Spring 2018

The Evaluation of Enhancing Biological Phosphorus Removal and Improving Settleability Using Mainstream Hydrocyclones for External Selection

Amanda Carrie Ford
Old Dominion University, lakelove99@gmail.com

Follow this and additional works at: https://digitalcommons.odu.edu/cee_etds

Part of the Environmental Engineering Commons

Recommended Citation
https://digitalcommons.odu.edu/cee_etds/29
The Evaluation of Enhancing Biological Phosphorus Removal and Improving Settleability Using Mainstream Hydrocyclones for External Selection.

By

Amanda Carrie Ford

A Thesis Submitted to the Faculty of

Old Dominion University in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

ENVIRONMENTAL ENGINEERING

OLD DOMINION UNIVERSITY, MAY 2018

Approved by:

__________________________
Gary Schafran

__________________________
Charles B. Bott

__________________________
Peter Pommerenk
Abstract

Hydrocyclones, which receive mixed liquor tangentially, separate lighter solids from more dense solids through their tapered shape. Increasing the velocity of liquid as it moves downward allows for the selection of a desired solids fraction. Limited research has been conducted utilizing 20 m$^3$hr$^{-1}$ hydrocyclones, with the intent of improving settleability and biological phosphorus removal (Bio-P) for mainstream processes. Improved settleability would allow for increased capacity in the secondary clarifiers which prevents the loss of biomass and subsequent treatment disruption, especially during wet weather scenarios. In addition, treatment intensification can be accomplished by maintaining a higher mixed liquor suspended solids concentration within the secondary process. The retention of phosphate accumulating organism (PAOs) in the underflow can lead to stabilization in secondary treatment systems by maintaining the biomass population. By amassing more denitrifying PAOs (dPAOs), which utilize either nitrate or nitrite as their electron acceptor during phosphorus uptake, allows treatment to become more efficient by utilizing influent chemical oxygen demand (COD) for both nitrogen and phosphorus removal. Achieving reliable Bio-P allows for a decrease in metal salt addition and, if operating in a low alkalinity system, a further decrease in caustic addition.

The site of the research was the Hampton Roads Sanitation District’s James River Wastewater Treatment Plant located in Newport News, VA. This facility is rated for an annual average design flow of 20 mgd, utilizes a 4-stage Bardenpho configuration with an integrated fixed film system IFAS system, and has had historically poor settleability, $SVI_{30} 140 \pm 34$ mL g$^{-1}$, not associated with filaments, nutrient deficiencies, or elevated monovalent to divalent cation ratios. The influent soluble chemical oxygen demand (sCOD) of 250 to 350 mg L$^{-1}$ allows for seasonal Bio-P without a formal anaerobic selector. In order to evaluate the potential to stabilize year-round Bio-P and improved settleability, eight hydrocyclones were installed and continuously operated from June 2015.

Hydrocyclone performance was evaluated with comparison of mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), hydraulic and mass split for the overflow and underflow, and initial settling velocity (ISV) analysis. Granulation analysis was performed at discrete particle settling concentrations of $\sim 150$ mg L$^{-1}$ MLSS to find the percentage of flocs, aggregates, and granules. Floc density was measured using the Percoll method with density beads. Activity measurements for ammonia oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOB), ordinary heterotrophic organisms (OHO), PAO, dPAO, and glycogen accumulating organisms (GAO) were performed on the plant aeration tank mixed liquor, cyclone feed, underflow, and overflow. With continued operation, the underflow MLSS measured $\sim 40$ g/L with ISV measurements of greater than 20 m hr$^{-1}$; however, the mass return was limited to less than 10 percent. Kinetic activity measurements indicated washout of AOBs, NOBs, and OHOs did not occur with hydrocyclone operation. The aeration effluent MLSS density increased indicating the potential for improved settleability. Biological phosphorus removal stabilized as indicated by activity measurements with hydrocyclone operation and better management of sidestream TP load.
©2018, by Amanda C Ford, All Rights Reserved.
ACKNOWLEDGMENTS

“We engineers thought we were so smart, but the whole time we were solving the wrong problem. Make sure you know the right problem and solve that one first” --- David Waltrip

I would like to thank my committee members Dr. Schafran and Dr. Pommenrek for their patient oversight and support during my time at ODU. Both of which are phenomenal, dedicated professors ensuring the next generation of engineers are prepared to face the ongoing and upcoming environmental challenges. I would also like to thank Dr. Unal for her enthusiastic teaching and kindness. Her engaging style made every class I took a joyful learning experience.

