to its simplicity, low cost, and high removal efficiencies of influent contaminants. While activated sludge may be one of the most researched and optimized treatment technologies, it still has its drawbacks and limitations. The most notable drawback being treatment disruption due to biomass loss from poor settling characteristics of conventional activated sludge (CAS). Since the early 1990's aerobic granular sludge has been deeply investigated and it has been found that in biological wastewater treatment, aerobic granules are "often more efficient" for the treatment of influent wastewaters than CAS (Adav et al. 2008).

Aerobic granules have demonstrated that they serve as stratified microbiomes for a wide variety of biological organisms and that the granular structure could be the very definition of bioflocculation. Organisms within the aerobic granule structures have been found to be: polyphosphate accumulating organisms (PAO), ammonia oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOB), denitrifying heterotrophs, and, depending on the application, anaerobic ammonia oxidizers (Anammox). The stratification of the aerobic granules provides a pathway for substrate diffusion through aerobic, anoxic and anaerobic layers. Each layer creates favorable conditions for enhancing carbon and biological nutrient removal (BNR) within a single biofilm. These aerobic granules have a higher density compared to that of CAS flocs due to the greater retention of inorganic material within the granule core (Winkler 2012).

Due to the increased density of aerobic granules, the settling rates compared to that of CAS flocs, would be vastly higher. When the relationship of density and settling rates were evaluated, it was found that CAS flocs with poor settling had densities of 1.038 to 1.041 g/mL and settled at <5 m/hr. Aggregates with significantly higher settling rates of 5 to 30 m/hr had densities of 1.041 to 1.049 g/mL. It was also found that granules with spherical physical properties would settle at rates >30 m/hr and had densities of 1.060 to 1.065 g/mL (Sears et al. 2006).

Since aerobic granules can perform nearly a complete treatment of wastewater (reduction/oxidation and uptake of influent ammonia, nitrate/nitrite and phosphorus) in a single step and currently understood need of a feeding regimen, most, if not all, research of aerobic granules has been conducted through the use of sequencing batch reactors (SBR). This study focuses on the improvement of settling performance and the possible cultivation of aerobic granules through external selection. External selection for faster settling particles, and the subsequent cultivation of aerobic granules, has been conducted through the use of a hydrocyclone implemented in the mainstream process of a wastewater treatment facility.

1.1 Project Motivation

This study was performed on site at a Hampton Roads Sanitation District (HRSD) facility. HRSD is a wastewater treatment public utility that is headquartered in southeastern Virginia. The utility treats wastewater for the majority of Hampton Roads bordering the Chesapeake Bay. Figure 1 shows the area of operations for HRSD which is comprised of nine major treatment facilities and five “small communities” facilities.

The main objective of any wastewater sanitation facility is to produce the highest quality effluent possible. A highly efficient activated sludge that possesses the ability to reduce organic constituents, as well as settle at high rates without the need for chemical addition, would drastically reduce operational costs associated with such an operation. In order to cultivate activated sludge of this nature a novel approach to the activated sludge process has been investigated.

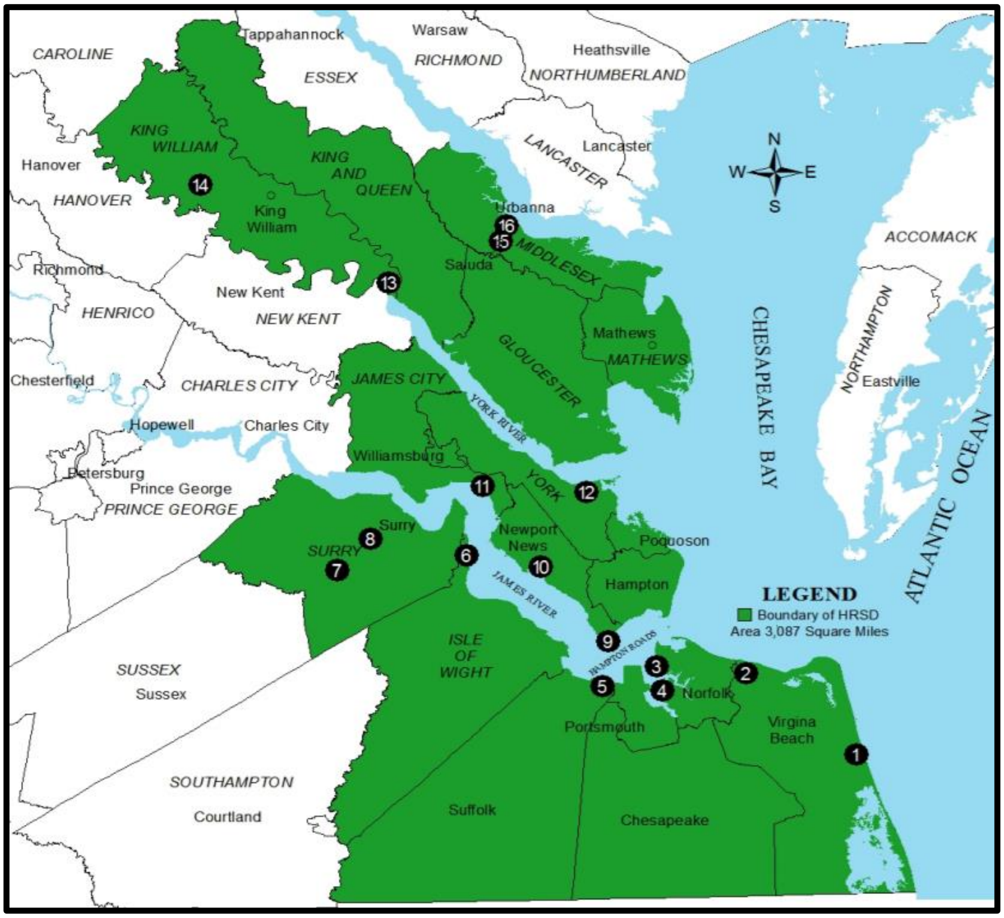

Figure 1. HRSD area of operations (HRSD 2017).

External selection studies are being conducted at two of HRSD’s facilities: The James River Wastewater Treatment Plant (JR WWTP) and the Urbanna Wastewater Treatment Plant (UB WWTP). The facilities are located in Newport News, VA on the James River just inside the mouth of the Chesapeake Bay and in Middlesex County, VA on the Rappahannock River respectively. Both of the receiving bodies of water are tributaries of the Chesapeake Bay. The UB WWTP study is the focus of this thesis.

1.2 Project Background and Objectives

The UB WWTP is an above ground package plant consisting of two nearly identical trains and is illustrated in Figure 2. The plant was accepted by HRSD in 1999 and has recently been upgraded in order to improve overall treatment ability. The upgrades consisted of changing the configuration from an extended aeration plug flow process into a Modified Ludzack-Ettinger (MLE) process in May of 2016.

The UB WWTP operates with a 0.085 million gallon equalization basin that is aerated to maintain particle suspension. Equalization effluent is transferred to each train for treatment. Each train consists of three treatment zones: anoxic zone, swing zone (aerobic/anoxic), and an aerobic zone. Each treatment zone has a total capacity of 6,250 gallons for a total capacity of 18,750 gallons per train and a 1.5 hour detention time for a total of 4.5 hours. Following the biological processes is a dedicated secondary clarifier for each train. The secondary clarifiers are circular in shape and center feed with a total volume of 6,970 gallons per unit and a weir loading rate of 1,351 gpd/ft. The total designed treatment capacity of the UB WWTP is 0.1 MGD.

Due to the format of this facility, two nearly identical trains operating in parallel, it was a key location for comparative research on the effects of an external selection process on the settleability of activated sludge. The external selector, or hydrocyclone, was supplied to HRSD by World Water Works™ in order to evaluate the InDense® (intensification) process and selection for granular material. The intensification process is hypothesized to be accomplished by supplying activated sludge to the external selector in order to select for more dense material. The external selector was added to the experimental train and operational in mid-June of 2016.

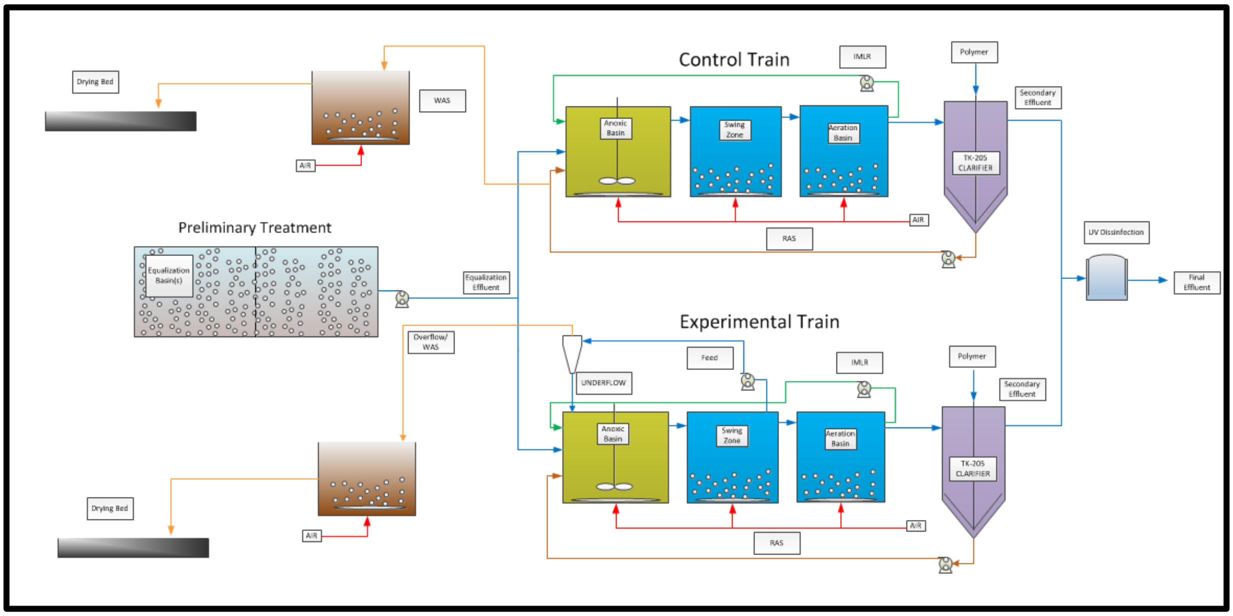

Figure 2. Process flow diagram for the Urbanna Wastewater Treatment Plant.

The objectives of this study are:

- To evaluate the use of external selection on the settling characteristics of activated sludge
- To evaluate the ability of an external selector to effectively select for more dense material and the possible cultivation of aerobic granular material from conventional activated sludge.
- To compare the effects of the use of an external selector on the process to that of conventional activated sludge in the parallel train.

CHAPTER 2

LITERATURE REVIEW

2.1 Aerobic Granular Sludge

Aerobic granular sludge (AGS) is becoming a more common technology for the treatment of influent wastewaters, but has only been successfully demonstrated in facilities utilizing SBRs. The first use of granular sludge was developed for strict application in anaerobic systems in 1980 and was then known only to be anaerobic granular sludge (AnGS). However, major drawbacks existed as the system required long start-up periods and high operating temperatures. The generation times of AnGS are highly dependent on operational temperatures as generation times vary significantly from 10°C to 35°C at 50 days and 5 days respectively. The system also lacked the ability to treat low strength wastewater and was inefficient in the removal of organic constituents such as nitrogen and phosphorus (Adav et al. 2008). Due to the AnGS drawbacks, AGS was researched and developed.

AGS is a relatively new technology in the wastewater treatment industry which was discovered through the use of a SBR in the late 1990’s by varying the sedimentation phases to shorter intervals. The granules of AGS consisted of layered compact structures and were biologically efficient with diverse microbial species, possessing excellent settling characteristics and nutrient removal capabilities (E. Morganroth 1997). A comparative illustration of an aerobic granule and CAS floc is shown in Figure 3. Due to the high settling characteristics of AGS, treatment facilities can operate at higher ML concentrations than CAS facilities which allows for an increased treatment capacity without the need for expansion of the facilities. The high settling velocities of AGS increases the biomass retention capacity within a reactor and also enhances the organic degradation capabilities which allows for smaller reactors to be utilized, thus decreasing the footprint of facilities that utilize the AGS treatment technology.

Since its conception, AGS has been extensively researched. Research has reported the settling velocities of aerobic granules typically range between 10 and 50 m/hr while the typical settling velocities of CAS are between 1 and 3 m/hr. Characteristics of AGS have been reported by many researchers (Hu et al. 2005, Kim et al. 2004, Liu et al. 2005, McSwain et al. 2004, Qin et al. 2004a, Qin et al. 2004b, Wang et al. 2004) and they are as follows:

- Regular, smooth and nearly round in shape
- Excellent stability
- Dense and strong microbial structure
- High in biomass retention
- Ability to withstand high organic loading
- Tolerance to toxicity

Due to the previously stated characteristics of granules, the technology was developed for the treatment of high strength wastewater containing organics such as nitrogen and phosphorus, toxic substances, and xenobiotics (Jiang et al. 2002, Moy et al. 2002, Tay et al. 2002b).

2.2 Formation of Aerobic Granular Sludge

Initial studies of AGS were done in a controlled environment at room temperatures of 20-25°C (de Kreuk et al. 2005, E. Morganroth 1997). Therefore, little was known about how temperature fluctuations would alter the effects of settling and treatment ability when implemented at full scale operations. It has been well documented that nitrification and denitrification rates decrease significantly with drops in temperature and cease at or below 5°C and would be expected with granular sludge just as it is with activated sludge. A study conducted recently by Winkler (2012) discovered that low operating temperatures can lead to a shift in populations away from granulation as well as decreased settling velocities of AGS.

The effects of temperature were studied in sequencing batch airlift reactors (SBAR) at various temperatures of 8, 15 and 20°C. de Kreuk et al. (2005) found that from start up at 8°C the time of biomass shift to granulation was double than the shift reported by E. Morganroth (1997) at room temperature of 20°C. It was found that the granules were unstable at this operating temperature and were comprised of irregular, fluffy structures. They were eventually washed out due to decreasing settling velocities. Effluent from the SBAR operated at 8°C was poor as nitrification rates were low and effluent ammonia was high.

A second test was conducted where the SBAR had a start-up temperature of 20°C and was decreased to 15°C and 8°C to simulate changing seasons over a long term period of 130 days. It was found that granule composition remained unchanged over all temperature ranges. However, the effluent quality suffered due to decreased NOB activity. Ammonia removal efficiency remained high at 97% but the NOx removal efficiency dropped to 44% at 15°C. At 8°C, effluent quality worsened and the AGS had an overall nitrogen removal efficiency of 35% (de Kreuk et al. 2005).

Beun et al. (1999) studied just how aerobic granules formed and what operating procedures allowed the formation through the use of SBRs. Short feeding periods were utilized in the study as the feast/famine period would effectively select the proper microorganism for granule development. The granule forming microorganisms could out-compete filamentous bacteria present in the influent and store the substrate for future consumption during the famine period. Short settling periods were also used and it was found during start-up that highly filamentous granules formed and broke apart after days of operation due to an unstable structure. The remaining bacteria then developed into granular material and were retained through the following decant phases. Since the filamentous constituents were washed out in the days prior, the newly formed granular material consisted primarily of a conglomerate of various bacteria.

Liu et al. (2005) conducted a study to further explore the formation evolution work that was conducted by Beun et al. (1999) by investigating the effects of various settling times on the formation of granules. The two stage formation of granules, unstable fungi dominated granules followed by stable bacteria dominated granules, was also observed in the Liu et al. (2005) study. It was also found that the settling times and diameter of the granules were inversely proportional. Sedimentation phases that exceeded 15 minutes produced sludge that was composed of primarily large flocculated biomass. While sedimentation phases that were nearer to 5 minutes produced AGS particles that were 2-3 mm in diameter and produced granules with a more compact microbial structure.

Granulation has been achieved through the use of real and synthetic wastewaters containing glucose, acetate, phenol, starch, ethanol, molasses, sucrose, and various other substrates (Adav et al. 2008, Liu and Tay 2004, Tay et al. 2002b, Wang et al. 2004). The presence of the positive divalent and trivalent ions such, as Ca^{2+}, Mg^{2+}, Fe^{2+} and Fe^{3+}, were able to form microbial nuclei by bonding the negatively charged cells (Mahoney et al. 1987). Jiang et al. (2003) concluded that the addition of Ca^{2+} ions significantly shortened the granulation process during their experiment to 16 days from 32 days during experimentation without the addition of calcium.

Since the granulation processes that have been researched and documented have been through the use of SBRs, the operational parameters that affect the granulation process revolve around the operational characteristics of SBRs. Various studies have documented the operational characteristics that play a role in the granulation process include: pH, wastewater temperature, cycling time (filling, sedimentation, decant, and idle phases), and hydrodynamic shear force (Liu and Tay 2007, Liu and Tay 2004). When pH was controlled during experimentation it was found that at a pH of 4.0 the granule size reached diameters of 7 mm and that granule growth was initiated by fungi presence (McSwain et al. 2004). Beun et al. (1999) found that the first stage of granulation was very unstable and was prone to breaking apart after days of operation. At a pH of 8.0 the granule diameter only reached 4.8 mm but growth was initiated by bacteria and was highly stable and capable of long life spans before breaking apart and washing out. The granulation formation has been reported by the numerous previously mentioned studies to be affected by many factors such as:

- Seed and feed sludge
    - Quantities of hydrophobic bacteria, substrate composition, ion presence, etc.
- Operational parameters
    - Temperature, settling times, feast/famine periods, pH, cycling time, hydrodynamic shear force, etc.

2.3 Composition of Aerobic Granular Sludge

AGS is similar to both suspended activated sludge and biofilm meaning that granular sludge develops similarly to biofilm without a supporting structure and is suspended within the matrix.

Similarities to suspended activated sludge can be seen due to the evolution from flocculating sludge and results in the formation of suspended microbial aggregates without the need for a carrier material. AGS is also similar to biofilm in the characteristics of mass transfer through the various layers of the aerobic, anoxic and the anaerobic layers of the granule. The center of the granule, the inorganic core, is comprised of a conglomerate of dead cells. As the granule ages, cells within the various layers will decay and be absorbed by the core of the granule which subsequently increases the diameter of the granule. The aerobic granule illustration shown in Figure 3 illustrates the conceptualization of the different layers and the microbial population that resides within.

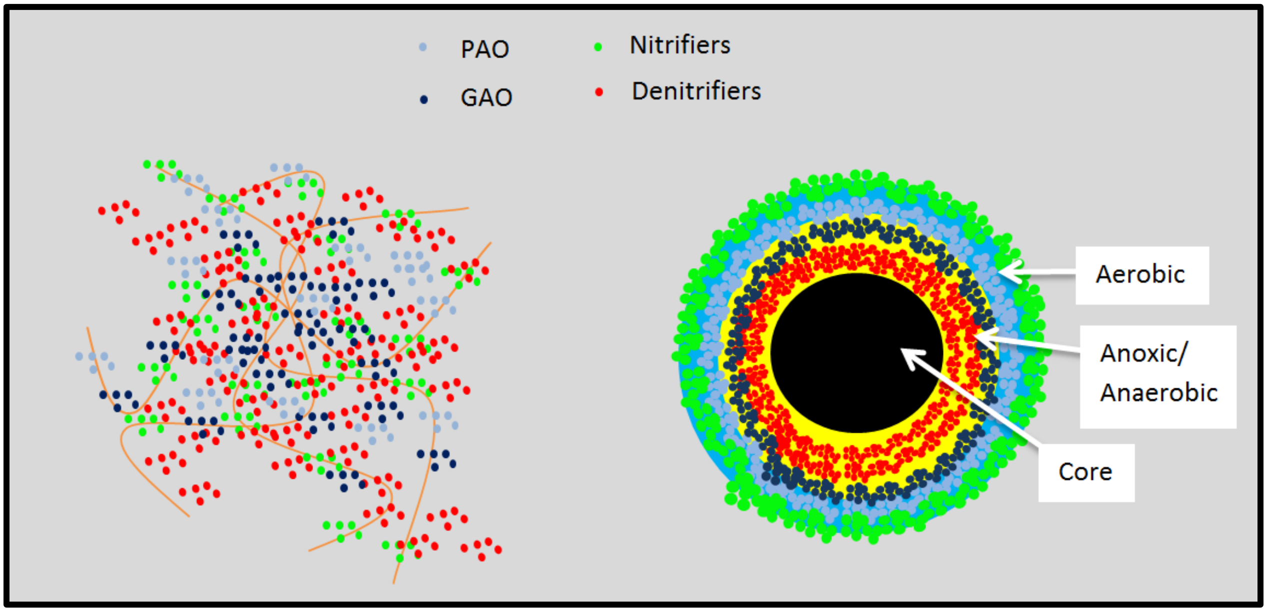

Figure 3. Illustration of CAS floc (left) and an aerobic granule (right).

Major advantages of AGS compared to CAS are that granules facilitate the growth of AOB, denitrifying phosphate accumulating organisms (dPAO), denitrifying glycogen accumulating organisms (dGAO) and PAO (Wang et al. 2009). The well-developed granule consists of three layers: an aerobic layer (nitrification) for the oxidation of ammonia to nitrite and nitrate, an anoxic/anaerobic layer where denitrification and phosphorus uptake are achieved. Due to the varying organisms that coexist within the granules, SND is achieved simultaneously with phosphorus uptake due to dPAO activity.

Confocal laser-scanning microscopy was used to study the microbial structure of aerobic granules. Tay et al. (2002a), Tay et al. (2003) found that the AOB *Nitrosomonas* spp. was present from depths of 70 – 100 μm within the granule. It was also found that pores existed to depths of 900 μm while the porosity peaked at depths of 300 – 500 μm. These channels facilitate the transfer of oxygen through the granule and expel metabolites. Anaerobic bacteria of the *Bacteroides* spp. were found to exist in the anoxic/anaerobic layer at depths of 800 – 900 μm (Tay et al. 2002c). Continuations of the study also lead to the discovery of the granule's core and the composition. The composition of the core was determined to be a conglomerate of dead cells from the anoxic/anaerobic layer to the center of the granule. It was determined that in order to fully utilize the capabilities of the aerobic microorganisms the granule should be less than 1600 μm due to the greater ratio of live cells to dead cells (Tay et al. 2002a).

2.4 Current Applications of Granular Sludge

There are approximately thirty full scale AGS facilities around the world and yet there is still little known about the optimal operating conditions for the formation of aerobic granules for the treatment of low-strength municipal wastewater. Many previous studies of AGS have been performed at the bench and laboratory scales with the primary source of influent wastewaters being synthetic (Derlon et al. 2016). These synthetic wastewaters were developed for the favorable production of aerobic granules with high substrate concentrations ranging up to thousands of mg/L of COD; allowing for the accelerated cultivation of aerobic granules within weeks (Beun et al. 2000). While the aforementioned method of granule cultivation is favorable for the study of AGS, they do not represent real and full scale applications for domestic wastewater.

Royal HaskoningDHV (RHDHV) used the information gathered from the previous studies to develop the Nereda® process in 1995 (Giesen 2015). RHDHV developed full scale AGS SBRs and shortened the sedimentation phase to approximately 10-minutes. The following wasting phase expelled any material that remained in suspension through decanting the SBR. This change in the SBR process selected for faster settling particles and the growth of granular sludge (Giesen 2015). Due to the high settling velocities of AGS (30-40 m/hr) the selection of faster settling biomass was feasible. The SBR operation also utilized a carefully selected feast/famine regime. This regime allowed for the selection of granules and granule forming microorganisms. The granule forming microorganisms would store substrate for use during famine phases when substrate was not available so that the filamentous bacteria would enter a starvation phase and begin to decay (Beun et al. 1999). During the draw or decant periods, the slower settling and decaying biomass was removed from the system. Granules began to form after 40 days and after 70 days of operation they became the dominant form of sludge in the process. Granule diameters were found to range between 2.35 mm and 7 mm. Trials at various HRTs (SBR cycle period) showed that short a HRT (8.0 hours) resulted in larger and faster cultivation of aerobic granules (E. Morganroth 1997).

Currently there are 30 Nereda® facilities that have demonstrated successful processes in the formation of aerobic granules using real domestic wastewater. However, there are only five facilities that cultivated AGS without the addition of supplemental substrate. Other systems were successful in forming aerobic granules but required supplemental substrate addition in order to form the granules due to wastewater characteristics (Derlon et al. 2016).

Reports from the previously mentioned studies demonstrated that long start up periods of greater than one year were required to achieve granulation of more than 80% (Ni et al. 2009). Representative settling characteristics of a well-functioning granular system include comparative SVI_{30} to SVI_5 values. Ratios of 1.0 represent nearly a complete shift to aerobic granulation. Granules formed under loading from synthetic wastewaters, in bench scale studies, yielded diameters in excess of 2000 μm while those formed with domestic wastewater, in real and full scale applications, formed much smaller granules with diameters ranging from 200 to 1300 μm (Liu et al. 2010, Ni et al. 2009).

Other processes that utilize granular sludge include the sidestream Paques and DEMON processes. Both processes are very similar and differences include granule separation schemes, feeding regimens, and air flow. In many DEMON applications a hyrocyclone is used to accomplish anammox granule separation from “fine particulate sludge” within a reactor that utilizes various feeding strategies depending on the needs of the facility. Feeding strategies include continuous, intermittent and pulse (Lackner et al. 2014). The granule in the DEMON process is solely comprised of anammox bacteria while AOB bacteria coexist in floc form. The coexistence of the two bacteria allows for nitrite shunt and deammonification to occur simultaneously (Wett 2007). Where approximately 50% of the ammonia/ammonium is oxidized to nitrite and residual ammonia and nitrite are anaerobically transformed to nitrogen gas.

The Paques process utilizes a continuous flow tank reactor integrated with patented lamella separator for granule retention and cultivation (Lackner et al. 2014). A continuous stream of air is introduced from fine bubble diffusers that completely canvas the base of the reactor creating an environment with high oxygen diffusion to the “all-in-one” granule. The same bacteria mentioned in the DEMON process are also responsible and follow the same pathway for nitrogen removal in the Paques process. Similar to AGS the “all-in-one” granule of the Paques process is of a compact layered structure. Where the outer layer is aerobic and inner layer is anoxic/anaerobic. Partial nitritation occurs in the outer oxygen penetrable shell for the partial oxidation of the ammonia to nitrite. The interior layer is ”shielded from oxygen” and is comprised of anammox bacteria for the anaerobic transformation of the residual ammonia and nitrite to nitrogen gas (Winkler et al. 2012).

2.5 Vesilind Settling Parameters

The Vesilind model is a useful tool that predicts the possible settling velocities of activated sludge within a user defined layer within a secondary clarifier. The model uses Equation 1 and the method of least squares using arbitrary values of k and Vo (Vesilind settling parameters) to compare the measured and predicted settling velocities of various sludge types. Optimization software (MS Excel) minimizes the sum of the square error between the predicted and observed settling velocities to determine real values of k and Vo.

$$V_s = V_o * e^{-kX} \tag{1}$$

Where:

V_S = Settling velocity (m/hr)
V_O = Maximum settling velocity (m/hr)
k = Settling parameter (L/g TSS)
X = Mixed liquor suspended solids (g TSS/L)

The solids flux can then be calculated using Equation 2.

$$SF_g = V_S * X \tag{2}$$

Where:

SF_g = Solids flux (lbs/day/ft^2)
V_S = Vesilind settling velocity (m/hr)
X = Mixed liquor suspended solids (g TSS/L)

The k parameter indicates the exponential decrease in settleability in reference to the increasing solids concentration, X. The Vo term indicates the maximum theoretical settling velocity of the sludge being evaluated. Higher Vo and lower k values represent better settling suspension of solids (Vesilind 1968).

Typical approaches to the Vesilind model are used with SVI data to predict the Vesilind settling parameters (Giokas et al. 2003, Vanderhasselt and Vanrolleghem 2000). However, SVI data is not as sound in the estimation of k and Vo due to the fact that SVI can change significantly with concentration of ML, cylinder geometry, stirring, and do not correlate to sludge zone settling velocity. Thus, Vesilind settling parameters found through SVI data will not be as accurate as those found through solids flux analysis.

2.6 Hydrocyclones

Hydrocyclones are devices used for the external selection of particles with varying densities as external selection is not dependent on process control which is required for internal (biological) selection. They have been used in a wide range of applications, which include gold mining, soil separation, and wastewater pretreatment for grit separation. During this research, the novel approach is to use the hydrocyclone to select for more dense particles within activated sludge.

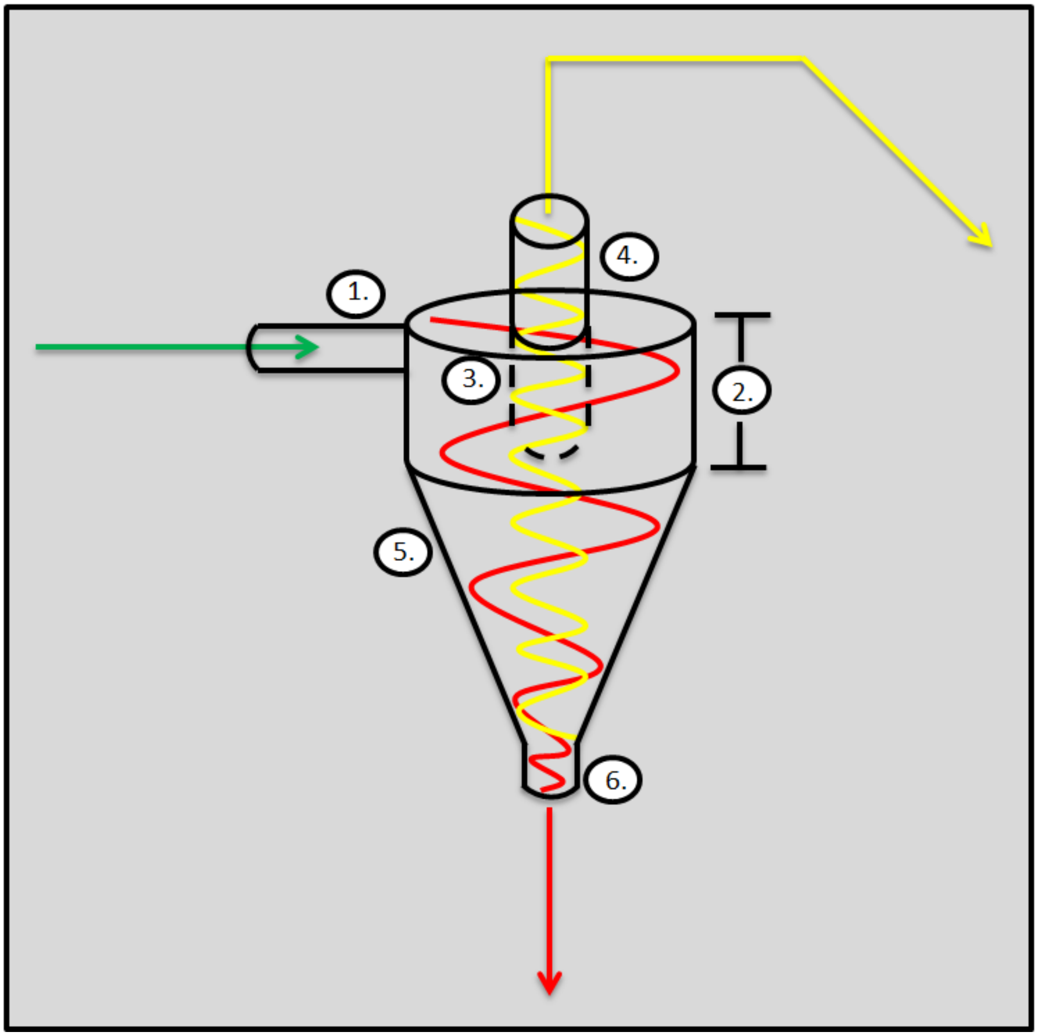

Figure 4. Schematic of a hydrocyclone (external selector).

There are many components to the hydrocyclone and are shown in Figure 4. Those parts are as follows:

1. Inlet feed adapter
2. Feed Chamber
3. Vortex Finder
4. Overflow (reject) return
5. Cone Body
6. Apex Nozzle

- Green: Feed (activated sludge)
- Yellow: Overflow (WAS, less dense, slower settling particles)
- Red: Underflow (more dense, faster settling particles)

The activated sludge (green) is fed to the hydrocyclone at a specific operating pressure through the inlet feed adapter. The operating pressure will affect the density of the sludge retained and rejected due to the increased or decreased sensitivity of the cyclone determined by the operating pressure. A lower operating pressure will be less selective when selecting for more dense particles while the opposite is true for the higher operating pressures. The cyclone process begins in the feed chamber as the activated sludge is fed perpendicular to the flow of the underflow and overflow. Pressure within the cyclone will increase as the activated sludge is transported through the cone body towards the apex nozzle. As pressure increases the more dense particles are forced towards the cone body and the outer layer of the cyclone, while the less dense material remains in the vortex of the cyclone.

Once the activated sludge reaches the apex nozzle, the denser material will exit via the apex nozzle as the selector underflow. While the less dense material is forced upwards through the vortex into the vortex finder, this is known as the selector overflow. The overflow then exits the cyclone through the vortex finder via the overflow return. In the application of this study the overflow becomes the waste activated sludge (WAS) and is deposited into the aerobic digester before being discharged into the drying bed.

The underflow and overflow are fractions of the feed flow. The overflow is the reject fraction of the process and is hypothesized to contain less dense particles while the underflow is comprised of denser particles. Cyclones are external classifiers that separate particles which are suspended in the feed liquid. The degree of particle separation that is desired is accomplished through the operating pressure of feed flow. A higher pressure will select for the denser particles in the feed flow, which will result in a greater hydraulic and mass fraction of the feed flow exiting the cyclone via the overflow. The hydrocyclone is an external particle classifier that is designed to increase or decrease the concentration of solids, liquids and/or gases of differing densities within a liquid stream through centripetal or centrifugal forces within a vortex.

2.7 Present Study

While AGS has been a well-studied treatment technology, it has only been researched through the use of SBRs and SBARs. The study of the effects on settling properties of activated sludge and the possible cultivation of granular sludge has never before been attempted through the use of external selectors. The present study was developed to document the effects that an external selector, such as a hydrocyclone, would have on activated sludge. By conducting this study at the UB WWTP the effects could be directly compared to the identical parallel train that was operated without a cyclone. The effects of the external selector on settling characteristics were measured through observations of settling rates, changes in biomass density, and changes in populations of various classifications of sludge. The purpose of this study was to determine whether a shift in the population from flocs and aggregates to granular material is feasible.

CHAPTER 3

MATERIALS AND METHODS

3.1 Urbanna Process

As previously mentioned, this research was conducted at the small Urbanna HRSD treatment facility (UB WWTP). The UB WWTP is a continuous flow process that treats domestic wastewater with two identical treatment trains. Train #1 was the experimental train, as it utilizes an external selector for the selection of more dense particles to be retained within the mixed liquor. Train #2, the control train, continued to treat domestic wastewater conventionally without the use of an external selector. The process flow diagram for the UB WWTP is shown again in Figure 5.

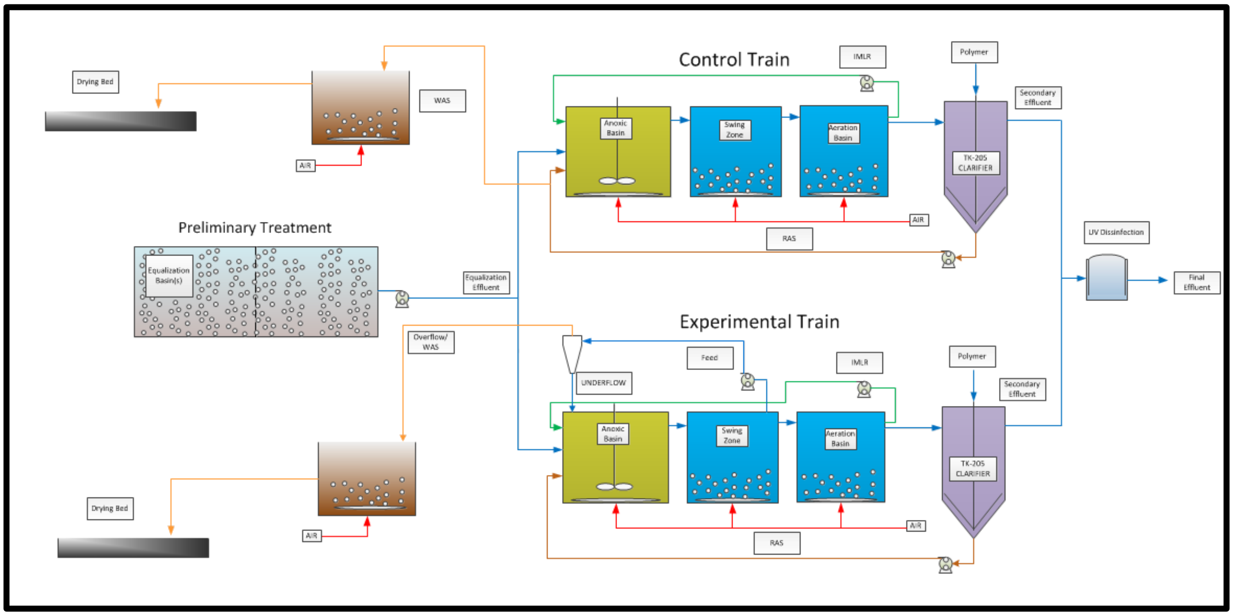

Figure 5. Process flow diagram for the Urbanna Wastewater Treatment Plant.

3.1.1 Preliminary Treatment

Raw wastewater influent (RWI) entered the UB WWTP through an 8-inch wide channel and passed through 1.5-inch screens for removal of large foreign objects. The RWI then entered a grit removal tank with a maximum designed capacity of 0.10 MGD. RWI was stored in an equalization basin with a total capacity of approximately 0.085 MG. Mixing in the equalization basin was accomplished through air mixing provided by three Roots Dresser Positive Displacement blowers (Gardener Denver, Milwaukee, WI). Each blower was rated for 153 actual cubic feet per minute (ACFM) at 14.7 psi. Influent wastewater was then transferred to the experimental and control train processes by submersible variable speed pumps (Ebara, Rock Hill, SC), one per train. Each pump was rated at 36 gpm at 26 TDH and pumping rates to each train were on average .027±0.013 MGD.

3.1.2 Treatment Process

Each train in the process was of a continuous stirred tank reactor design that operated in an MLE format and operated with a maximum design capacity of 50,000 gallons per day for a total design capacity of 0.1 MGD. Each train (Figure 5) was comprised of three biological reactors; a single center feed secondary clarifier, and an aerobic digester. The three biological reactors within each train operated in the following order: an anoxic zone, a swing zone (Anoxic/Aeration zone), and an aeration zone.

As shown in Figure 5, RWI entered the process and the internal mixed liquor recycle (IMLR) and return activated sludge (RAS) were returned to the head of the process in the anoxic zone. The anoxic zone also employed a course bubble diffuser and had the ability to be fully aerated during periods of high ammonia loading and low influent wastewater temperatures additional nitrification capacity was needed. The flow rates for RAS and IMLR were each approximately 300% of the influent flow rate. The anoxic reactor in train #1 also utilized a single 5 m^3/hr hydrocyclone for the cultivation of AGS. The overflow from the hydrocyclone was wasted into the aerobic digester and, for this project, was the WAS. The target operating pressure for the cyclone feed adapter was 30.5 psi (explained in section 3.2.4) which was determined through evaluation of various apex nozzles. The target operating pressure resulted in an approximate cyclone feed flow rate of 23 gpm. When determining the amount required to be wasted each day, in order to maintain the target SRT, the previous day's solids concentration of the overflow was used. The cyclone was operated for approximately 53.3 ± 11.5 minutes.

The second reactor, swing zone, was typically operated as an aerobic process; though airflow to this zone could be lowered to create an extended anoxic zone to further reduce nitrite and nitrate. The swing zone of train #1 also utilized a submersible variable speed pump (Ebara, Rock Hill, SC) that transported activated sludge to the external selector for the retention of denser material and cultivation of AGS.

The final reactor is a fully aerobic process for the oxidation of ammonia. This reactor utilized a return pump for IMLR to recycle the nitrate/nitrite to enhance the denitrification process in the anoxic reactor. The IMLR pumps were submersible variable speed pumps (Ebara, Rock Hill, SC) which were rated for 3-hp and a capacity of 80-gpm. IMLR pumping rates varied through the course of this study between 200% and 300% of the influent flow.

Each reactor had a volume of 6,250 gallons. All reactors were outfitted with two stainless steel course bubble diffusers with air supplied by four Sutorbilt rotary lube blowers with a rated 7.5-hp per unit and a capacity of 292-scfm per unit. Following the biological processes was secondary clarification. The secondary clarifier was a circular in shape, center feed, and peripheral weir clarifier with a total volume of 6,970 gallons per train. Each clarifier had a weir loading rate of 1,350 gpd/ft (0.688 $m^3/hr/m^2$) with a weir length of 37-ft per unit. The RAS pumps were horizontal suction lift centrifugal variable speed pumps (All Prime, Jacksonville, FL) rated at 2-hp and capacity of-35 gpm. The rate of return for the RAS was 100% for the duration of this study. Polymer was also fed to each train in the center feed well of each clarifier. Concentrations of polymer dosing are shown in Figure 12 in a later section of this thesis.

In order to maintain comparability between each train, the volume wasted daily from each train was adjust so that similar SRT values could be achieved. The average SRT was 21.3±3.3 days and 18.8±4.8 days for the experimental and control trains respectively. Due to the SRT control, the MLSS concentrations were also comparable between the two trains. The MLSS concentrations were 4707±915 mg/L and 3917±611 mg/L for the experimental and control train respectively.

3.2 Methods

3.2.1 Zone Settling Velocity

While SVI testing is the more common empirical testing method for assessing the settleability performance of sludge once mixing ceases, the Zone Settling Velocity (ZSV) test provides accurate and precise values for settling velocities at designated solids concentrations. This test was performed in a glass 2L graduated cylinder. The cylinders were outfitted with metric measuring tapes so that accurate settling distances could be recorded for the determination of settling velocities. MLSS samples were diluted or concentrated to 4,000 mg TSS/L due to the median operating MLSS concentrations of the treatment facility being studied and for the uniform evaluation of settling velocities between samples.

Once sludge was transferred to the graduated cylinders, settling measurements were recorded at intervals of 30 seconds (0-5 min), 1 minute (5-10 min) and 2 minutes (10-30 min) over a 30 minute period. The recorded data was plotted for the 30 minute period and the most linear initial portion was evaluated to yield the settling velocities for each sample. Due to the fact the samples were evaluated at a uniform MLSS concentration, the settling performance of a particular sludge could be directly compared to that of another. Well settling sludge is known to have settling velocities in excess of 5 m/hr while poor settling sludge is known to have settling velocities of <5 m/hr. Typical settling velocities of CAS range from 1 – 3 m/hr.

As the ZSV test utilizes a graduated cylinder that is outfitted with a metric measuring tape, sludge settling volume data can be collected from the settling distances recorded during the evaluation. SSV data can be collected when using the formula for the volume of a cylinder while substituting the distance settled for the height variable in the equation. Once sludge settling volume data can be obtained from the ZSV test, SVI data can then be collected and evaluated.

3.2.3 External Selector

The external selector, hydrocyclone, that was utilized throughout this research had an operating capacity of 5 m^3/h and was supplied by World Water Works^{TM}. The ability of the selector to effectively select for more dense particles is dependent on the operating pressure and the diameter of the apex opening in the nozzle. Three nozzles were evaluated and were also supplied by World Water Works^{TM}. Those nozzles and their corresponding diameters of the apex opening are as follows:

- Nozzle A: (13.58 mm)
- Nozzle B: (10.98 mm)
- Nozzle C: (9.34 mm)

Each nozzle was evaluated at varying pressures. Those pressures are: 27.5 psi, 29 psi, 30.5 psi and 33 psi. The evaluations conducted on samples collected from the nozzle evaluation were mass and hydraulic splits as well as ZSV which will be further explained in the following sections.

3.2.4 Nozzle Evaluation

In order to successfully optimize hydrocyclone performance, nozzles of varying sizes must be evaluated. The evaluation criteria were mass and hydraulic ratios as well as settling velocities of produced sludge. All criteria are further explained in the following sections.

3.2.4.1 Mass and Hydraulic Splits

In order to evaluate the nozzles mentioned in section 3.2.3, the mass and hydraulic splits were evaluated. Once a nozzle was added to the hydrocyclone, samples of feed, underflow, and overflow were collected. The values of the flow rate (gpm) to the cyclone, change in the liquid level (inches) of the aerobic digester, and the amount of time the cyclone was in operation (minutes) was recorded. The concentration of TSS of all samples collected was then immediately evaluated in order to determine the mass split values.

The setup of the hydrocyclone included only a flow meter on the feed line supplying activated sludge to the external selector. In order to determine flow rates of the remaining fractions of sludge produced by the external selector (overflow and underflow), some calculated values were needed. The overflow was wasted into an adjacent aerobic digester which was outfitted with radar to supply the operator with liquid level read outs. Based on the digester's dimensions, it was determined that a 1 inch rise in liquid level was equal to 104 gallons wasted.

Once the flow rates of the feed and overflow were found, the determination of the underflow flow rate is a simple subtraction calculation. In order to find the underflow, the user needed to subtract the overflow flow rate from the feed flow rate. Since the overflow and underflow flow rates were fractions of the feed flow rate, the determination of the hydraulic ratios were also a simple division calculation. The ratios were determined by dividing the overflow or the underflow flow rates by the feed flow rates and multiplying by 100%.