I owe thanks to Belinda Sturm, for being an excellent principle investigator for the aerobic granular sludge research project which encompassed my work. I thoroughly enjoyed working with her and her talented group of students. I look forward to our continued collaboration in the future.

Thank you, Mark Miller, and Pusker Regmi for all the insightful conversations during my research and I hope we continue to have many more.

I would also like to express my deep gratitude to the James River plant staff for their extremely patient support and commitment to ensuring I had every available resource to be successful. I am especially appreciative of Bob Rutherford for the many process talks and reminding me of all the challenges of operating a treatment plant, so I stayed focused. Thanks to Joe Battersby for reminding me daily about dedication and maintaining the drive to ensure good science is always achieved. I am extremely appreciative of Bob Jones for the time he invested in providing the drawings for my thesis and in demonstrating to me the careful art of perfection. I will be forever thankful to Laura Shields for her continuous support, curiosity, and most of all friendship.

I am most fortunate in having had the opportunity to work with Arba Williamson who provided every piece of equipment I could ever dream of, an endless supply of technical knowledge, and an incessant stream of encouragement to always be better. I owe thanks to Germano Salazar-Benites for always listening and being such an enthusiastic supporter of science. I have infinite appreciation to Kshitiz Uprety for teaching me the exquisiteness of control logic, providing endless punctuation during the editing of my papers, willingness to assist with an experiment, and being a tremendous, energetic friend that made sure I laughed daily with his comical antics.

Lastly, I owe a life time of gratitude to Charles Bott for being my mentor and friend. I am grateful for his reams of advice such as: the work load never goes away you just have to carry on and hope for the best, never trust anyone’s math, always cross out your units during conversions, and significant digits are the utmost importance. The list goes on just like his energy, encouragement, and dedication. I am thankful for his willingness to always answer my questions of curiosity and for all the morning process discussion phone calls. Charles exemplifies excellence in every aspect.
# Table of Contents

1. Introduction ........................................................................................................................................... 1-1
   1.1 Motivation......................................................................................................................................... 1-1
   1.2 Project Background............................................................................................................................. 1-2
   1.2.1 James River Wastewater Treatment Plant ..................................................................................... 1-2
   1.2.2 Operational Challenges................................................................................................................ 1-4
   1.3 Research Objectives.......................................................................................................................... 1-7

2. Literature Review .................................................................................................................................... 2-8
   2.1 Aerobic Granular Sludge .................................................................................................................... 2-8
      2.1.1 Structure ...................................................................................................................................... 2-8
      2.1.2 Morphology .................................................................................................................................. 2-8
      2.1.3 Substrate...................................................................................................................................... 2-9
      2.1.4 Shear .......................................................................................................................................... 2-9
      2.1.5 Density ........................................................................................................................................ 2-9
      2.1.6 Settling Characteristics ................................................................................................................ 2-9
      2.1.7 Existing Technologies Utilizing Aerobic Granular Sludge ............................................................ 2-10
   2.2 Hydrocyclones ................................................................................................................................... 2-10
      2.2.1 Structure ...................................................................................................................................... 2-10
      2.2.2 Operation ...................................................................................................................................... 2-11
      2.2.3 Air Core ...................................................................................................................................... 2-11
      2.2.4 Separation .................................................................................................................................... 2-12
      2.2.5 Shear .......................................................................................................................................... 2-12
      2.2.6 Existing Technologies within Wastewater Treatment Utilizing Hydrocyclones .................................. 2-13
         2.2.6.1 Grit Classifiers ...................................................................................................................... 2-13
         2.2.6.2 High Rate Clarification ......................................................................................................... 2-13
         2.2.6.3 Deammonification Sidestream Treatment .............................................................................. 2-13