The mass split ratios were also needed to fully evaluate each nozzle. By adding the concentration of TSS values found from the samples collected, multiplying by the flow rate would yield the loading rate (lbs/day). Once each loading rate was determined, the same process used to find the hydraulic ratios was applied. The loading rates of the underflow and overflow were divided by the feed loading rate and multiplied by 100%. The calculations of the loading rates and the hydraulic splits supplied the necessary information to fully evaluate the nozzle.

3.5 Analytical Methods

In order to fully assess the overall performance of the UB WWTP full nutrient plant profiles were conducted. Samples were collected weekly at every stage of the treatment process. The samples collected were immediately filtered so that no further biological reduction or oxidation of nutrients could take place. Samples were stored at roughly 4°C during transport to an alternate facility for evaluation. Analytical methods included evaluations of nutrients, sludge volume index; solids flux analysis and intrinsic settling classification.

3.5.1 Nutrient Testing

In order to assess the overall performance, influent and effluent samples were collected from every stage of the treatment process. Samples were then immediately filtered through 0.45 μm cellulose filter membranes, stored at 4°C for transport, and analyzed for nutrients in accordance with standard methods (APHA 2012). The evaluations of nutrient samples were conducted through the use of a Hach DR 2800 spectrophotometer and the following Hach testing kits:

- Ammonia High Range – TNT 832
- Ammonia Low Range – TNT 831
- Ammonia Ultra Low Range – TNT 830
- Nitrate High Range – TNT 836
- Nitrate Low Range – TNT 835
- Nitrite High Range – TNT 840
- Nitrite Low Range – TNT 839
- Ortho-Phosphate – TNT 846

3.5.2 Diluted Sludge Volume Index (DSVI)

DSVI testing was performed daily by plant staff on activated sludge samples and was spot checked biweekly by research staff. SVI testing was also conducted for all samples that entered and exited the hydrocyclone (feed, underflow and overflow sludge). SVI was reported as mL/g and values of <100 mL/g were desirable. When SVI data did not yield values <100 mL/g dilutions were performed until 100 mL/g or better were reached and then multiplied by the dilution factor to yield true SVI values. When sludge settling values of a poor settling sludge are used, then the reporting of SVI will be erroneous without necessary dilutions being performed to yield true SVI values. The testing was performed in accordance with standard methods (APHA 2012). Further testing of SVI was conducted at TSS concentrations of 4,000 mg/L, which was the average operating condition for the UB WWTP. The testing was conducted at 4,000 mg TSS/L in order to accurately compare the SVI of the differing samples.

3.5.4 Solids Flux Analysis

To further assess the settling characteristics of the various types of sludge, a solids flux analysis (SFA) was performed in order to determine the Vesilind Settling Parameters (Vo and k). The SFA evaluation followed the same procedure as the ZSV test with one notable difference; solids concentration. Multiple ZSV tests were performed on a single sample at various solids concentrations. Before the ZSV testing began for the SFA, all samples were lightly aerated for approximately one hour while TSS concentrations were determined.

Once TSS concentrations were determined and the dilution and concentration ratios were determined, the samples were diluted and/or concentrated using secondary clarifier effluent from each respective process. Sample solid concentrations were determined so that the solid-liquid separation ranges from no solid-liquid separation (for the most concentrated sample) to immediate solid-liquid separation (for the most diluted sample) within the 30 minute time period. The data from the SFA produced a solids-flux curve, based on the empirical Vesilind settling parameters, which can yield data useful for the design/evaluation of secondary clarifiers in regard to maximum solid loading rates and settling parameters.

3.5.5 Intrinsic Settling Classification

The intrinsic settling classification (ISC) test was adapted from the work of Mancell-Egala (2016). The ISC test is the simulation of a clarifier with a high surface overflow rate (SOR) of approximately 900 gpd/ft^2. This overflow rate has been found to be the point at which clarifiers tend to fail during stress tests (Daigger 1998). This test was adapted as it was an accurate and reliable testing method to classify discretely settling particles into the five classifications shown in Table 1.

Table 1 Intrinsic settling classifications and criteria

CSV m/h	Classes	Settling time seconds	Fraction of TSS %
> 9.0 m/h	Granule	20	
3-9 m/h	Large Aggregate	60	
1.5-3 m/h	Small Aggregate	120	
0.6-1.5 m/h	Flocs	300	
< 0.6 m/h	Fines	>300	

Each sample was diluted to 100 mg TSS/L, which was below the threshold of flocculation (TOF), in 4L containers and evaluated for TSS to ensure accuracy as well as for the determination of solids remaining in suspension at the conclusion of the test. Dilutions were performed with tap water to ensure that solids were not being added to the solution. The 4L samples were then transferred into a 4L Nalgene graduated cylinder which were outfitted with Teflon tubing and clamps extending from plastic nipples installed 65 mm below the 4L mark. The samples were allowed to settle for periods of 20, 60, 120 and 300 seconds.

Once the allotted time expired, the clamps were opened to allow for the supernatant and remaining suspended solids to exit the cylinder into an alternate container. The supernatant would be used for determination of the final TSS concentration. A new sample would be prepared, transferred to the graduated cylinder and allowed to settle for the next time period. When the initial and final TSS values were compared, the percentage of remaining TSS for each time period could then be determined. The classifications and settling velocities were determined by the percentage of the TSS remaining in suspension after each time trail and recorded under "Fraction of TSS".

3.5.6 Density Measurements

The purpose of the implementation of the hydrocyclone at the UB WWTP was to increase the density of the activated sludge within the control train which would subsequently result in the increased settling rates of the activated sludge. In order to determine if the density of the sludge had been increased, density measurements were taken. Using the Percoll method, a Stock Isotonic Percoll (SIP) solution was created that possessed similar conductivity characteristics to the activated sludge at the UB WWTP. The SIP solution was created from the combination of 1.5M NaCl, Percoll solution, and deionized water.

Once the solution was created, it was mixed at a high setting for approximately two minutes. Following mixing, the solution was transferred into 16 mL centrifuged vials leaving room for mixed liquor to be added at a later step. Before the vials were centrifuged, approximately 200-300 µL of density marker beads from each density were added to one of the vials and can be seen in Figure 6. Each color of the density beads corresponds to a different density. Those colors and densities are as follows:

- Green: 1.02 g/cm^3
- Orange: 1.04 g/cm^3
- Violet: 1.06 g/cm^3
- Blue: 1.08 g/cm^3
- Red: 1.09 g/cm^3
- Fluorescent blue: 1.13 g/cm^3

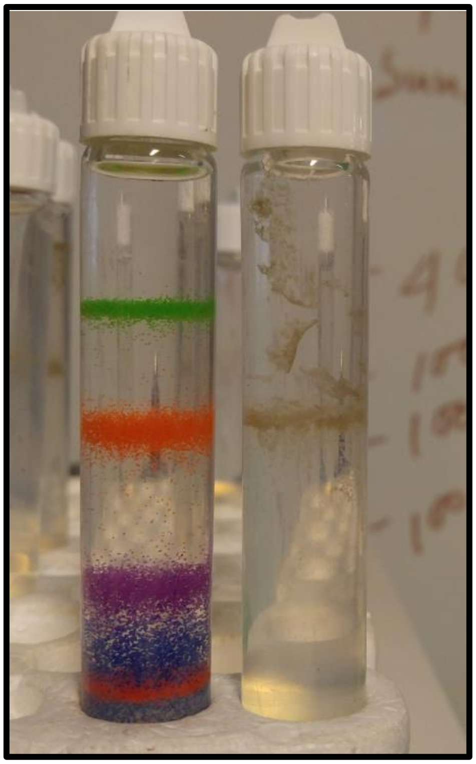

Figure 6. Vials containing SIP solution, density marker beads, and sludge following centrifugation.

After the density beads were added, all vials were centrifuged at 18,000xg for 90 minutes so that a density gradient was created in all of the vials containing the SIP solution. Approximately 200-300 µL of sludge was added to each vial that only contained the SIP solution and then re-centrifuged at 400xg for 45 minutes. The sludge vials were then compared to the vials containing the density beads to determine the density of the sludge.

CHAPTER 4

RESULTS and DISCUSSION

4.1 Urbanna Study Operational Data

The UB WWTP consisted of two trains that are mostly identical and operate in parallel. Train #1 was the experimental train and utilized the external selector to select for denser material to improve overall settleability within the activated sludge. Train #2 was the control train and operated without the use of an external selector. Both trains were operated in the Modified-Ludzack Ettinger (MLE) configuration. The observation and comparison of external selection results pertaining to activated sludge settling performance in a suspended growth process are discussed in this chapter.

4.2 Settling Characteristics

Data from the external selector were collected over the course of 374 operational days. Many different tests have been conducted that provided insight into the different classifications and percentages of sludge particles, settling rates, sludge volume index, and the efficiency of the performance of the external selector.

4.2.1 Selection of an Appropriate Nozzle

As previously stated, World Water Works® provided the external selector (hydrocyclone) and various nozzles. Each nozzle was installed on the external selector and evaluated at various operating pressures. It was found that nozzle C, with an apex diameter of 9.34 mm, created the best environment available for the selection of denser material. Figure 7 shows that the underflow and overflow produced by nozzle C experienced the fastest and slowest settling rates respectively; furthermore, the operating pressure that produced underflow with the greatest settling velocity was 30.5 psi. This evaluation was performed once every season to ensure the selector efficiency and that the proper nozzle was in use.

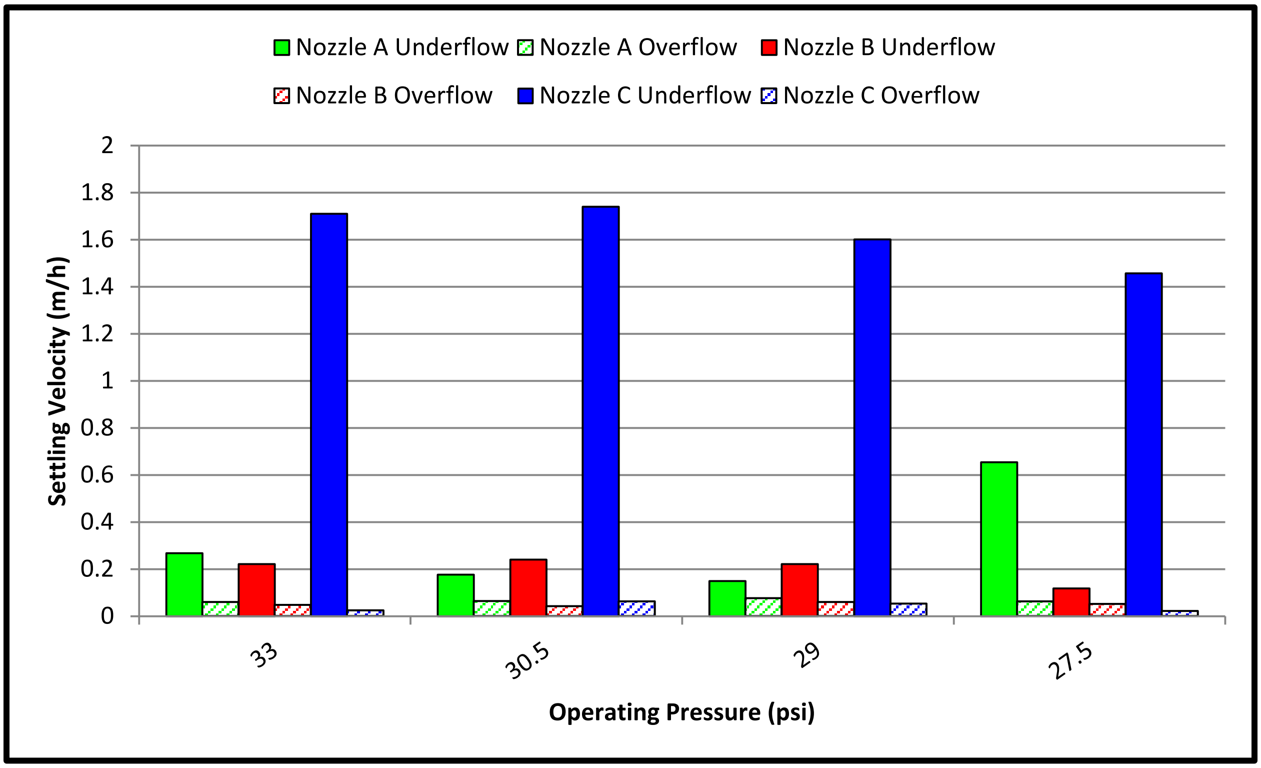

Figure 7. Settling velocities for the underflow and overflow produced by the external selector at various operating pressures for various nozzles (6/15/2016).

In order to ensure the external selector was operating as efficiently as possible, the submersible pump that feeds the external selector was removed, de-ragged, and flushed clean monthly. This submersible pump was outfitted with a suction screen, shown in Figure 8, in order to keep any debris within the activated sludge from entering the selector. The suction screen had openings that were approximately 10 mm in diameter so any small foreign debris (leaves, rags, etc.) that were in the system would cause the pump to clog. The feed pump was also removed when the variable frequency drive setpoint exceeded 58.5 Hz (maximum of 60 Hz) when maintaining the correct operational pressure during selector operation. The nozzle of the external selector was also removed when the submersible pump was cleaned to ensure that there are no disruptive blockages or when the underflow spray pattern has visibly changed.

Figure 8. Ebara submersible feed pump for the external selector showing the suction screen at the UB WWTP.

Data collected on the settling velocities of the underflow sludge produced by the external selector during periods of cold wastewater temperatures (< 20°C, Figure 11) suggest that the wastewater's temperature impacts the performance of the external selector. A reevaluation of the available nozzles during extremely low wastewater temperatures (< 15°C) was not conducted for this study and is recommended for future studies to improve the efficiency of the selector during the low operating temperatures. A reevaluation of the appropriate nozzle did not take place during the period where wastewater temperatures were <15°C as a relationship between wastewater temperature and underflow settling velocity was not discovered until a large amount of data over a period of approximately 50 days. Once the relationship was discovered, the experimental train was beginning a shutdown procedure for preventative maintenance and recoating of the interior and exterior of the facility. Since the UB WWTP is an above ground package plant, constructed of coated steel, it is highly vulnerable to rust and must be shut down, sand blasted and recoated periodically in order to maintain the operation.

4.2.2 Performance of the External Selector

Performance of the external selector was evaluated through mass and hydraulic split analysis. This analysis allowed for the quantification of what and how much was being retained and wasted based on what was being supplied to the selector.

The data shown in Figure 9 are the mass and hydraulic split data from the underflow and overflow produced by the external selector. It can be seen that the selected nozzle produced, approximately, an 80:20 hydraulic split between the overflow and underflow respectively. It can also be seen from Figure 9, for the time period of 0 – 164 days, that the there was a gradual, but steady, deviation of the overflow and underflow mass splits. This deviation shows that the selector was experiencing a steady increase in the retention of particles in the underflow. This suggests that a change towards granulation could be occurring in the activated sludge of the experimental train. During days 165 – 186 there was a system shutdown so that necessary preventative maintenance could be conducted on the interior and exterior walls of the experimental train. The activated sludge was drained from the experimental train and transferred to one of the equalization basins, as flow and loading during this time was minimal. The ML was fed intermittently with RWI and kept under extended aeration in order to maintain biological activity during the shut-down period.

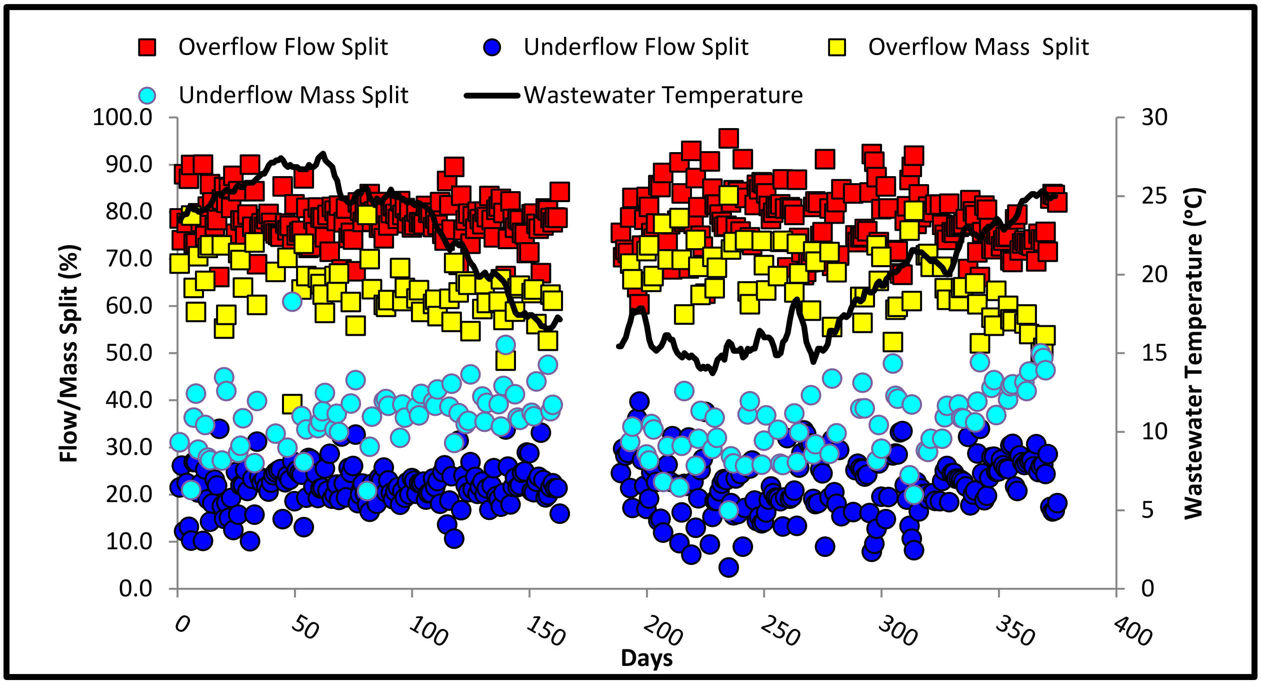

Figure 9. Data for the wastewater temperature and mass and hydraulic splits collected from days 0 – 374.

The data in Figure 9 show the strong deviation, beginning at approximately day 315, of the mass splits as an increased percentage of the solids were retained from the feed sludge through the physical solid-liquid separation process that the selector imparts on the activated sludge. This deviation shows that there was again an increase in particulates being retained in the underflow. The increased retention of solids in the underflow occurring roughly 150 days from start-up (day 150 and 315) suggested that 150 days may be a potential start-up period for the possible shift towards granulation. It is hypothesized that temperature does not play a role in the effectiveness of the hydrocyclone as the observed deviations occurred at times of high and low wastewater temperatures, above and below 20°C.

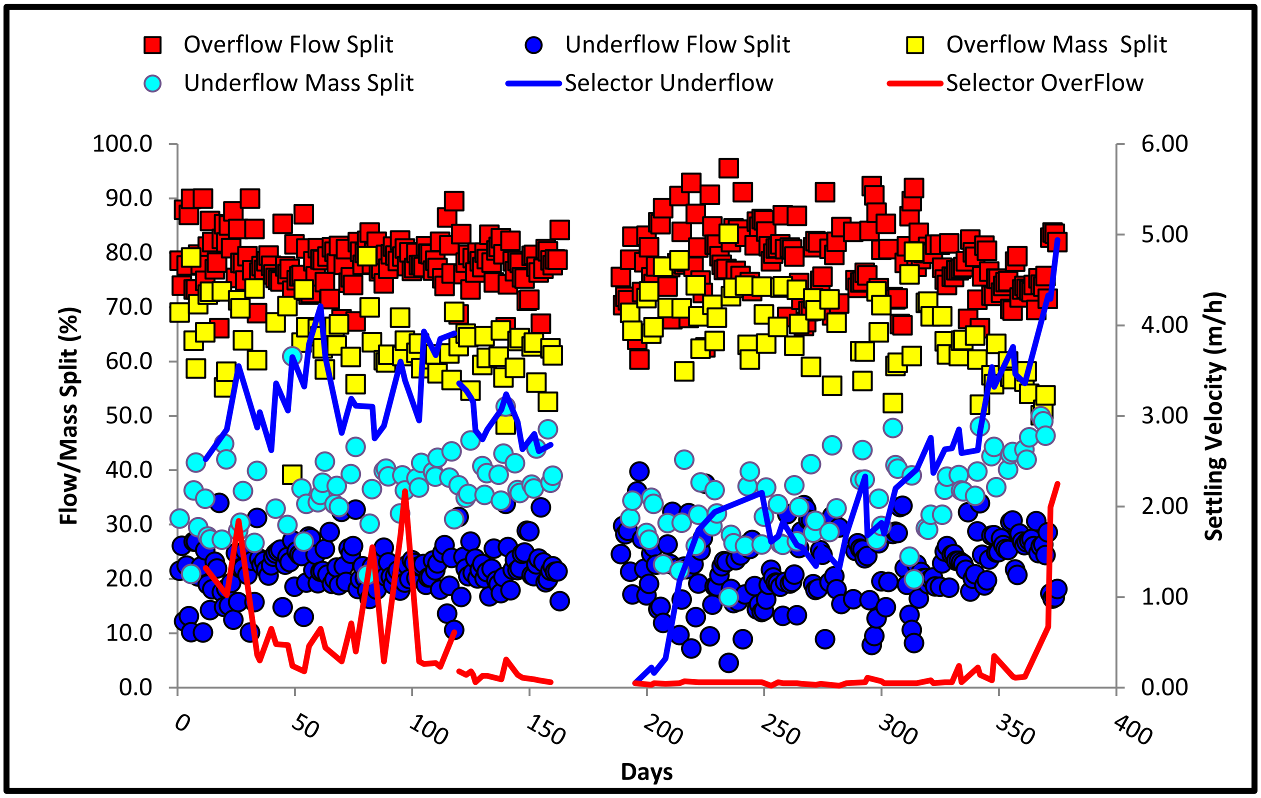

Figure 10. Mass and hydraulic split data collected from days 0 – 374 as well as settling velocity of the selector underflow and overflow.

Figure 10 shows the settling velocities of the underflow and overflow sludge produced from the external selector. It can be seen that the selector was consistently producing underflow that was settling at an elevated rate compared to typical settling rates of CAS (<1 m/hr), while the overflow was settling at rates that were on average representative of CAS at <1 m/hr during the first 150 days of operation. Following the system shut down, ML was returned to the experimental train and the control train was wasting from the secondary clarifier into the experimental train to elevate the MLSS concentration and essentially revive the activated sludge. Due to an extended period of inactivity and sludge mixing, the settling rates of the sludge in the experimental train were extremely poor. The settling rates of the underflow and the overflow were comparable. After a period of approximately 10 days the settling velocity of the underflow began to increase until the underflow once again was achieving settling rates that were elevated above settling rates of CAS.

4.2.4 Effects of the External Selector

Much data was collected through a multitude of testing methods to evaluate the impact of the external selector when fed activated sludge. Overall, the impact of the external selector was positive in improving the settleability of the activated sludge when compared to that of the control train and is reported in the following figures.

One of the two most notable comparisons and largest indicators, short of microscope and sieve analysis, of a shift towards granulation is the settling velocity and the classification of the activated sludge. Literature suggests, activated sludge whose settling velocity exceeds 5 m/h is an indicator of a shift towards granulation while CAS with good settling rates typically settles at roughly 1 – 3 m/h. In some cases CAS can reach settling velocities of up to 5 m/hr. Activated sludge that has made a complete shift to granulation can even reach settling velocities of up to 70 m/h. Settling velocities of 70 m/h has only been observed in a few cases and has not been achieved in full scale operation, therefore, such extreme settling velocities were not expected to be observed. Average observed settling velocities in full scale operations were reported to be between 10 – 30 m/h, so the desired consistent settling velocities for this study was >9 m/h.

As an upgrade of this facility to the MLE process format was completed when this study began, there is no historical data that could be used to compare the effects of the external selector on the activated sludge within the facility. ZSV testing has shown that immediate positive effects were imparted on the activated sludge of the experimental train by the external selector. The experimental train's activated sludge was settling at rates that were, on average, 7x faster than the activated sludge in the control train during periods where the wastewater temperatures were consistently >19°C (Figure 11). The time periods when wastewater temperatures exceeded 19°C were days 0 – 140 and days 306 – 374. The initial warm period (days 0-164) allowed for 128 days of operation with consistently above average settling characteristics. The average settling velocity of the activated sludge during this period was approximately 1.8 m/h while the underflow produced by the selector achieved an average settling rate of 3.27±0.43 m/hr and peaked at 4.21 m/hr. The average settling velocity for the CAS in the control train was significantly less at only 0.40 m/h during the same period.

The data set collected from the entirety of the operation (Figure 11) show that not only were the settling rates of the activated sludge significantly impacted by the wastewater temperature but so were the underflow and overflow sludge produced by the external selector. Data suggests that warmer wastewater temperatures lead to improved selector performance as well.

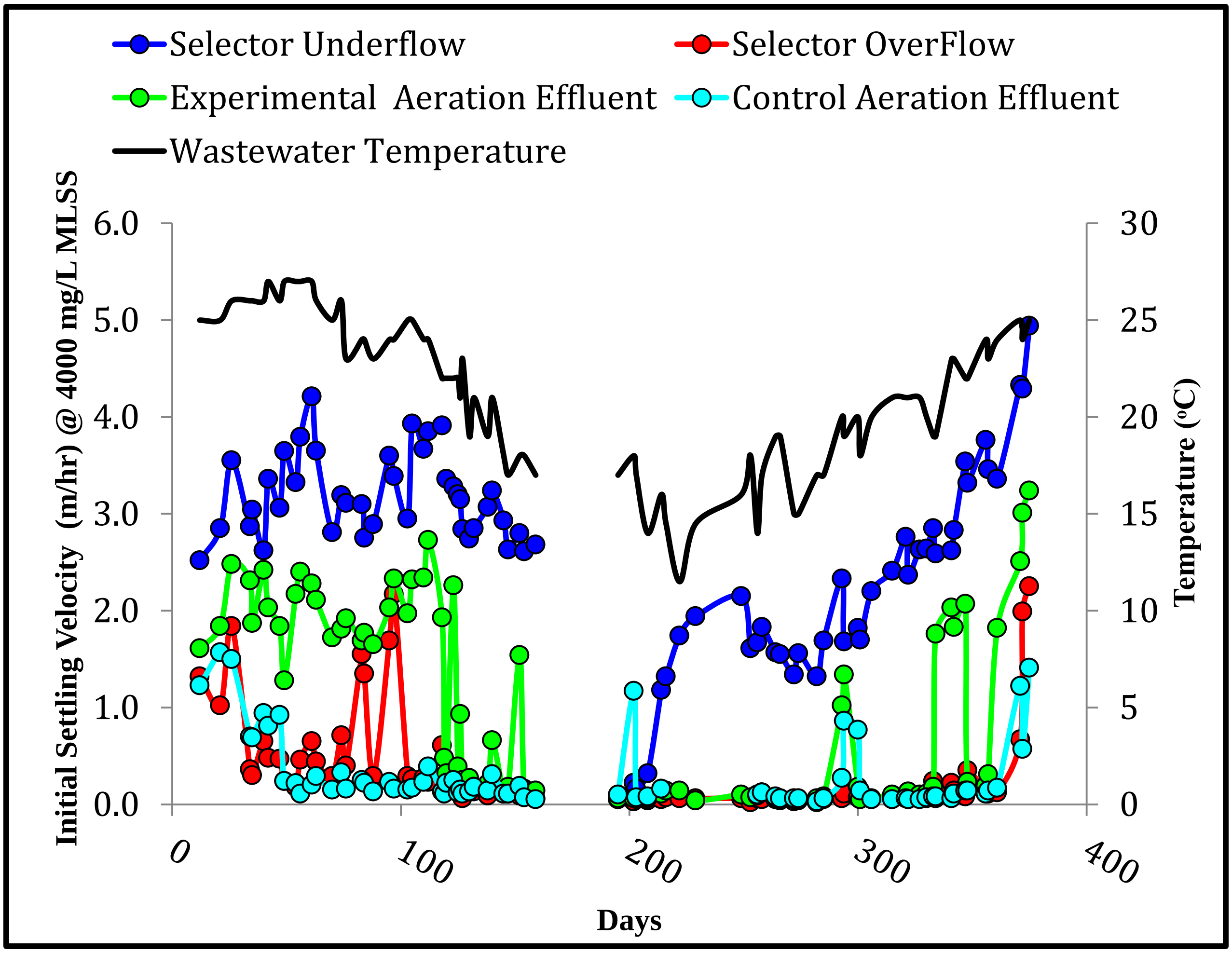

Figure 11. Zone settling velocity results from days 0 – 374.

More recent data suggests, days 187-374, that after lengthy operation through the cold weather period, the external selector was able to operate during a lengthy potential start-up period during expected periods of negatively impacted settling due to changes in water density and viscosity. During this time, continued accumulation of large aggregates and granular classified material appeared to have taken place even though settling performance did not reflect this and were determined through ISC testing (Figure 15). Once wastewater temperatures reached levels >19°C, settling velocities began returning to the elevated levels observed early in the study. While it is theorized that settling was negatively impacted due to a drop in wastewater temperature, resulting in an increase in waster viscosity, there was also an extended period of sludge bulking taking place as filamentous bacteria were prevailing within the activated sludge of both the experimental and control trains. At the conclusion of the collected data used for this thesis, settling velocities for the activated sludge of the experimental train had averaged 1.724 m/h for the short period that wastewater temperatures were > 19°C and peaked at 3.24 m/h. While that average is a low rapid improvement of the activated sludge, settling velocity occurred and trended towards more elevated settling velocities.

The underflow produced by the external selector had also reached unexpectedly higher settling rates at the conclusion of this study, based on data from days 0 – 108 (summer months of 2016). The settling velocities observed from the underflow had averaged 3.65 m/h and peaked at 4.94 m/h on the final day of data collection (days 187 - 374). A trend towards more elevated settling rates can be seen for the underflow data set in Figure 11. The activated sludge in the control train was observed to be 0.40 m/hr during the same period which was expected based on the data collected during the warm period from days 0 - 108.

Figure 11 shows the settling velocity data with the polymer concentrations for each day ZSV testing took place for the experimental train. During the first 100 days of the selector operation while the wastewater temperature was >20°C, polymer was being fed to both the experimental and control trains. At this time the settling velocity of the activated sludge in the experimental train was approximately 1.98±0.32 m/h and continued to settle at similar rates once polymer dosing was ended until the wastewater temperatures dropped below 20°C. These data suggest that the polymer dose (<20 mg/L) had little effect on the settling velocity of the activated sludge.

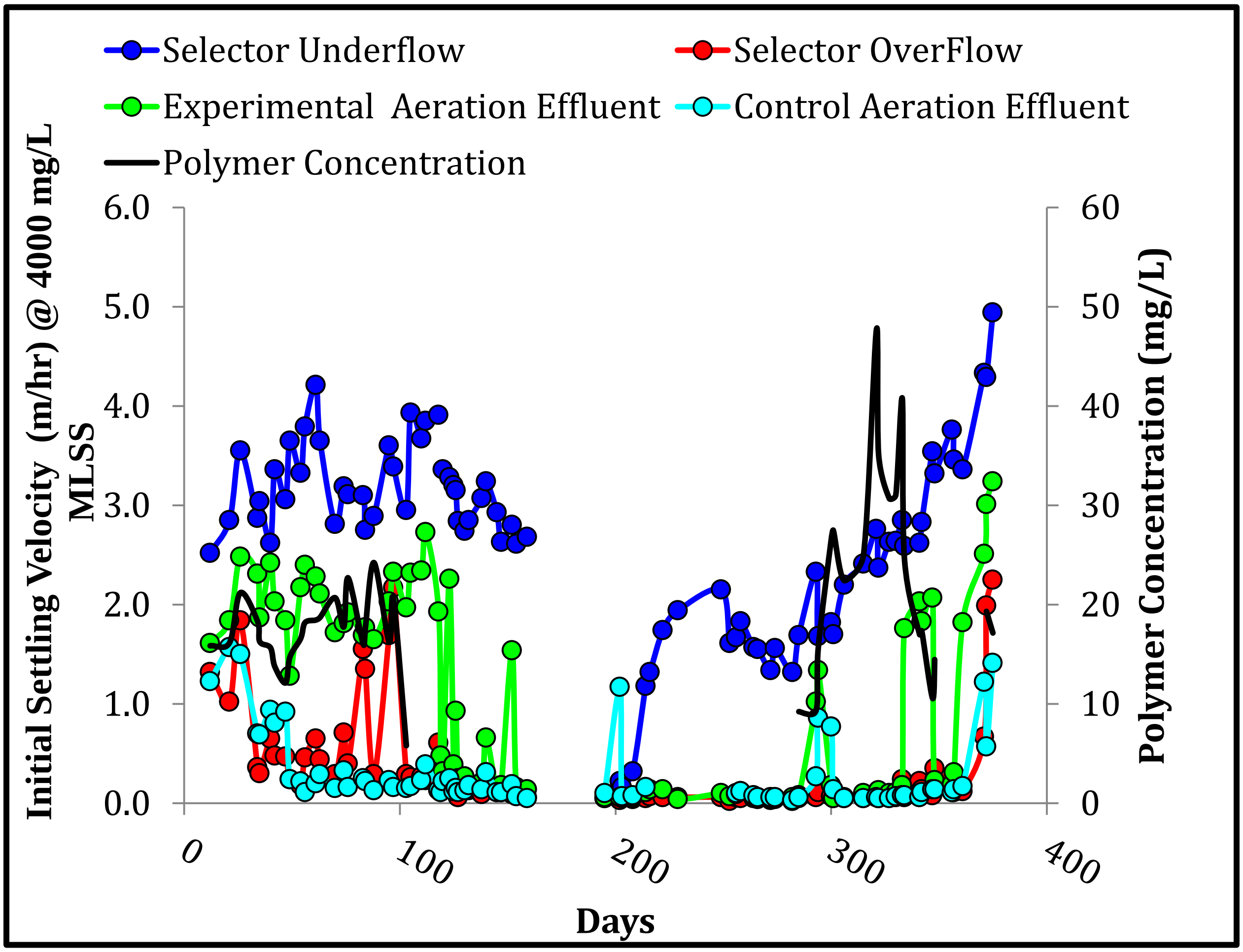

Figure 12. Zone settling velocity results and polymer dosing concentration for days 0- 374.

The polymer feed was resumed around day 300, which was approximately the time that the wastewater temperature rose above 20°C, and was being dose at concentrations below 20 mg/L. Again it was assumed that the polymer had little effect on the settling rates due to data collected after polymer dosing was discontinued around day 100. It was assumed that the settling rates of the activated sludge had not increased due to an increase in filamentous bacteria and the polymer dose was increased. The concentration of the dose had reached levels in excess of 40 mg/L and settling had been significantly inhibited. Data suggest that an overdose of polymer negatively impacted settling. In an exploratory effort, the polymer dose was, again, dropped to concentrations below 20 mg/L and settling rates increased around day 340. Settling rates continued to climb as wastewater temperatures continued to increase until the conclusion of this study at day 374.

4.2.5 Sludge Characteristics

Due to the nature of operation of hydrcyclones, it is hypothesized that that the external selector would retain more grit and inorganic material when supplied with activated sludge, thus the percentage of VSS was expected to decrease in the underflow as denser particles were selected and retained. Figure 14 shows that the selector’s underflow %VSS was consistently at lower percentages than the activated sludge as inert material was retained in the underflow. While the selector retained more grit and inorganic material, healthy granules and large aggregates were also retained from the activated sludge due to their increased density. The increase in density allows for the increase in operating capacity, as the higher TSS concentrations coupled with faster settling rates allow for an increase in overall flow through the facility.

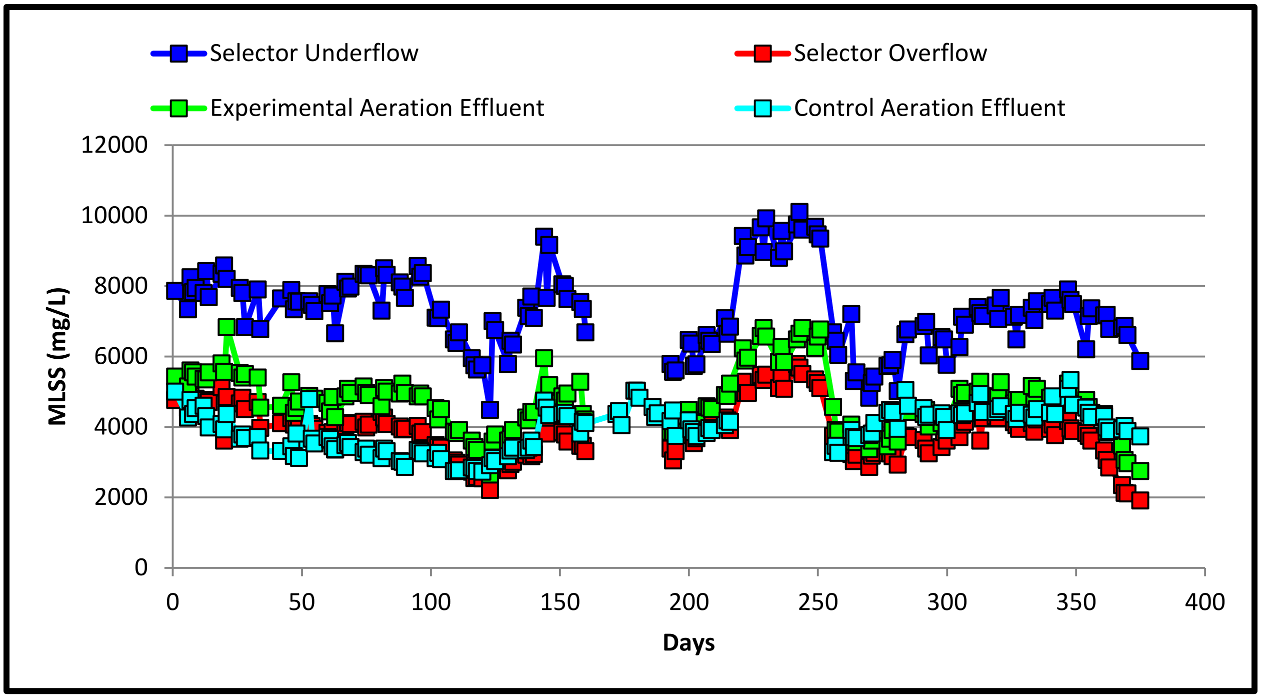

Figure 13. TSS concentration data for both trains from days 0 – 374.

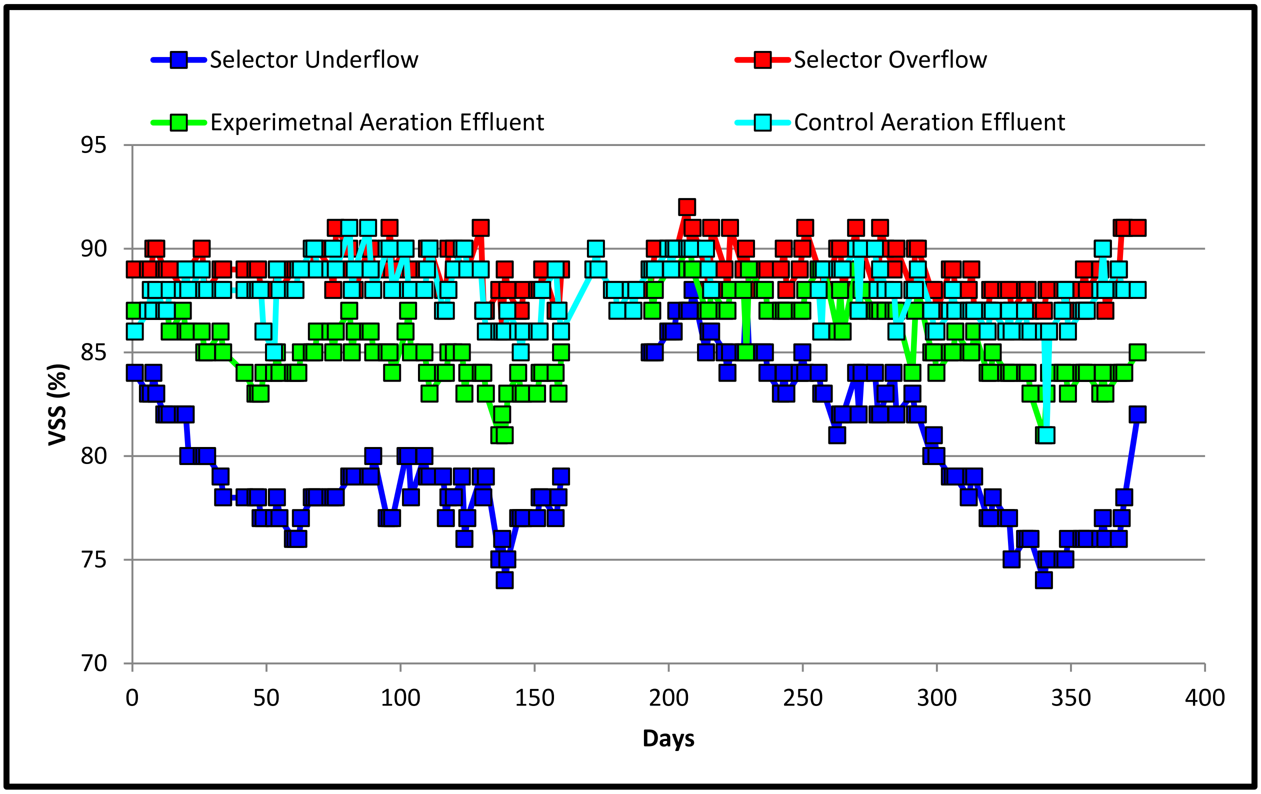

Figure 14. VSS data for both trains from days 0 – 374.

Since this study was performed as a comparison to a CAS treatment train, the SRT in the experimental train was controlled to be similar to the control train. While AGS technology allows for the intensification of the process (allowing a facility to be operated at elevated MLSS concentrations), elevated solids concentrations were not permitted in order to maintain similarities between trains and therefore are not represented in Figure 13.

A disruption can be seen in the Figures 13 and 14 from days 164 – 187. That disruption is the shut-down of the experimental train for the recoating of the interior and exterior walls of the train. Before the shutdown all of the mixed liquor was transferred to an offline equalization basin, only one of the two equalization basins are needed in the winter due to decreased flow through the facility. After completion of the recoating of the side walls of the facility, the mixed liquor was transferred back into the experimental train. In order to revive and repopulate the mixed liquor the WAS from the control train was wasted into the experimental train to expedite the process of increasing the MLSS concentration so that normal operation could be resumed.

From days 217 – 255 the control train was shutdown which is also the time period where the MLSS concentration of the underflow spiked. The selector produced underflow with MLSS concentrations at approximately 10,000 mg/L during the shutdown of the control train as all of the flow through the facility was routed into the experimental train. For the duration of the time that the ML from each train was in the equalization basin, a continuous aeration strategy and intermittent feeding regimen was applied to the equalization basin to ensure the continued activity of the microorganisms.

Monthly ISC testing occurred during the course of this comparative study. The ISC did not occur from December through March due to the system shut down when each train was independently taken out of service for repairs. This test was useful in visually representing the time-lapse of the changes in sludge classifications throughout the duration of this study. As previously mentioned in the methods section, the ISC evaluates sludge on settling rate criteria and classifies sludge into the five categories listed below. All ISC data are shown in Figure 15.

- Fines (<0.6 m/hr) (Cyan)
- Flocs (0.6-1.5 m/hr) (Purple)
- Small Aggregates (1.5-3.0 m/hr) (Green)
- Large Aggregates (3.0-9.0 m/hr) (Red)
- Granular Material (>9.0 m/hr) (Blue)

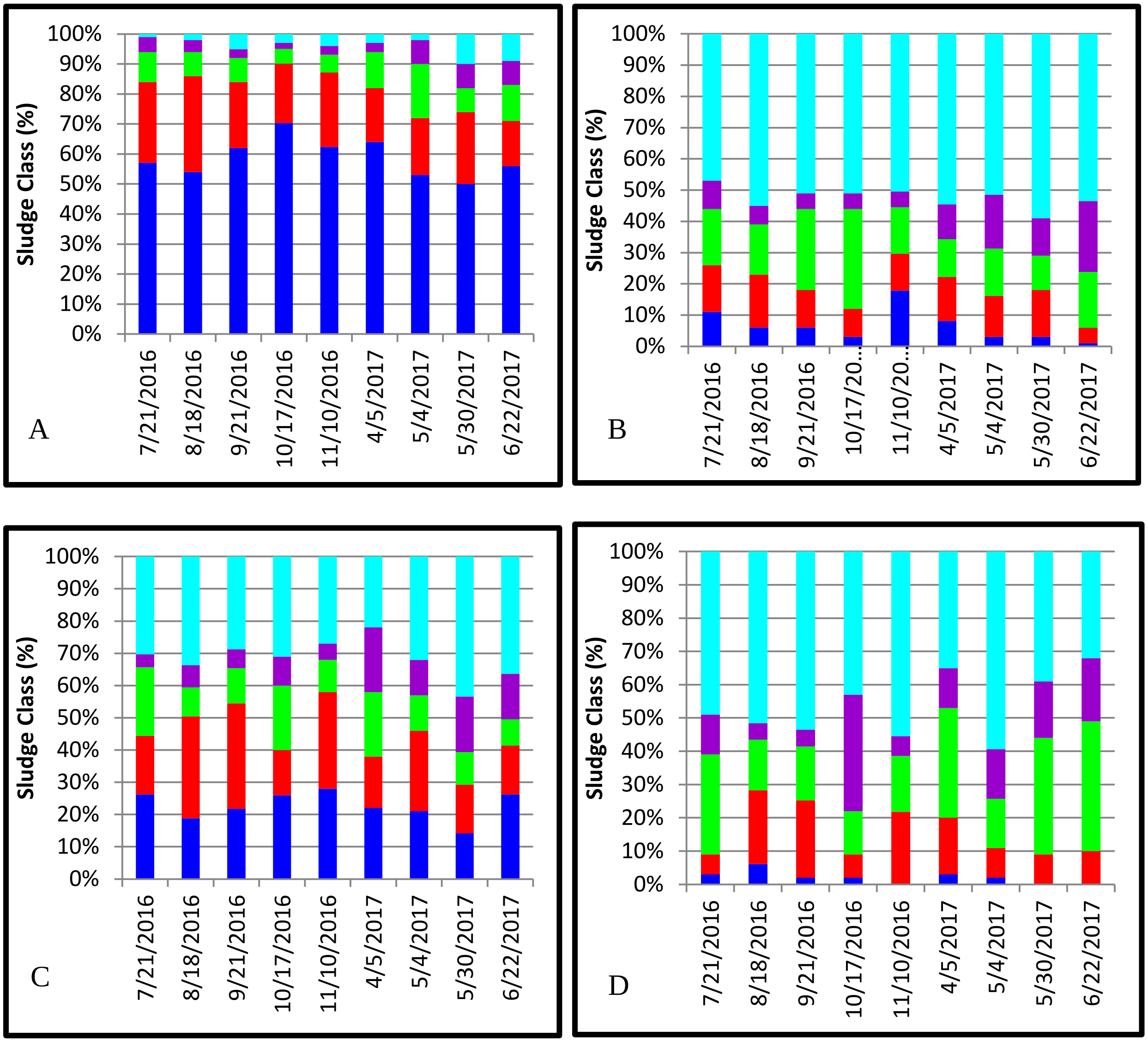

Figure 15. Sludge classification data for (a) selector underflow, (b) selector overflow, (c) experimental activated sludge, (d) control activated sludge.

From June 2016 to June 2017 Figure 15a shows that there were little changes experienced in the distribution of particle settling rates of the external selector and that the external selector was successful in the retention of faster settling particles. It can also be seen from Figure 15a that the selector underflow was composed primarily of sludge particles that settled at rates that correspond to granular material. The settling rates of the discrete particles that corresponded to granular material was consistently present at percentages above 50% and even peaking at 71% in mid-October. Recalling Figure 11, it can be seen that settling rates of the selector underflow declined during the period where wastewater temperatures were <20°C while the ISC data for the same sludge shows a comparable selection for faster settling sludge particles to the periods where wastewater temperatures were >19°C. It is hypothesized that the change in wastewater temperature and viscosity slowed not only the activity of the biomass but actually affected the density of the solid particles and liquid which in turn affected the settling rates of the underflow.

While Figure 15a shows the selection of granular material being the primary constituent in the underflow, the exact opposite is true of the selector overflow. The discrete settling data for the selector overflow is shown in Figure 15b and shows that the settling rates correspond to a primary composition of the slow settling flocs and fines. In fact, the percentages of fines consistently existed at levels exceeding 50% throughout the duration of this study.

The combination of Figures 15a and b suggest that the selector is quite efficient in the selection for denser material and rejection of the less dense material that exists within the activated sludge. These data are promising in that settling rates corresponding to granular sludge could be achieved through the use of external selection utilizing hydrocyclones. Even though the underflow sludge itself was never able to reach settling rates corresponding to granular material at either normal operating concentrations or at discrete concentrations

Figure 15c shows that the composition of the sludge that corresponds to granular material fluctuated between 14% and 38% during this study. The maximum settling rates of the experimental train's activated sludge was experienced in June of 2017 (days 351 – 374) even though the maximum amount of granular material was observed to have existed in November of 2016 (days 131 – 168). While November 2016 (days 131 – 168) showed the highest levels of granular material, Figure 11 shows that this period experienced some of the lowest consistent settling rates. The same hypothesis that was theorized for the selector underflow rates is theorized for the activated sludge of the experimental train, in that changes in temperature and viscosity adjusted the density to extremes where the presence of granular material was hidden when not evaluated below the threshold of flocculation.

The activated sludge of the control train varied drastically in the particle composition over the course of this study. The variance can be seen in Figure 15d. While the activated sludge was primarily composed of fines and flocs, the composition of small and large aggregates never remained consistent. Comparably speaking, the control train settled consistently at rates less than those corresponding to small aggregates at normal operating conditions of MLSS and the composition was evident in Figure 15d as to why.

The ZSV test also yielded information about the SVI of each sample. The ZSV test was performed at 4,000 mg TSS/L; the SVI data collected from the ZSV test allowed all samples evaluated to be directly compared to one another other. It can be seen from Figure 16 that during periods where the wastewater temperature was >19°C that the settleability (SVI_5) of the activated sludge in the experimental train improved when compared to the activated sludge in the control train. The average SVI_5 values for the experimental train’s activated sludge was 134±27 mL/g while the control train’s average SVI_5 was 176±28 mL/g.

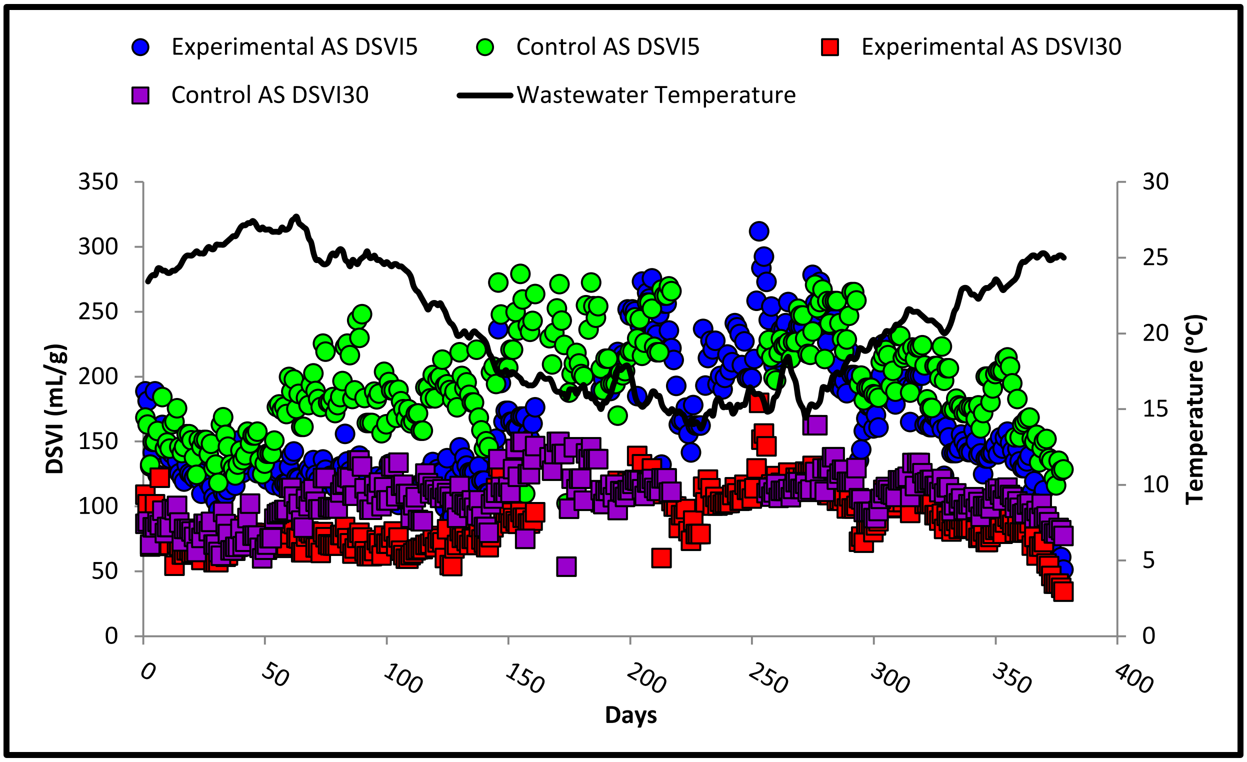

Figure 16. DSVI data from both the experimental and control trains from days 0 – 374.

The thickening ability (SVI_{30}) of the experimental train was dramatically improved as the average SVI_{30} values were 77±14 mL/g while the control train average was 100±16 mL/g. The SVI values are not representative of activated sludge that has undergone a population shift towards granular material. Nevertheless, the settling rates and the SVI values of the sludge produced by the external selector shows much promise that this technology, when optimized, could potentially produce sludge that results in a shift to granular sludge. The underflow produced by the external selector had average SVI_5 and SVI_{30} values of 116±25 and 45±13 mL/g respectively. While the overflow rejected by the external selector had average SVI_5 and SVI_{30} values of 232±20 and 164±54 mL/g respectively.

Solids flux analysis (SFA) was conducted on the selector underflow and overflow as well as the experimental and control activated sludge, to determine the Vesilind settling parameters (k and Vo) for each fraction of sludge produced at the UB WWTP. Each fraction of sludge was either concentrated or diluted to both extremes of solid-liquid separation; no separation and immediate separation. Figure 17 shows that the sludge that was produced by the external selector (underflow and overflow) remained fairly stable with little variation in either of the estimated Vesilind settling parameters.

While the activated sludge of both trains experienced vast changes in both k and Vo, it can be seen in Figure 17 that the differences between the Vesilind settling parameters (k and Vo) changed more in the experimental train compared to the control train. As previously mentioned in section 2.2, the k parameter represents exponential decrease in the settleability of the sludge evaluated in reference to the increasing solids concentration; while the Vo parameter represents the maximum theoretical settling velocity of the sludge evaluated. Figure 17 shows that the activated sludge of the experimental train demonstrated consistently higher Vo and lower k values when compared to the control train, this data explains the extremely poor settling found by the ZSV testing and high SVI values.

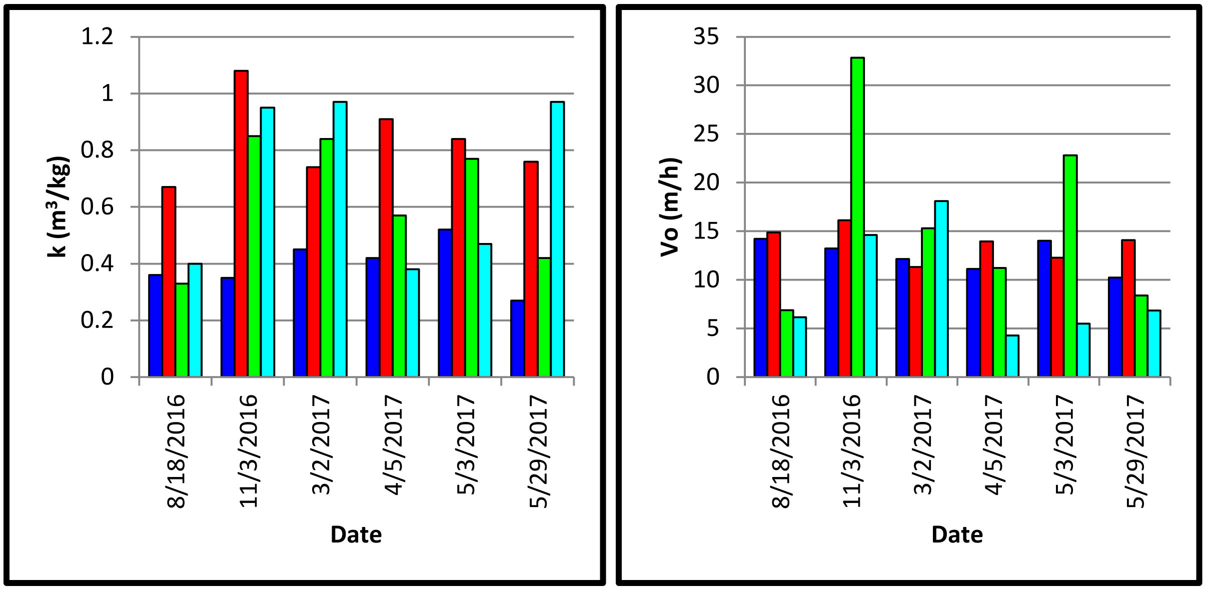

Figure 17. SFA derived Vesilind settling parameters. Selector underflow (Blue), Selector overflow (Red), Experimental activated sludge (Green), Control activated sludge (Cyan).

4.3 Effects of Temperature

As the UB WWTP is an above ground package plant, the facility is highly susceptible to fluctuating temperatures. The effects of the changing temperatures were seen in all of the varying tests used to measure the performance and effects of the external selector. A sharp decrease in performance was seen once the temperature dropped below 20°C in:

- Settling rates
- Sludge densities
- SVI
- Turbidity
- Microbial activity

It was unexpected to see the decreased settling velocity in the underflow sludge produced by the external selector from days (120 – 164). This effect was unexpected as the selector operates through physical means to retain the "building blocks" granules rather than biological means. The density of the various sludge fractions in both trains is seen to drop significantly in Figure 18. Due to the late realization and the preventative maintenance a nozzle evaluation was not conducted during the period where settling was hindered. If the evaluation was performed it may have been evident that the need for a cold weather nozzle (wastewater temperature <20°C) and warm weather nozzle (wastewater temperature <20°C) were necessary.

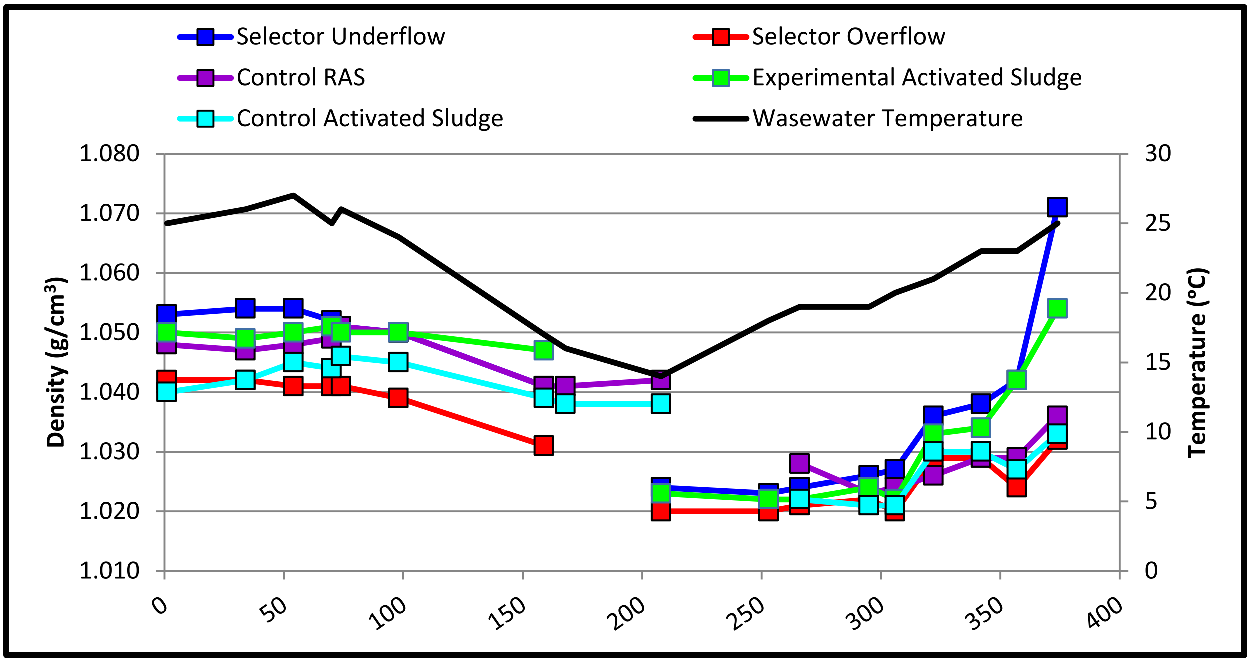

Figure 18. Density of the various fractions of sludge in both experimental and control trains overlaid with the wastewater temperature.

From the beginning of the study (14 June 2016) until the wastewater temperature dropped below 20°C at approximately day 145, the density of the experimental train's activated sludge and selector underflow were consistent at 1.050 g/cm^3 and 1.052 g/cm^3 respectively. The density of the CAS averaged 1.044±0.007 g/cm^3 during the same period. This suggested that the external selector effectively increased the density of the activated sludge within the experimental train, thus improving overall settleablity. Once operation of the external selector resumed after the conclusion of the coatings project on the experimental train, the density of all fractions of sludge in the experimental train remained low until wastewater temperatures were, once again, >20°C.

At the conclusion of this study in June of 2017 the densities of the experimental train's activated sludge and selector underflow were rapidly climbing along with the settling velocities of the same sludge. The final data points taken for the experimental train's activated sludge and selector underflow were 1.054 g/cm^3 and 1.071 g/cm^3. The observed densities of the activated sludge were consistent with the findings of Sears et al. (2006) which stated that CAS with poor settling characteristics possessed densities of 1.038 to 1.041 g/cm^3 and aggregates with settling rates of 5 – 30 m/hr possessed densities of 1.041 to 1.049 g/cm^3.

Increases in water density and viscosity were expected during the 15°C decrease in wastewater temperature during the seasonal variation from roughly 0.995 g/cm^3 to 1.00 g/cm^3; while the decrease in the density of sludge was not expected. The increase in filamentous bacteria and the decrease in sludge density do explain the loss in settling rates in all fractions of sludge from the UB WWTP. After a brief system shutdown in December, the operation of the external selector was resumed in late-December and operated with little success in achieving desirable settling velocities in any fraction of the sludge until the wastewater temperature reached levels in excess of 19°C. The decrease in sludge density and settling rates suggests that the fraction of large aggregates and granular material present in the activated sludge of the experimental train and the selector underflow would also have decreased, the ISC testing data suggests otherwise.

ISC data in Figure 15 shows that large aggregates and granular material were present in similar quantities during times of decreased settling as to the quantities present during times of desirable settling. The density data coupled with the ISC data suggest that there was an accumulation, or at least a sustainment, of granular material and large aggregates within the experimental train. As wastewater temperatures had risen, rapid improvements in settleability were observed suggesting that a shift towards granulation occurred.

4.4 Nutrient Evaluation

Nutrient plant profiles were conducted over the course of this study and combined with nutrient data collected by treatment staff in order to monitor the facility's effluent quality. It was found that there were no major differences in the ability of each train to reduce organic constituents. Figures 19 and 20 show, that on average, the effluent NH_4^+ - N exiting each train was approximately 0.20 mg/L Many of the spikes in effluent ammonia were attributed to difficulties with maintaining proper dissolved oxygen levels in the preceding aerobic basins.

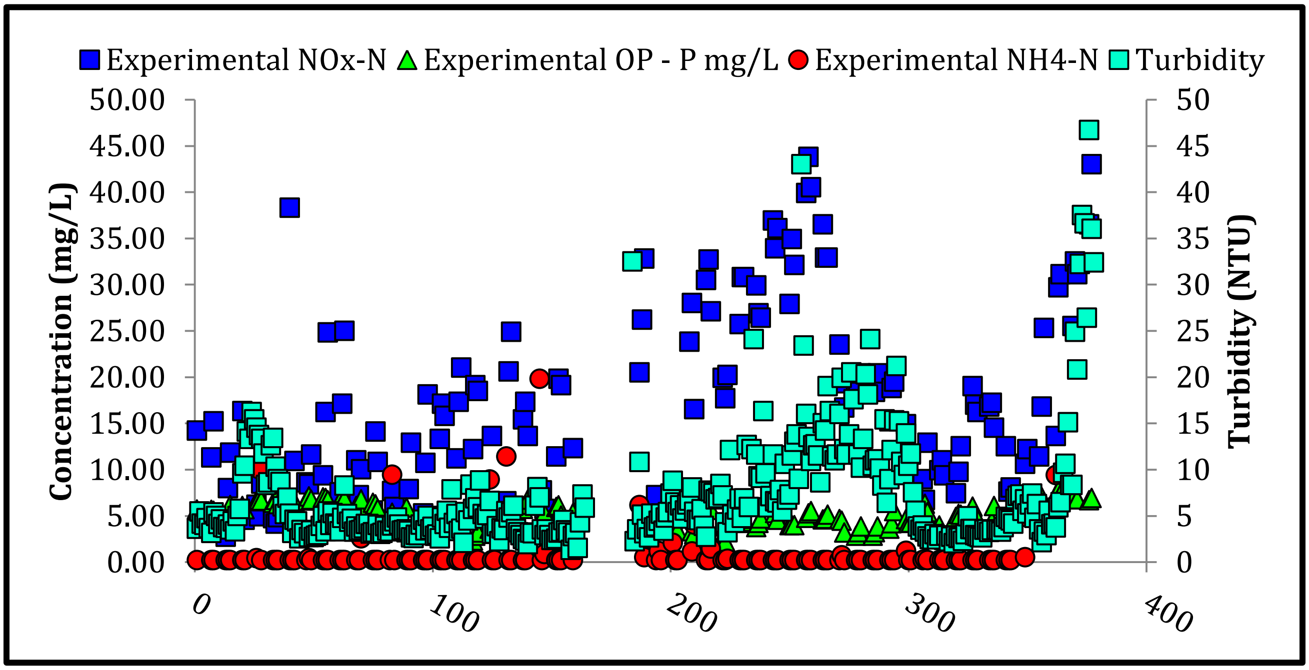

Figure 19. Process effluent data collected from the Experimental Train.

Effluent NOx–N concentrations were observed to fluctuate daily. It was found that the spike in NOx concentrations were due to the discharge from a nearby campground. The effects of the discharge were seen to be attenuated over the course of several days after the discharged occurred. Effluent NOx–N concentrations were also observed at significantly higher levels during the final weeks of the study than levels observed in the control train (Figure 20). The IMLR was secured in both trains in order to decrease a total approximate return of 500% (100% RAS and 400% IMLR) to just 100% RAS. This was found to have solved the issue in the experimental train but the reason behind the elevated NOx–N levels in the experimental train were never determined.

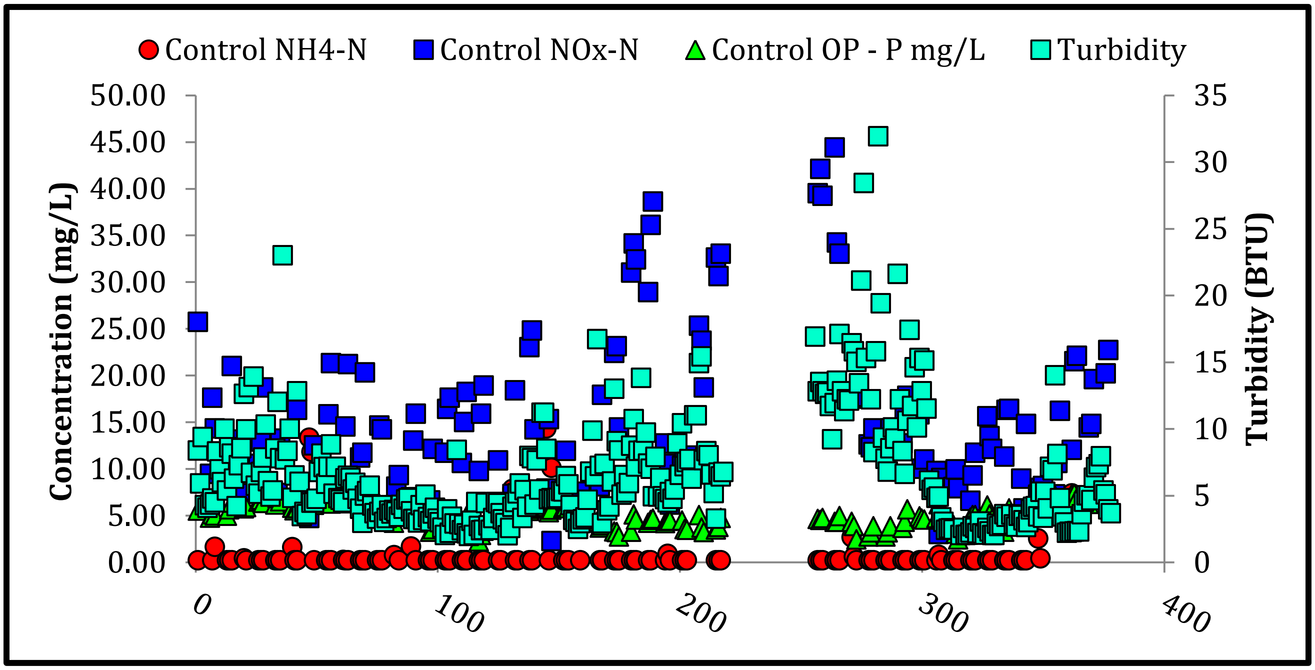

Figure 20. Process effluent data collected from the Control Train.

As the UB WWTP is not a phosphorus removing facility there is no phosphorus removal taking place throughout the biological processes in the facility. Raw wastewater to the UB WWTP contained approximately 5.13±1.73 mg/L and thus the process effluent from each train is approximately 4.87±1.19 mg/L and 4.84±1.21 mg/L for the experimental and control trains respectively. At the conclusion of this study a large amount of salt water entered the facility which prompted an upset in the facility's ability to effectively treat wastewater. Days after the conclusion of this study, the UB WWTP reseeded the experimental and control trains.

CHAPTER 5

CONCLUSION AND ENGINEERING SIGNIFICANCE

5.1 Conclusion

The goal of this study was to compare the effects, if any, that an external selector for more dense material would have on the settling properties of activated sludge to a MLE process that operated without an external selector and as to whether it was possible to cultivate aerobic granular sludge. Currently there are no full-scale pilot plants or full-scale operations that have successfully developed an AGS system through the use of external selectors. The only operations that have successfully demonstrated an AGS system are those that operate with SBRs.

After the operation of the external selector for a period 374 days, it was apparent that the external selector had, in fact, promoted a shift in the microbial population towards sludge that would be classified as granular material based on evaluations performed in this study. The increase in settling velocities of the experimental train's activated sludge corresponded to the classification of granular material and large aggregate being present in relatively large quantities, 23±4% and 22±8% respectively. The settling velocities of the activated sludge from the control train remained low. Average settling rates of the activated sludge in the control train corresponded to a composition of 84% fines, flocs, and small aggregate. Average ratios for each are 46±10%, 14±9% and 24±10%. In fact, the settling velocities were consistently 5-15x higher than the settling velocities of the activated sludge before the system disruption in the control train during periods of sustained wastewater temperatures above 19°C. The interruption of the external selection operation by the coatings project is hypothesized to have been detrimental to the objective of increasing the settling velocity of the activated sludge to rates that correspond to granular material. Figure 9 shows that a deviation in the underflow and overflow sludge mass was beginning to occur around 150 days of operation, 14 days before the train was taken offline. This deviation is not observed again until approximately day 350, which is, again, approximately 150 days from the re-start of the cyclone process. This deviation is believed to be much more prominent due to the accumulation of more dense particles during the period where wastewater temperatures were <20°C and effectively jumpstarted when water density and viscosity decreased and wastewater temperatures exceeded 20°C.

The wastewater temperature was highly susceptible to outside influence and was incapable of maintaining wastewater temperatures near 20°C, wastewater temperatures fluctuated between 13 and 29°C during this study. The settling velocities of the activated sludge and selector underflow were lower during periods when the wastewater temperature was between 13 and 20°C. The experimental train's activated sludge settling velocities dropped to levels comparable to that of the settling velocities measured in the control train and leads to the obvious requirement of further research and evaluations in order to optimize the performance of the external selector during periods with extremely low operating temperatures. It is hypothesized that the settling velocity suffered due to the decrease in wastewater temperatures which resulted in an increase in water density and viscosity. At the same time the density of the activated sludge of the experimental train decreased to similar densities of the control train, 1.023±0.001 and 1.025±0.007 g/cm^3. A change to a wider nozzle during the colder temperatures could potentially combat the negative effects of the drop in wastewater temperatures during the winter months as the wider nozzle would allow for more material, and/or larger material, to exit the cyclone via the underflow.

While complete granulation could not be achieved, this research has shown that the influence of the external selector made a positive impact on the settling properties of the activated sludge at the UB WWTP.

5.2 Engineering Significance

This study has produced data that provides supporting evidence that external selection, through the use of hydrocyclones, will improve the settling of activated sludge in a suspended growth format. It was observed that the hydrocyclone will produce sludge with settling properties that correspond to being primarily composed of granular material. The wasting of less dense particles and retention of more dense particles will effectively increase the overall density of the activated sludge in a suspended growth format. Effluent data from this study suggests that the retention and physical selection of more dense material did not negatively impact the overall performance of the UB WWTP.

While the hydrocyclone was operational for approximately one year an extended interruption in the operation may have prevented determination as to whether a shift towards granulation was feasible within a year’s time. Before the interruption, the experimental train was operational for 164 days. Following the interruption, the experimental train was operational for 187 days. Since the mixed liquor from the experimental train needed to be mixed with the mixed liquor from the control train, the study was effectively restarted. The mass and hydraulic and ISC data collected suggests that a shift was beginning to occur and that a possible start-up period for the shift towards granulation using a hydrocyclone could be around 150-175 days. This could not be definitively determined before the conclusion of this study. It is also unclear that as to whether this operation would be sustainable with proper nozzles to combat temperature fluctuations due to seasonal variation.

This study has shown that if a hydrocyclone was scaled to a particular WWTP then the settleability of the activated sludge would be improved upon given that the facility operated in a suspended growth format. Start-up times would vary based on the operational SRT of the given facility. Theoretically, if a facility operates with a longer SRT then the start-up period, the time the cyclone requires to impart a shift towards granulation, will be shorter than 150-175 days. If future studies in cultivating well-established AGS are successful then an intensification of a treatment process that is similar to the UB WWTP could be possible. As a well-established granule will be capable of SND as well as biological phosphorus removal requiring a facility, similar to Urbanna, to establish a dedicated anaerobic zone and shorten the aerobic zone. The granule could decrease the aeration requirement as well as provide a greater level of treatment without the need for expansion.

The location of this study, the UB WWTP, provided a unique set of pros and cons. This facility was a great location for a comparative study at a full scale location as the WWTP plant operates with two identical trains. So, a direct comparison could be made to fully illustrate the changes imparted by the hydrocyclone. While the configuration of the facility allowed for an easy comparison the construction proved to be challenging yet insightful. Since the facility is an above ground package plant the effect of the ambient air temperature played a major role by adjusting the wastewater temperature and thus decreasing the settling velocity. Due to the temperature change it was theorized that a different nozzle could be beneficial and could potentially produce an underflow that would not experience the negative effects on settling that were attributed to changes in temperature. Also, due to the construction of the facility, the system needed to be taken offline and the study effectively re-started in order to perform preventative maintenance.

5.3 Future Research Needs

As the UB WWTP is a small capacity above ground package plant, further evaluation and optimization is required to demonstrate a successful year round operation. Due to the timing of a system shutdown during this research optimization of nozzle selection and operating pressure for periods where the wastewater temperature is <20°C was not able to be accomplished. Unfortunately the relationship between cyclone performance and wastewater temperature was not observed until after the seasonal temperature change had occurred. Throughout this study only nozzle C (9.34 mm) was determined to be effective in the production of underflow with increased settling rates. It is hypothesized that more nozzles with smaller apex diameters may lead to further optimization of the selector to produce sludge with more elevated settling rates during periods when the wastewater temperature is >19°C.

Since the ISC test is based on TSS measurements, which can vary from the same sample, sieve analysis is recommended to be coupled with ISC testing to further evaluate the existence of granular material and the growth in floc size. Sieve analysis would be an improved method for the quantification of the differing classes of sludge that exists within activated sludge.

Since the UB WWTP is only staffed part time it would be recommended to upgrade this facility to an automated DO control and optimize the airflow delivery system. As temperature fluctuations have proved to be a significant issue in maintaining proper DO levels within the process. Further evaluations will need to be conducted when fine bubble diffusers are implemented in the fall of 2017. Additional mechanical mixers will also be implemented in the swing zone to allow for an anaerobic zone to be established preceding the anoxic zone, providing an A^2O process configuration with the ability to convert to an A/O process should SND be accomplished or the development of dPAOs occur.

It has been well documented that the presence of PAOs can be a cause for concern since they compete for organic carbon with denitrifying organisms. PAOs store organic carbon which would leave an anoxic zone carbon limited and subsequently hinder denitrification. Since the UB WWTP already has low influent carbon (~120 mg BOD/L) this would be a major issue for nitrogen removal. However, PAOs also have the ability to utilize nitrite/nitrate as electron acceptors under anoxic conditions in order to accomplish phosphorus removal, these organisms are dPAOs. Since they grow under anaerobic and anoxic conditions, the PAOs/dPAOs will be formed in the inner layers of an aerobic granule where oxygen does not penetrate.

The establishment of a formal anaerobic selector would require that the IMLR line have a valve added so the flow could be changed from where the anaerobic selector would be to where the anoxic zone would be. Since the hydrocyclone is a physical selection process, not a biological selection process, the feed sludge can be activated sludge from the anoxic zone rather than the aerobic as was the configuration in this study.

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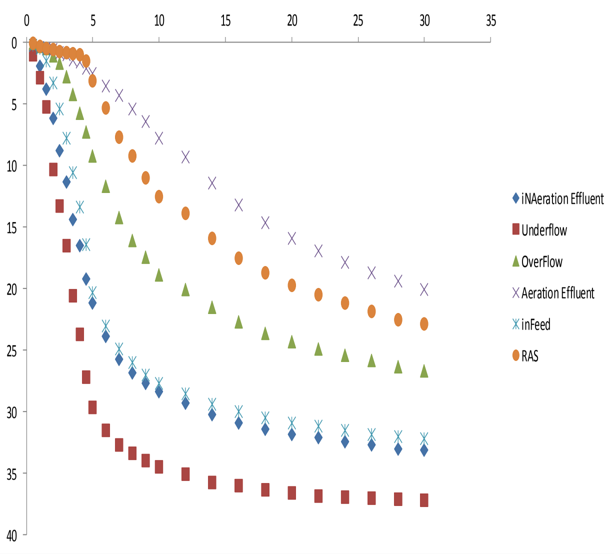
APPENDIX A

SINGLE TEST RAW SVI DATA

A.A. 1. Raw SVI data 6/23/2017

							SSV						SVI					
Min	iNAeration Effluent	Underflow	OverFlow	Aeration Effluent	inFeed	RAS	iNAeration Effluent	Underflow	OverFlow	iNFeed	Aeration Effluent	RAS	iNAeration Effluent	Underflow	OverFlow	iNFeed	Aeration Effluent	RAS
0.5	0.9	1	0.1	0.2	0.2	0.1	977.4	974.9	997.5	995.0	995.0	997.5	244.3	243.7	249.4	248.7	248.7	249.4
1	1.9	2.9	0.3	0.4	0.5	0.3	952.3	927.2	992.5	987.4	990.0	992.5	238.1	231.8	248.1	246.9	247.5	248.1
1.5	3.8	5.2	0.5	0.5	1.5	0.5	904.5	869.4	987.4	962.3	987.4	987.4	226.1	217.3	246.9	240.6	246.9	246.9
2	6.2	10.3	1.1	0.6	3.3	0.6	844.3	741.3	972.4	917.1	984.9	984.9	211.1	185.3	243.1	229.3	246.2	246.2
2.5	8.8	13.3	1.7	0.8	5.4	0.7	778.9	665.9	957.3	864.4	979.9	982.4	194.7	166.5	239.3	216.1	245.0	245.6
3	11.3	16.5	2.8	1	7.8	0.8	716.1	585.5	929.7	804.1	974.9	979.9	179.0	146.4	232.4	201.0	243.7	245.0
3.5	14.4	20.6	4.2	1.4	10.6	0.9	638.3	482.5	894.5	733.7	964.8	977.4	159.6	120.6	223.6	183.4	241.2	244.3
4	16.5	23.7	5.7	1.6	13.4	1	585.5	404.7	856.8	663.4	959.8	974.9	146.4	101.2	214.2	165.8	240.0	243.7
4.5	19.2	27.2	7.3	2.1	16.4	1.5	585.5	316.7	816.6	588.0	947.2	962.3	146.4	79.2	204.2	147.0	236.8	240.6
5	21.2	29.6	9.2	2.5	20.3	3.1	517.7	256.4	768.9	490.1	937.2	922.1	129.4	64.1	192.2	122.5	234.3	230.5
6	23.9	31.5	11.7	3.5	23	5.3	467.5	208.7	706.1	422.2	912.1	866.9	116.9	52.2	176.5	105.6	228.0	216.7
7	25.7	32.7	14.2	4.3	24.9	7.7	399.6	178.6	643.3	374.5	892.0	806.6	99.9	44.6	160.8	93.6	223.0	201.6
8	26.8	33.4	16.1	5.4	26	9.2	354.4	161.0	595.6	346.9	864.4	768.9	88.6	40.2	148.9	86.7	216.1	192.2
9	27.7	34	17.4	6.4	27	11	326.8	145.9	562.9	321.8	839.2	723.7	81.7	36.5	140.7	80.4	209.8	180.9
10	28.4	34.5	18.9	7.8	27.7	12.5	304.2	133.4	525.2	304.2	804.1	686.0	76.0	33.3	131.3	76.0	201.0	171.5
12	29.3	35.1	20.1	9.3	28.5	13.9	286.6	118.3	495.1	284.1	766.4	650.8	71.6	29.6	123.8	71.0	191.6	162.7
14	30.2	35.7	21.5	11.4	29.4	15.9	241.4	103.2	459.9	261.5	713.6	600.6	60.3	25.8	115.0	65.4	178.4	150.1
16	30.9	36	22.7	13.2	30	17.5	223.8	95.7	429.8	246.4	668.4	560.4	55.9	23.9	107.4	61.6	167.1	140.1
18	31.4	36.3	23.6	14.6	30.5	18.7	211.2	88.1	407.2	233.8	633.2	530.3	52.8	22.0	101.8	58.5	158.3	132.6
20	31.8	36.6	24.3	15.9	30.9	19.7	201.2	80.6	389.6	223.8	600.6	505.1	50.3	20.2	97.4	55.9	150.1	126.3
22	32.1	36.8	24.9	16.9	31.2	20.5	193.6	75.6	374.5	216.3	575.5	485.0	48.4	18.9	93.6	54.1	143.9	121.3
24	32.4	36.9	25.4	17.9	31.5	21.2	186.1	73.1	362.0	208.7	550.4	467.5	46.5	18.3	90.5	52.2	137.6	116.9
26	32.7	37	25.8	18.7	31.8	21.8	178.6	70.6	351.9	201.2	530.3	452.4	44.6	17.6	88.0	50.3	132.6	113.1
28	33	37.1	26.3	19.4	32	22.5	171.0	68.0	339.3	196.2	512.7	434.8	42.8	17.0	84.8	49.0	128.2	108.7
30	33.1	37.2	26.7	20.1	32.2	22.9	168.5	65.5	329.3	191.1	495.1	424.8	42.1	16.4	82.3	47.8	123.8	106.2

Sample Point	TSS mg/L	Sample (L)	Water (L)	Diluted TSS mg/L	ISV cm/min	ISV m/hr
iNAeration Effluent	3875	2.06	-0.06	4000	5.02	3.01
Underflow	6800	1.18	0.82	4000	7.15	4.29
OverFlow	3075	2.60	-0.60	4000	3.32	1.99
Aeration Effluent	3650	2.19	-0.19	4000	0.95	0.57
inFeed	3905	2.05	-0.05	4000	5.89	3.53
RAS	5275	1.52	0.48	4000	2.43	1.46



APPENDIX B

SETTLING VELOCITY DATA

A.B. 1. Settling velocity data

Date	Experimental Aeration Effluent	Feed	Selector OverFlow	Selector Underflow	Control RAS	Control Aeration Effluent	Wastewater Temperature
6/27/2016	1.61	1.47	1.32	2.52	1.02	1.23	25
7/6/2016	1.84	1.66	1.02	2.85	1.39	1.57	25
7/12/2016	2.48	2.38	1.84	3.55	2.19	1.50	26
7/20/2016	2.31	2.22	0.36	2.87	0.63	0.70	26
7/21/2016	1.87	2.00	0.30	3.04	0.68	0.69	26
7/26/2016	2.42	2.45	0.65	2.62	0.11	0.94	26
7/28/2016	2.03	2.10	0.48	3.36	0.82	0.81	27
8/2/2016	1.84	2.11	0.47	3.06	0.49	0.92	26
8/4/2016	1.28	1.71	0.24	3.65	0.27	0.24	27
8/9/2016	2.17	1.97	0.18	3.32	0.22	0.22	27
8/11/2016	2.40	2.34	0.46	3.79	0.18	0.11	27
8/16/2016	2.28	2.20	0.65	4.21	0.19	0.20	27
8/18/2016	2.11	0.60	0.44	3.65	0.29	0.29	26
8/25/2016	1.72	2.11	0.29	2.81	0.20	0.15	25
8/29/2016	1.81	3.65	0.71	3.19	0.26	0.33	26
8/31/2016	1.92	1.86	0.40	3.11	0.17	0.16	23
9/7/2016	1.69	1.66	1.55	3.1	0.26	0.25	24
9/8/2016	1.77	1.62	1.35	2.75	0.2	0.22	24
9/12/2016	1.65	1.66	0.29	2.89	0.13	0.13	23
9/19/2016	2.03	1.99	1.69	3.6	0.22	0.23	24
9/21/2016	2.33	0.63	2.17	3.39	0.15	0.16	24
9/27/2016	1.97	2.49	0.29	2.95	0.23	0.15	25
9/29/2016	2.32	2.33	0.26	3.93	0.16	0.17	25
10/4/2016	2.34	2.45	0.27	3.67	0.25	0.23	24
10/6/2016	2.73	2.57	0.23	3.85	0.27	0.39	24
10/12/2016	1.93	0.94	0.61	3.91	0.13	0.13	22
10/13/2016	0.48				0.13	0.11	22
10/14/2016	0.32	2.22	0.18	3.36	0.14	0.22	22
10/17/2016	2.26	2.35	0.14	3.28	0.19	0.25	22
10/19/2016	0.39	0.12	0.18	3.2	0.89	0.12	22
10/20/2016	0.93	0.1	0.14	3.15	1.45	0.15	21
10/21/2016	0.25	0.11	0.06	2.84	1.06	0.11	23
10/24/2016	0.27	1.11	0.13	2.74	0.25	0.13	19
10/26/2016	0.18	0.24	0.13	2.85	0.09	0.18	21
11/1/2016	0.21	0.27	0.09	3.07	0.14	0.14	19
11/3/2016	0.66	0.5	0.31	3.24	0.19	0.31	21

11/8/2016	0.11	0.14	0.14	2.93	0.14	0.11	18
11/10/2016	0.18	0.8	0.11	2.63	0.13	0.11	17
11/15/2016	1.54	0.24	0.09	2.8	0.11	0.19	18
11/17/2016	0.16	0.16	0.08	2.61	0.07	0.07	18
11/22/2016	0.14	0.16	0.06	2.68	0.04	0.05	17
12/1/2016							
12/28/2016	0.06	0.08	0.05	0.05	0.15	0.1	17
1/4/2017	0.06	0.06	0.03	0.22	0.09	1.17	18
1/5/2017	0.07	0.07	0.05	0.16	0.08	0.07	17
1/10/2017	0.06	0.05	0.04	0.32	0.07	0.08	14
1/16/2017	0.11	0.65	0.05	1.18	0.51	0.16	16
1/18/2017	0.14	0.09	0.07	1.32			15
1/24/2017	0.14	0.18	0.06	1.74			12
1/31/2017	0.04	0.08	0.06	1.94			15
2/20/2017	0.1	0.09	0.06	2.15			16
2/24/2017	0.07	0.15	0.02	1.61			18
2/27/2017	0.09	0.09	0.06	1.67		0.1	14
3/1/2017	0.12	0.11	0.05	1.83	0.11	0.12	17
3/7/2017	0.06	0.06	0.05	1.57	0.07	0.08	19
3/9/2017	0.06	0.07	0.04	1.55	0.09	0.06	19
3/15/2017	0.05	0.06	0.03	1.34	0.03	0.06	15
3/17/2017	0.05	0.04	0.04	1.56	0.09	0.06	15
3/25/2017	0.06	0.05	0.02	1.32	0.04	0.03	17
3/28/2017	0.08	0.08	0.05	1.69	0.05	0.06	17
4/5/2017	1.02	0.99	0.06	2.33	1	0.27	20
4/6/2017	1.34	0.9	0.11	1.68	0.15	0.86	19
4/12/2017	0.18	0.14	0.07	1.82	0.98	0.77	20
4/13/2017	0.05	0.09	0.05	1.7	0.2	0.14	18
4/18/2017	0.06	0.08	0.05	2.2	0.07	0.05	20
4/27/2017	0.1	0.11	0.05	2.41	0.12	0.05	21
5/3/2017	0.08	0.12	0.08	2.76	0.06	0.06	21
5/4/2017	0.13	0.1	0.05	2.37	0.06	0.05	21
5/9/2017	0.1	0.11	0.06	2.63	0.06	0.05	21
5/12/2017	0.11	0.15	0.06	2.64	0.08	0.07	20
5/15/2017	0.18	0.15	0.24	2.85	0.09	0.08	19
5/16/2017	1.76	1.76	0.06	2.59	0.08	0.08	19
5/23/2017	2.03	2.04	0.22	2.62	0.06	0.06	23
5/24/2017	1.83	1.82	0.14	2.83	0.1	0.11	23
5/29/2017	2.07	2.25	0.08	3.54	0.06	0.14	22
5/30/2017	0.23	0.68	0.35	3.32	0.13	0.14	22
6/7/2017	0.19	0.61	0.12	3.76	0.3	0.11	24
6/8/2017	0.31	0.3	0.11	3.46	0.28	0.14	23
6/12/2017	1.82	1.22	0.12	3.36	0.28	0.17	24

6/22/2017	2.51	3.01	0.67	4.33	1.4	1.22	25
6/23/2017	3.01	3.53	1.99	4.29	1.46	0.57	24
6/26/2017	3.24	3.83	2.25	4.94	2	1.41	25

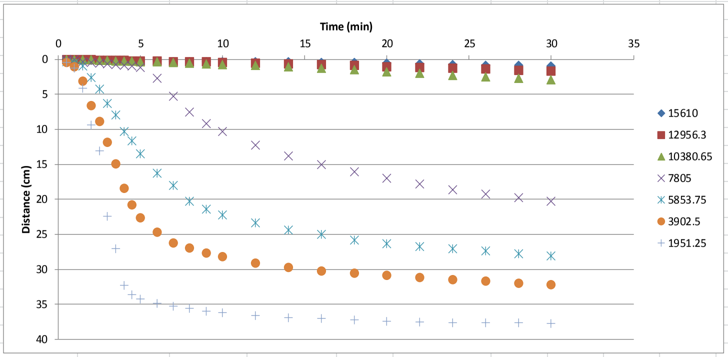
APPENDIX C

SINGLE SFA TEST RAW DATA

A.C. 1. Selector underflow SFA raw data

Underflow

	2	1.66	1.33	ML	0.75	0.5	0.25
TSS	15610	12956.3	10380.65	7805	5853.75	3902.5	1951.25
Time (min)	0	0	0	0	0	0	0
0.5	0	0	0	0	0.3	0.5	0.5
1	0.1	0	0	0	0.6	1.1	1.3
1.5	0.1	0	0	0.4	1	3.1	4.2
2	0.1	0	0	0.5	2.6	6.6	9.4
2.5	0.1	0.1	0.1	0.6	4.3	8.9	13.1
3	0.1	0.1	0.1	0.7	6.3	11.9	22.4
3.5	0.1	0.1	0.2	0.8	8	14.9	27.1
4	0.1	0.1	0.2	0.9	10.3	18.4	32.3
4.5	0.2	0.2	0.2	1	11.7	20.8	33.6
5	0.2	0.2	0.3	1.2	13.5	22.6	34.2
6	0.2	0.2	0.4	2.7	16.3	24.7	34.9
7	0.3	0.3	0.5	5.3	18	26.2	35.3
8	0.3	0.4	0.6	7.5	20.3	27	35.6
9	0.3	0.4	0.7	9.2	21.4	27.7	36
10	0.3	0.5	0.8	10.3	22.2	28.2	36.2
12	0.4	0.6	0.9	12.3	23.4	29.1	36.6
14	0.4	0.7	1.1	13.8	24.4	29.7	36.9
16	0.5	0.8	1.3	15	25	30.2	37
18	0.5	0.9	1.5	16.1	25.8	30.6	37.2
20	0.6	1.1	1.8	17	26.3	30.9	37.4
22	0.7	1.2	2	17.8	26.7	31.2	37.5
24	0.8	1.3	2.3	18.6	27.1	31.5	37.6
26	0.9	1.4	2.5	19.2	27.4	31.7	37.6
28	0.9	1.6	2.7	19.8	27.8	32	37.6
30	1	1.7	2.9	20.3	28.1	32.2	37.7



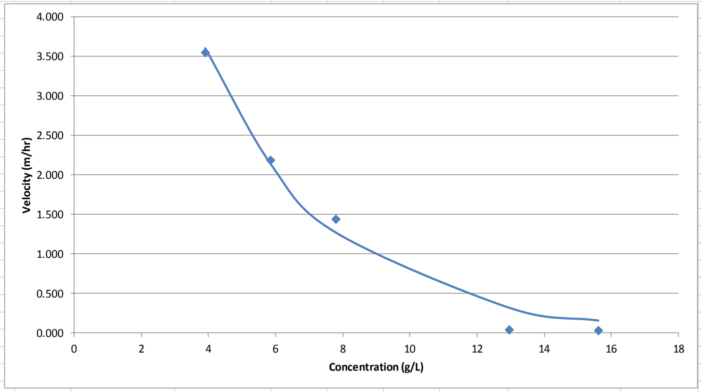
Sample Point	TSS mg/L	Sample (L)	Water (L)	Diluted TS	ISV cm/min	ISV m/hr
2	15610	0.26	1.74	2000	0.05	0.03
1.66	12956.3	0.31	1.69	2000	0.06	0.04
1.33	10380.65	0.39	1.61	2000	0.12	0.07
ML	7805	0.51	1.49	2000	2.40	1.44
0.75	5853.75	0.68	1.32	2000	3.64	2.18
0.5	3902.5	1.02	0.98	2000	5.91	3.54
0.25	1951.25	2.05	-0.05	2000	5.97	3.58

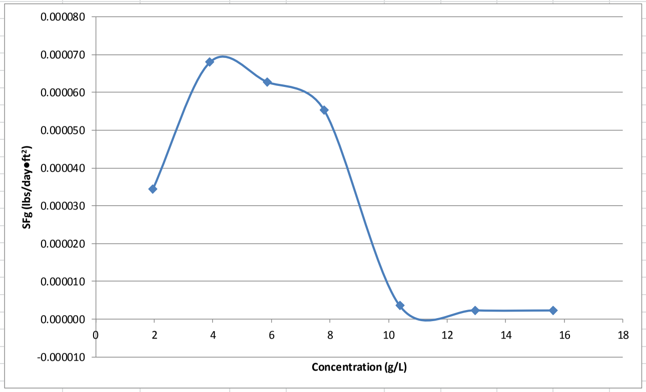
ML TSS

Vesilind Empirical Coefficients

V0	10.24
K	0.27

	Conc.	Conc.	Velocity (V)	Velocity (V)		k	Vo	Vo	V (Vesilind)	error^2	SF$_g$
	g/m^3	g/L	cm/min	m/hr		L/g	m/hr	m/d	m/hr		lbs/day/ft^2
1	15610	15.61	0.05	0.03		0.268	10.242	245.807844	0.157	0.016	0.000002
2	12956.3	12.9563	0.06	0.04					0.319	0.080	0.000002
3	10380.65	10.38065	0.12	0.07					0.635	0.320	0.000004
4	7805	7.805	2.40	1.44					1.267	0.030	0.000055
5	5853.75	5.85375	3.64	2.18					2.136	0.002	0.000063
6	3902.5	3.9025	5.91	3.54					3.602	0.003	0.000068
7	1951.25	1.95125	5.97	3.58					6.074	6.221	0.000034
										0.131	

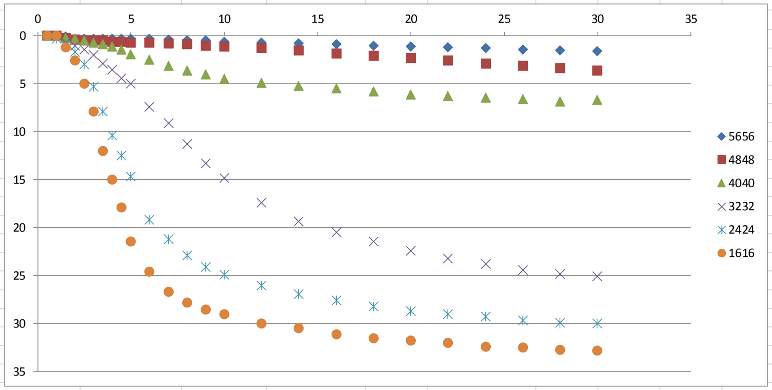




A.C. 2. Selector overflow SFA raw data

Overflow

	1.4	1.2	ML	0.8	0.6	0.4
TSS	5656	4848	4040	3232	2424	1616
Time (min)	0	0	0	0	0	0
0.5	0	0	0	0	0	0
1	0	0	0	0	0.3	0
1.5	0.1	0.2	0.2	0.7	0.9	1.2
2	0.3	0.4	0.3	1	1.7	2.6
2.5	0.3	0.5	0.5	1.4	3	5
3	0.3	0.5	0.7	2	5.3	7.9
3.5	0.3	0.5	0.9	2.9	7.9	12
4	0.3	0.6	1.1	3.5	10.4	15
4.5	0.3	0.6	1.4	4.4	12.5	17.9
5	0.3	0.7	1.9	5	14.7	21.4
6	0.3	0.7	2.5	7.4	19.2	24.6
7	0.4	0.8	3.1	9.1	21.2	26.7
8	0.5	0.9	3.6	11.3	22.9	27.8
9	0.5	1	4	13.3	24.1	28.5
10	0.6	1.1	4.5	14.8	24.9	29
12	0.7	1.3	4.9	17.4	26	30
14	0.8	1.5	5.2	19.3	26.9	30.5
16	0.9	1.8	5.5	20.5	27.6	31.1
18	1	2.1	5.8	21.4	28.2	31.5
20	1.1	2.3	6.1	22.4	28.7	31.8
22	1.2	2.6	6.3	23.2	29	32
24	1.3	2.9	6.4	23.8	29.3	32.4
26	1.4	3.1	6.6	24.4	29.7	32.5
28	1.5	3.4	6.8	24.8	29.9	32.7
30	1.6	3.6	6.7	25.1	30	32.8

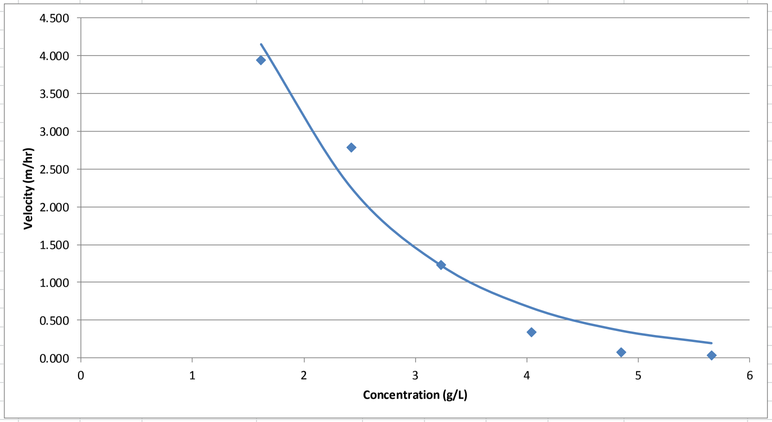


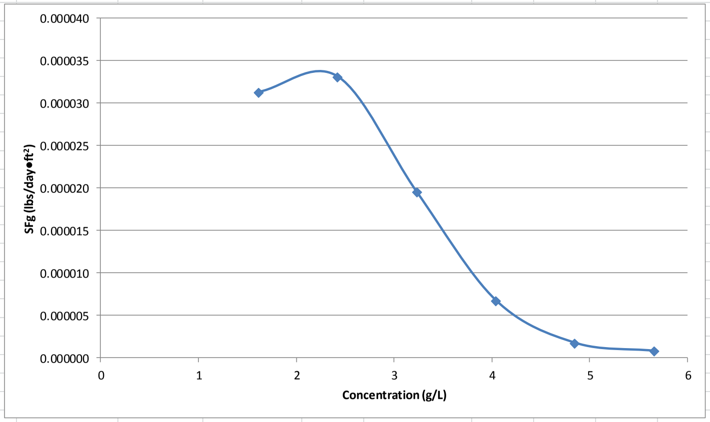
Sample Point	TSS mg/L	Sample (L)	Water (L)	Diluted TSS mg/L	ISV cm/m	ISV m/hr
1.4	5656	1.41	0.59	4000	0.05	0.03
1.2	4848	1.65	0.35	4000	0.13	0.08
ML	4040	1.98	0.02	4000	0.57	0.34
0.8	3232	2.48	-0.48	4000	2.05	1.23
0.6	2424	3.30	-1.30	4000	4.63	2.78
0.4	1616	4.95	-2.95	4000	6.57	3.94

Vesilind Empirical Coefficients

VO	14.08
K	0.76

	Conc.	Conc.	Velocity (V)	Velocity (V)	k	Vo	Vo	V (Vesilind)	error^2	SF$_g$
	g/m^3	g/L	cm/min	m/hr	L/g	m/hr	m/d	m/hr		lbs/day/ft^2
1	5656	5.656	0.05	0.03	0.756	14.084	338.007087	0.195	0.027	0.000001
2	4848	4.848	0.13	0.08				0.360	0.081	0.000002
3	4040	4.04	0.57	0.34				0.663	0.103	0.000007
4	3232	3.232	2.05	1.23				1.222	0.000	0.000020
5	2424	2.424	4.63	2.78				2.252	0.280	0.000033
6	1616	1.616	6.57	3.94				4.149	0.042	0.000031
									0.534	

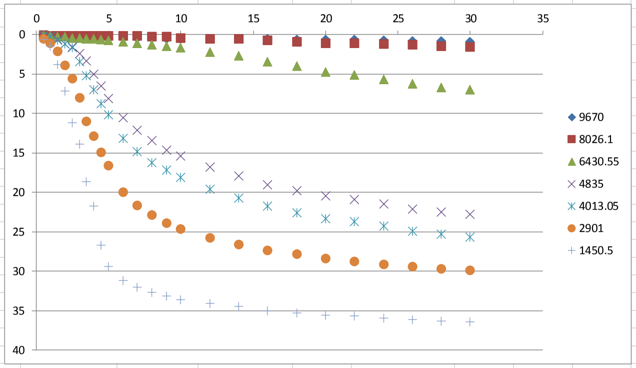




A.C. 3. Experimental Train SFA raw data

Indense Aeration Effluent

	2	1.66	1.33	ML	0.83	0.6	0.3
TSS	9670	8026.1	6430.55	4835	4013.05	2901	1450.5
Time (min)	0	0	0	0	0	0	0
0.5	0.1	0.1	0.1	0.1	0.1	0.5	0.6
1	0.2	0.2	0.2	0.3	0.3	1.1	1.5
1.5	0.3	0.2	0.3	0.6	0.7	2.1	3.8
2	0.3	0.2	0.3	1.2	1.2	3.9	7.2
2.5	0.3	0.2	0.4	1.6	1.7	5.6	11.2
3	0.3	0.2	0.4	2.4	3.4	8	13.9
3.5	0.4	0.2	0.5	3.3	5.2	11	18.7
4	0.4	0.2	0.5	5	7	12.9	21.7
4.5	0.4	0.2	0.6	6.5	8.8	14.9	26.7
5	0.4	0.2	0.7	8.1	10.2	16.6	29.4
6	0.4	0.2	0.9	10.5	13.1	20	31.2
7	0.4	0.2	1.1	12.1	14.8	21.6	32
8	0.4	0.3	1.3	13.4	16.2	22.9	32.7
9	0.5	0.3	1.5	14.6	17.2	23.9	33.1
10	0.5	0.4	1.7	15.4	18.1	24.6	33.6
12	0.5	0.5	2.2	16.8	19.6	25.8	34.1
14	0.5	0.5	2.7	17.9	20.7	26.6	34.4
16	0.5	0.7	3.4	19	21.7	27.3	35
18	0.6	0.9	4	19.8	22.6	27.8	35.3
20	0.6	1.1	4.7	20.4	23.3	28.4	35.6
22	0.6	1.1	5.1	20.9	23.7	28.7	35.7
24	0.7	1.2	5.7	21.5	24.3	29.1	35.9
26	0.8	1.3	6.2	22.1	24.9	29.4	36.1
28	0.8	1.5	6.7	22.5	25.3	29.7	36.3
30	0.9	1.6	7	22.8	25.7	29.9	36.4



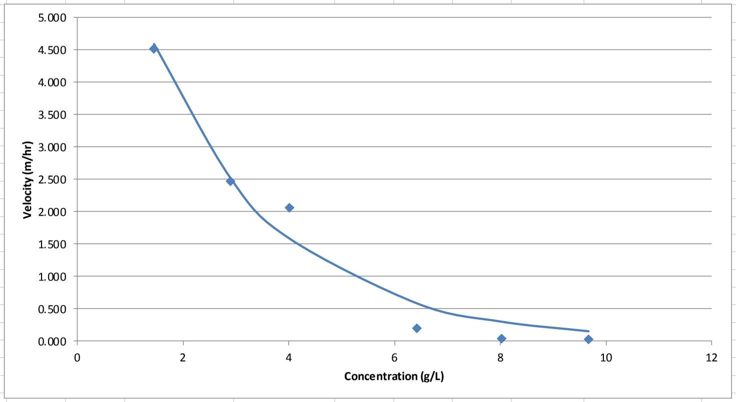
Sample Point	TSS mg/L	Sample (L)	Water (L)	Diluted TS	ISV cm/m	ISV m/hr
2	9670	0.83	1.17	4000	0.04	0.02
1.66	8026.1	1.00	1.00	4000	0.07	0.04
1.33	6430.55	1.24	0.76	4000	0.33	0.20
ML	4835	1.65	0.35	4000	2.92	1.75
0.83	4013.05	1.99	0.01	4000	3.44	2.06
0.6	2901	2.76	-0.76	4000	4.11	2.46
0.3	1450.5	5.52	-3.52	4000	7.53	4.52

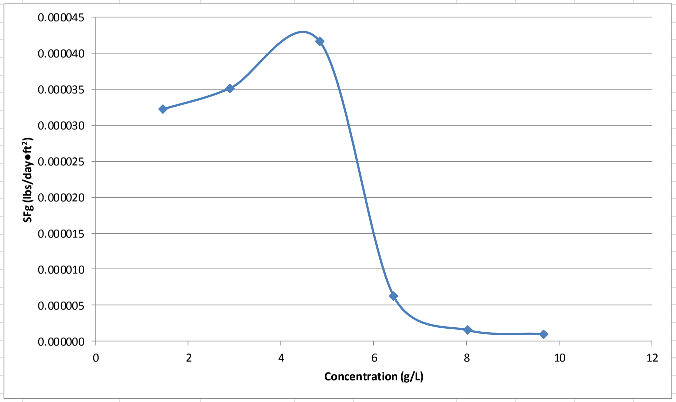
ML TSS

Vesilind Empirical Coefficients

V0	8.38
K	0.42

	Conc.	Conc.	Velocity (V)	Velocity (V)		k	Vo	Vo	V (Vesilind)	error^2	SF$_g$
	g/m^3	g/L	cm/min	m/hr		L/g	m/hr	m/d	m/hr		lbs/day/ft^2
1	9670	9.67	0.04	0.021		0.415	8.378	201.065	0.151	0.017	0.000001
2	8026.1	8.0261	0.07	0.039					0.299	0.068	0.000002
3	6430.55	6.43055	0.33	0.198					0.580	0.146	0.000006
4	4835	4.835	2.92	1.752					1.125	0.393	0.000042
5	4013.05	4.01305	3.44	2.064					1.583	0.231	0.000041
6	2901	2.901	4.11	2.464					2.512	0.002	0.000035
7	1450.5	1.4505	7.53	4.517					4.587	0.005	0.000032
										0.469	

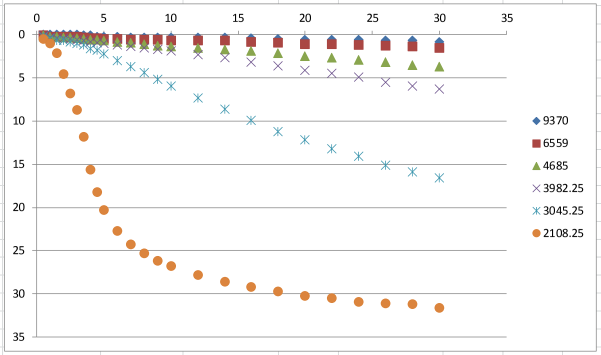




A.C. 4. Control train SFA raw data

Control Aeration Effluent

	2	1.4	ML	0.85	0.65	0.45
TSS	9370	6559	4685	3982.25	3045.25	2108.25
Time (min)	0	0	0	0	0	0
0.5	0	0.1	0.1	0.1	0.2	0.5
1	0	0.2	0.2	0.3	0.4	1
1.5	0	0.2	0.2	0.4	0.7	2.1
2	0	0.2	0.3	0.4	0.7	4.6
2.5	0	0.2	0.3	0.5	0.8	6.8
3	0	0.2	0.4	0.6	1	8.7
3.5	0.1	0.3	0.5	0.7	1.2	11.8
4	0.1	0.4	0.6	0.8	1.6	15.6
4.5	0.2	0.4	0.6	0.9	1.8	18.2
5	0.2	0.5	0.7	1	2.2	20.3
6	0.2	0.5	0.8	1.2	3	22.7
7	0.3	0.6	0.9	1.4	3.7	24.3
8	0.3	0.6	1.1	1.5	4.4	25.3
9	0.3	0.6	1.3	1.7	5.2	26.2
10	0.3	0.7	1.4	1.9	5.9	26.8
12	0.3	0.7	1.5	2.3	7.3	27.8
14	0.3	0.7	1.7	2.7	8.6	28.6
16	0.4	0.8	1.9	3.2	9.9	29.2
18	0.5	0.9	2.1	3.6	11.2	29.7
20	0.6	1.1	2.5	4.1	12.2	30.2
22	0.6	1.1	2.7	4.5	13.2	30.5
24	0.6	1.2	2.9	4.9	14.1	30.9
26	0.7	1.3	3.2	5.5	15.1	31.1
28	0.7	1.4	3.5	5.9	15.9	31.2
30	0.8	1.5	3.7	6.3	16.6	31.6



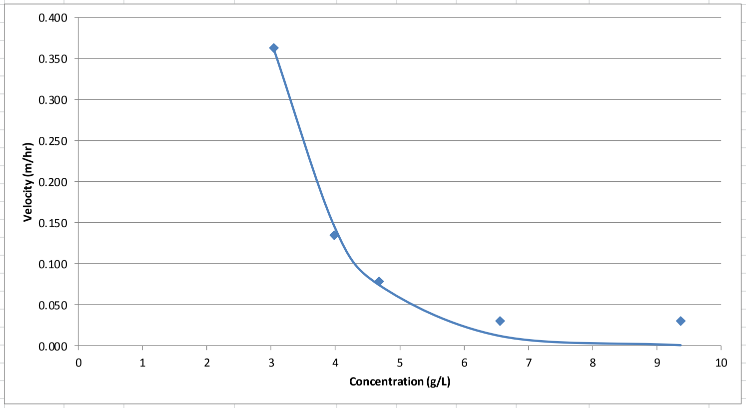
Sample Point	TSS mg/L	Sample (L)	Water (L)	Diluted TS	ISV cm/m	ISV m/hr
2	9370	0.85	1.15	4000	0.05	0.03
1.4	6559	1.22	0.78	4000	0.05	0.03
ML	4685	1.71	0.29	4000	0.13	0.08
0.85	3982.25	2.01	-0.01	4000	0.22	0.13
0.65	3045.25	2.63	-0.63	4000	0.60	0.36
0.45	2108.25	3.79	-1.79	4000	5.35	3.21

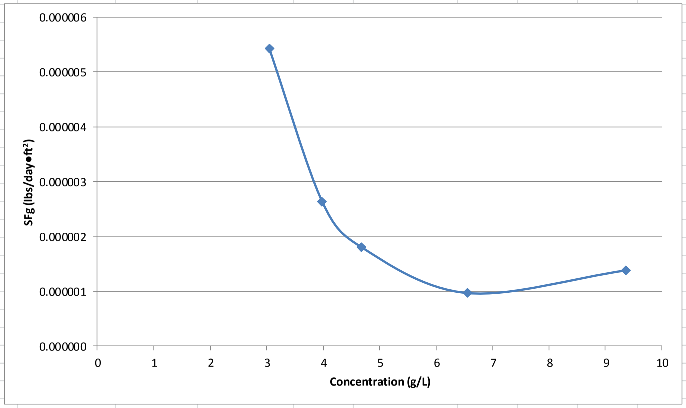
ML TSS

Vesilind Empirical Coefficients

V0	6.84
K	0.97

	Conc.	Conc.	Velocity (V)	Velocity (V)	k	Vo	Vo	V (Vesilind)	error^2	SF$_g$
	g/m^3	g/L	cm/min	m/hr	L/g	m/hr	m/d	m/hr		lbs/day/ft^2
1	9370	9.37	0.05	0.030	0.967	6.842	164.215	0.001	0.001	0.000001
2	6559	6.559	0.05	0.030				0.012	0.000	0.000001
3	4685	4.685	0.13	0.078				0.074	0.000	0.000002
4	3982.25	3.98225	0.22	0.135				0.146	0.000	0.000003
5	3045.25	3.04525	0.60	0.363				0.360	0.000	0.000005
6	2108.25	2.10825	5.35	3.213				0.891	5.390	0.000033
									0.001	

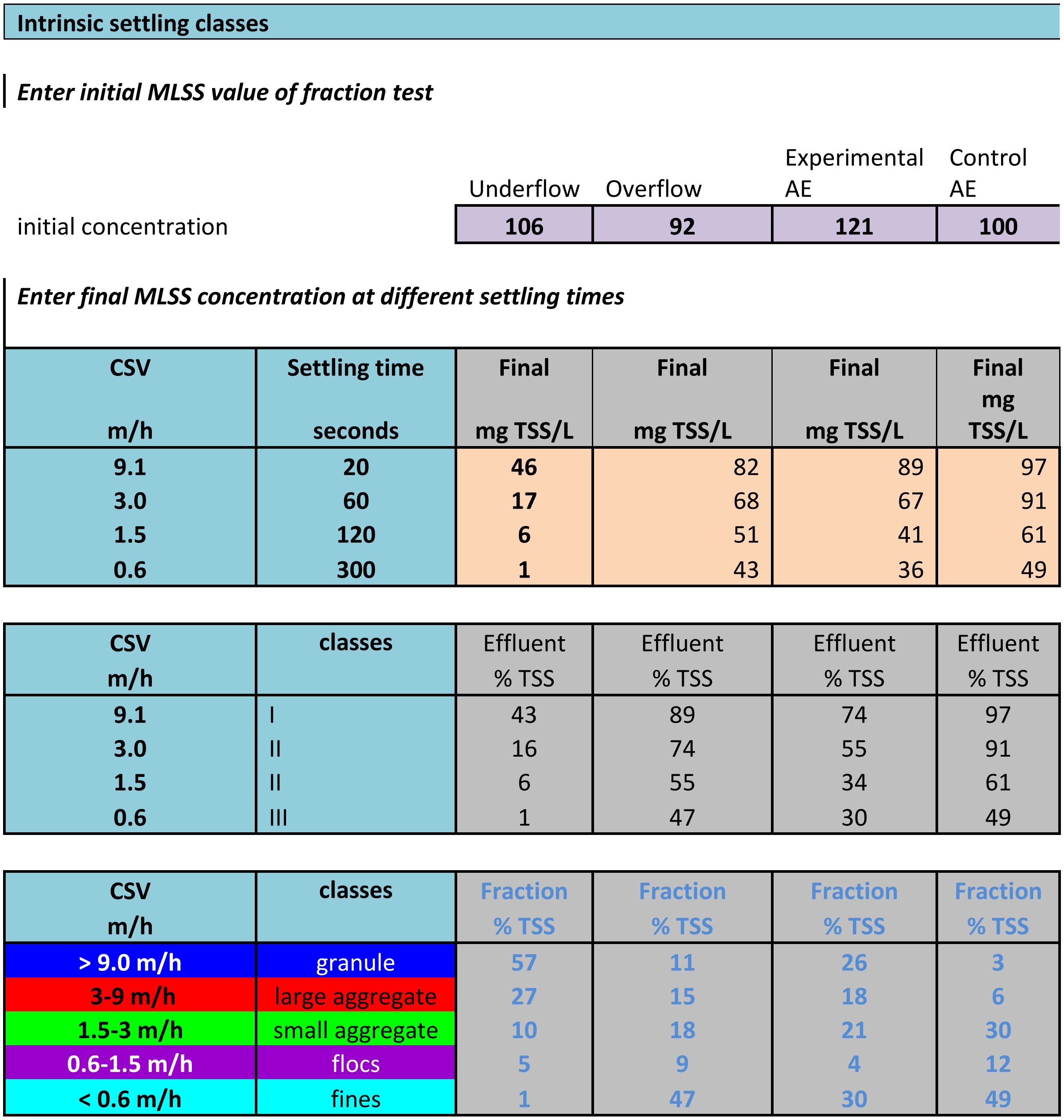




APPENDIX D

ISC ANALYSIS DATA

A.D. 1. ISC data 7/21/2016



Intrinsic settling classes

Enter initial MLSS value of fraction test

	Underflow	Overflow	Experimental AE	Control AE
initial concentration	**106**	**92**	**121**	**100**

Enter final MLSS concentration at different settling times

CSV **m/h**	**Settling time** **seconds**	**Final** **mg TSS/L**	**Final** **mg TSS/L**	**Final** **mg TSS/L**	**Final mg TSS/L**
9.1	**20**	**46**	82	89	97
3.0	**60**	**17**	68	67	91
1.5	**120**	**6**	51	41	61
0.6	**300**	**1**	43	36	49

CSV **m/h**	**classes**	Effluent % TSS	Effluent % TSS	Effluent % TSS	Effluent % TSS
9.1	I	43	89	74	97
3.0	II	16	74	55	91
1.5	II	6	55	34	61
0.6	III	1	47	30	49

CSV **m/h**	**classes**	**Fraction** **% TSS**	**Fraction** **% TSS**	**Fraction** **% TSS**	**Fraction** **% TSS**
> 9.0 m/h	granule	**57**	**11**	**26**	**3**
3-9 m/h	large aggregate	**27**	**15**	**18**	**6**
1.5-3 m/h	small aggregate	**10**	**18**	**21**	**30**
0.6-1.5 m/h	flocs	**5**	**9**	**4**	**12**
< 0.6 m/h	fines	**1**	**47**	**30**	**49**

A.D. 2. ISC data 8/18/2016

Intrinsic settling classes

Enter initial MLSS value of fraction test

	Underflow	Overflow	Experimental AE	Control AE
initial concentration	**92**	**87**	**104**	**98**

Enter final MLSS concentration at different settling times

CSV **m/h**	**Settling time** **seconds**	**Final** **mg TSS/L**	**Final** **mg TSS/L**	**Final** **mg TSS/L**	**Final** **mg TSS/L**
9.1	**20**	**42**	82	84	92
3.0	**60**	**13**	67	51	70
1.5	**120**	**6**	53	42	55
0.6	**300**	**2**	48	35	50

CSV **m/h**	**classes**	Effluent % TSS	Effluent % TSS	Effluent % TSS	Effluent % TSS
9.1	I	46	94	81	94
3.0	II	14	77	49	71
1.5	II	7	61	40	56
0.6	III	2	55	34	51

CSV **m/h**	**classes**	**Fraction** **% TSS**	**Fraction** **% TSS**	**Fraction** **% TSS**	**Fraction** **% TSS**
> 9.0 m/h	granule	**54**	**6**	**19**	**6**
3-9 m/h	large aggregate	**32**	**17**	**32**	**22**
1.5-3 m/h	small aggregate	**8**	**16**	**9**	**15**
0.6-1.5 m/h	flocs	**4**	**6**	**7**	**5**
< 0.6 m/h	fines	**2**	**55**	**34**	**51**

A.D. 3. ISC data 9/21/2016

Intrinsic settling classes

Enter initial MLSS value of fraction test

	Underflow	Overflow	Experimental AE	Control AE
initial concentration	**87**	**94**	**120**	**94**

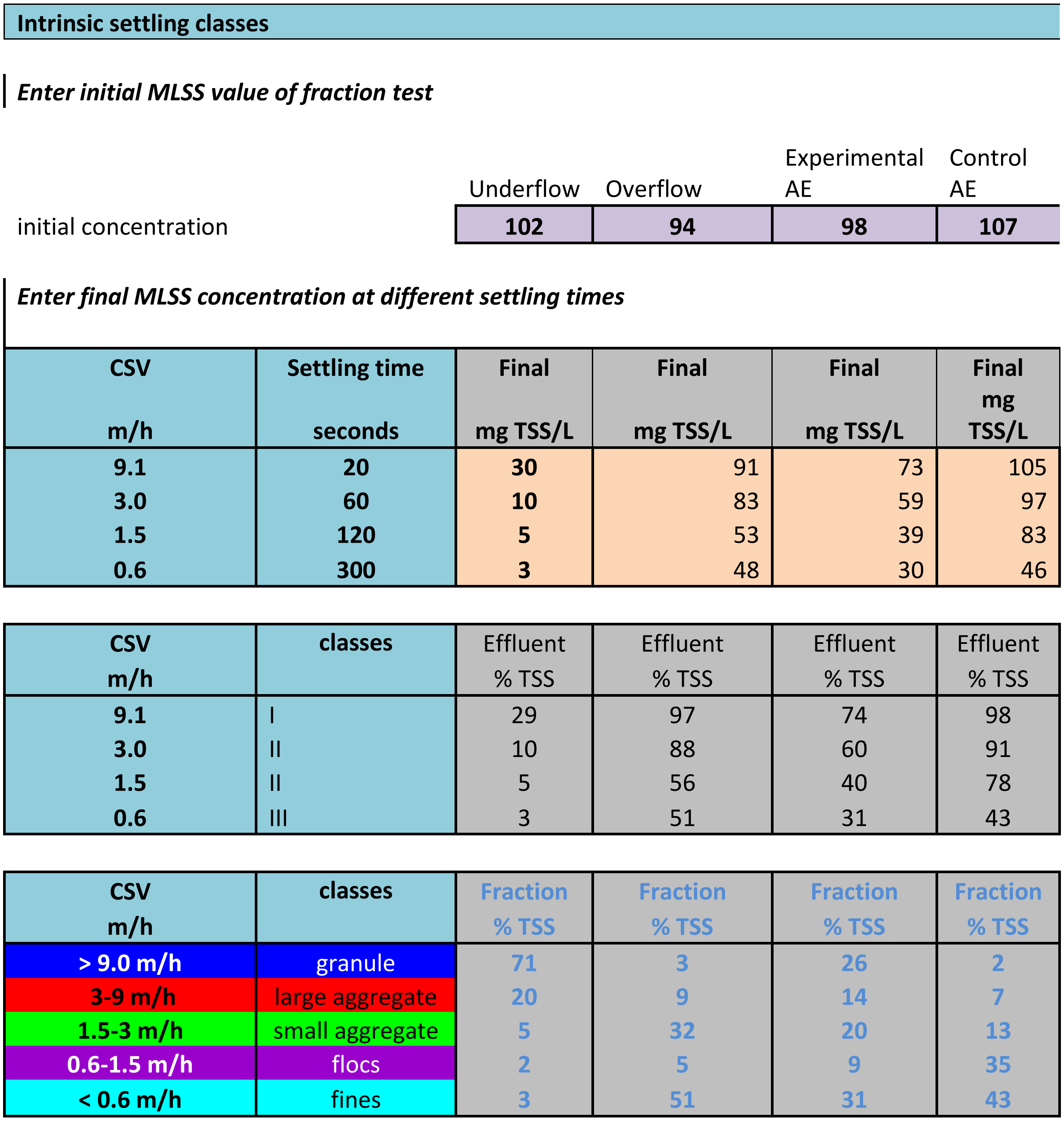
Enter final MLSS concentration at different settling times

CSV **m/h**	**Settling time** **seconds**	**Final** **mg TSS/L**	**Final** **mg TSS/L**	**Final** **mg TSS/L**	**Final** **mg TSS/L**
9.1	**20**	**33**	88	94	92
3.0	**60**	**14**	77	55	70
1.5	**120**	**7**	53	42	55
0.6	**300**	**4**	48	35	50

CSV **m/h**	**classes**	Effluent % TSS	Effluent % TSS	Effluent % TSS	Effluent % TSS
9.1	I	38	94	78	98
3.0	II	16	82	46	74
1.5	II	8	56	35	59
0.6	III	5	51	29	53

CSV **m/h**	**classes**	**Fraction** **% TSS**	**Fraction** **% TSS**	**Fraction** **% TSS**	**Fraction** **% TSS**
> 9.0 m/h	granule	**62**	**6**	**22**	**2**
3-9 m/h	large aggregate	**22**	**12**	**33**	**23**
1.5-3 m/h	small aggregate	**8**	**26**	**11**	**16**
0.6-1.5 m/h	flocs	**3**	**5**	**6**	**5**
< 0.6 m/h	fines	**5**	**51**	**29**	**53**

A.D. 4. ISC data 10/17/2016



Intrinsic settling classes

Enter initial MLSS value of fraction test

	Underflow	Overflow	Experimental AE	Control AE
initial concentration	**102**	**94**	**98**	**107**

Enter final MLSS concentration at different settling times

CSV m/h	Settling time seconds	Final mg TSS/L	Final mg TSS/L	Final mg TSS/L	Final mg TSS/L
9.1	**20**	**30**	91	73	105
3.0	**60**	**10**	83	59	97
1.5	**120**	**5**	53	39	83
0.6	**300**	**3**	48	30	46

CSV m/h	classes	Effluent % TSS	Effluent % TSS	Effluent % TSS	Effluent % TSS
9.1	I	29	97	74	98
3.0	II	10	88	60	91
1.5	II	5	56	40	78
0.6	III	3	51	31	43

CSV m/h	classes	Fraction % TSS	Fraction % TSS	Fraction % TSS	Fraction % TSS
> 9.0 m/h	granule	71	3	26	2
3-9 m/h	large aggregate	20	9	14	7
1.5-3 m/h	small aggregate	5	32	20	13
0.6-1.5 m/h	flocs	2	5	9	35
< 0.6 m/h	fines	3	51	31	43

A.D. 5. ISC data 11/10/2016

Intrinsic settling classes

Enter initial MLSS value of fraction test

	Underflow	Overflow	Experiemtnal AE	Control AE
initial concentration	**80**	**95**	**130**	**90**

Enter final MLSS concentration at different settling times

CSV m/h	**Settling time seconds**	**Final mg TSS/L**	**Final mg TSS/L**	**Final mg TSS/L**	**Final mg TSS/L**
9.1	**20**	**30**	78	94	92
3.0	**60**	**10**	67	55	70
1.5	**120**	**5**	53	42	55
0.6	**300**	**3**	48	35	50

CSV m/h	**classes**	Effluent % TSS	Effluent % TSS	Effluent % TSS	Effluent % TSS
9.1	I	38	82	72	100
3.0	II	13	71	42	78
1.5	II	6	56	32	61
0.6	III	4	51	27	56

CSV m/h	**classes**	**Fraction % TSS**	**Fraction % TSS**	**Fraction % TSS**	**Fraction % TSS**
> 9.0 m/h	granule	**63**	**18**	**28**	**0**
3-9 m/h	large aggregate	**25**	**12**	**30**	**22**
1.5-3 m/h	small aggregate	**6**	**15**	**10**	**17**
0.6-1.5 m/h	flocs	**3**	**5**	**5**	**6**
< 0.6 m/h	fines	**4**	**51**	**27**	**56**

A.D. 6. ISC data 4/5/2017

Intrinsic settling classes

Enter initial MLSS value of fraction test

	Underflow	Overflow	Experimental AE	Control AE
initial concentration	**94**	**105**	**100**	**110**

Enter final MLSS concentration at different settling times

CSV m/h	Settling time seconds	Final mg TSS/L	Final mg TSS/L	Final mg TSS/L	Final mg TSS/L
9.1	**20**	**34**	97	78	107
3.0	**60**	**17**	82	62	88
1.5	**120**	**6**	69	42	52
0.6	**300**	**3**	57	22	39

CSV m/h	classes	Effluent % TSS	Effluent % TSS	Effluent % TSS	Effluent % TSS
9.1	I	36	92	78	97
3.0	II	18	78	62	80
1.5	II	6	66	42	47
0.6	III	3	54	22	35

CSV m/h	classes	Fraction % TSS	Fraction % TSS	Fraction % TSS	Fraction % TSS
> 9.0 m/h	granule	64	8	22	3
3-9 m/h	large aggregate	18	14	16	17
1.5-3 m/h	small aggregate	12	12	20	33
0.6-1.5 m/h	flocs	3	11	20	12
< 0.6 m/h	fines	3	54	22	35

A.D. 7. ISC data 5/4/2017

Intrinsic settling classes

Enter initial MLSS value of fraction test

	Underflow	Overflow	Experimental AE	Control AE
initial concentration	**115**	**115**	**100**	**55**

Enter final MLSS concentration at different settling times

CSV m/h	**Settling time seconds**	**Final mg TSS/L**	**Final mg TSS/L**	**Final mg TSS/L**	**Final mg TSS/L**
9.1	**20**	**54**	111	79	54
3.0	**60**	**32**	96	54	49
1.5	**120**	**11**	79	43	41
0.6	**300**	**2**	59	32	33

CSV m/h	**classes**	Effluent % TSS	Effluent % TSS	Effluent % TSS	Effluent % TSS
9.1	I	47	97	79	98
3.0	II	28	83	54	89
1.5	II	10	69	43	75
0.6	III	2	51	32	60

CSV m/h	**classes**	**Fraction % TSS**	**Fraction % TSS**	**Fraction % TSS**	**Fraction % TSS**
> 9.0 m/h	granule	**53**	**3**	**21**	**2**
3-9 m/h	large aggregate	**19**	**13**	**25**	**9**
1.5-3 m/h	small aggregate	**18**	**15**	**11**	**15**
0.6-1.5 m/h	flocs	**8**	**17**	**11**	**15**
< 0.6 m/h	fines	**2**	**51**	**32**	**60**

A.D. 8. ISC data 5/30/2017

Intrinsic settling classes

Enter initial MLSS value of fraction test

	Underflow	Overflow	Experimental AE	Control AE
initial concentration	**105**	**100**	**145**	**115**

Enter final MLSS concentration at different settling times

CSV **m/h**	**Settling time** **seconds**	**Final** **mg TSS/L**	**Final** **mg TSS/L**	**Final** **mg TSS/L**	**Final mg TSS/L**
9.1	**20**	**52**	97	124	115
3.0	**60**	**27**	82	102	105
1.5	**120**	**19**	71	87	65
0.6	**300**	**11**	59	62	45

CSV **m/h**	**classes**	Effluent % TSS	Effluent % TSS	Effluent % TSS	Effluent % TSS
9.1	I	50	97	86	100
3.0	II	26	82	70	91
1.5	II	18	71	60	57
0.6	III	10	59	43	39

CSV **m/h**	**classes**	**Fraction** **% TSS**	**Fraction** **% TSS**	**Fraction** **% TSS**	**Fraction** **% TSS**
> 9.0 m/h	granule	**50**	**3**	**14**	**0**
3-9 m/h	large aggregate	**24**	**15**	**15**	**9**
1.5-3 m/h	small aggregate	**8**	**11**	**10**	**35**
0.6-1.5 m/h	flocs	**8**	**12**	**17**	**17**
< 0.6 m/h	fines	**10**	**59**	**43**	**39**

A.D. 9. ISC data 6/22/2017

Intrinsic settling classes

Enter initial MLSS value of fraction test

	Underflow	Overflow	Experimental AE	Control AE
initial concentration	**95**	**97**	**107**	**103**

Enter final MLSS concentration at different settling times

CSV m/h	**Settling time seconds**	**Final mg TSS/L**	**Final mg TSS/L**	**Final mg TSS/L**	**Final mg TSS/L**
9.1	**20**	**42**	96	79	103
3.0	**60**	**28**	91	63	93
1.5	**120**	**17**	74	54	53
0.6	**300**	**9**	52	39	33

CSV m/h	**classes**	Effluent % TSS	Effluent % TSS	Effluent % TSS	Effluent % TSS
9.1	I	44	99	74	100
3.0	II	29	94	59	90
1.5	II	18	76	50	51
0.6	III	9	54	36	32

CSV m/h	**classes**	**Fraction % TSS**	**Fraction % TSS**	**Fraction % TSS**	**Fraction % TSS**
> 9.0 m/h	granule	**56**	**1**	**26**	**0**
3-9 m/h	large aggregate	**15**	**5**	**15**	**10**
1.5-3 m/h	small aggregate	**12**	**18**	**8**	**39**
0.6-1.5 m/h	flocs	**8**	**23**	**14**	**19**
< 0.6 m/h	fines	**9**	**54**	**36**	**32**

VITA

Tyler A. Brickles

Department of Civil and
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Old Dominion University
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Employment

United States Army Second Lieutenant, Medical Service (May 2017 – Present)

HRSD Graduate Student Research Intern (June 2015 – October 2017)

HDR Inc. Water and Natural Resources Intern (December 2014 – January 2015)

HDR Inc. Water and Natural Resources Intern (June 2014 – August 2014)

Education

M.S., Old Dominion University, Environmental Engineering, Graduate GPA: 3.16

Tentative Completion: December, 2017

Co-Directors: Charles Bott, Gary Shafran, and Mujde Erten-Unal

Topic: A Comparative Study of the Effects of a Hydrocyclone on Settleability and the Formation of Aerobic Granular Sludge (AGS)

B.S., Virginia Military Institute, Civil Engineering, Undergraduate GPA: 2.74

Honors and Awards

Keydets Without Borders Vice President, VMI (2014-2015)

VWEA Student Design Competition, 1st Place, (May 2014)

WEF Student Design Competition, 3rd Place, (October 2014)

Publications and Presentations

Moore, T.O, Brickles, T.A., Beuhlmann, P.H., Thomas, W.R., (2016) **Implementation of Sustainable Drinking Water Infrastructure and "Pipe-in-Bottle" Solar Showers/Eco-Latrines in Pampoyo, Bolivia** *International Journal of Research and Engineering (IJERT)*. Issue. 9, Vol. 5.

Virginia Environmental Symposium, Implementation of Sustainable Drinking Water and Sanitation Infrastructures in Pampoyo, Bolivia, (April 2015)