   3.1 Method and Apparatus for Wastewater Treatment Using External Selection .............................. 3-13
   3.2 Method and Apparatus for Wastewater Treatment Using Gravimetric Selection ......................... 3-13

4. Methods .................................................................................................................................................. 1
Table of Contents

4.1 Hydrocyclone Installations at James River Wastewater Treatment Plant ........................................ 1
    4.1.1 Hydrocyclone Mainstream Operation ......................................................................................... 1
    4.1.2 Hydrocyclone Demonstration Manifold Operation ....................................................................... 3
    4.1.3 Data Collection .......................................................................................................................... 5

5. Results and Discussion .......................................................................................................................... 10
    5.1 20 m³ hr⁻¹ Hydrocyclone Mainstream Operation ............................................................................. 10
        5.1.1 Short Duration Nozzle and Pressure Evaluation ...................................................................... 10
        5.1.1.1 Hydraulic Percent and Initial/Zone Settling Velocities (ISV or ZSV) for the Overflow and Underflow Fractions .................................................................................................................. 10
        5.1.2 Long Duration Nozzle and Pressure Evaluation ........................................................................ 11
        5.1.2.1 Hydraulic and Mass Percent for the Overflow and Underflow Fractions ............................. 12
        5.1.3 Mixed Liquor Total Suspended Solids and Volatile Suspended Solids ........................................ 14
        5.1.4 Mixed Liquor Density Measurements ......................................................................................... 15
        5.1.5 Initial/Zone Settling Velocities (ISV or IZV) .............................................................................. 15
        5.1.6 Intrinsic Settling Class Analysis ................................................................................................. 17
        5.1.7 Five and Thirty Minute Sludge Volume Index .......................................................................... 19
        5.1.8 Kinetic Activity Measurements ................................................................................................... 20
        5.1.9 Simultaneous Operation Comparative Study Between the 18 mm and 15 mm Nozzle .......... 22
        5.1.10 Mainstream Hydrocyclone Operation Impact on Overall Plant Process ................................ 24
    5.2 Hydrocyclone Demonstration Manifold ............................................................................................. 27
        5.2.1 Initial Settling Velocities, Hydraulic and Mass Split for the Overflow and Underflow Fractions for Each Manufacturer ................................................................................................................. 27

6. Conclusion and Engineering Significance ............................................................................................. 35
    6.1 Conclusion and Engineering Significance ......................................................................................... 35

7. References .............................................................................................................................................. 36

8. VITA ...................................................................................................................................................... 42
List of Tables

Table 1.1: JRWWTP influent characteristics based on yearly average (2013-2015) ............... 1-3
Table 1.2: Physical characteristics for JR WWTP’s secondary clarifiers .................................. 1-3
Table: 1.3: JRWWTP’s operational and influent characteristics promoting Bio-P .................. 1-4
Table 4.1: Feed pressures and nozzle size evaluation grid for 20 m$^3$ hr$^{-1}$ short duration testing ... 3
Table 4.2: Feed pressures and nozzle size evaluation grid for 20 m$^3$ hr$^{-1}$ continuous operation ...... 3
Table 4.3: Hydrocyclones with volumetric flow rates, nozzle sizes, and operating pressures tested on the demonstration manifold. ......................................................................................... 4
Table 5.1: Hydraulic and mass percent for hydrocyclone fractions from continuous operation nozzle and pressure evaluation .......................................................................................... 12
Table 5.2: Mixed liquor suspended solids for hydrocyclone fractions ........................................ 14
Table 5.3: Mixed liquor volatile suspended solids for hydrocyclone fractions from nozzle and pressure evaluation ........................................................................................................ 14
Table 5.4: Initial/Zone settling velocities for underflow, overflow, and aeration basin mixed liquor from the nozzle and pressure evaluation. ................................................................. 16
Table 5.6: SVI$_5$ and SVI$_{30}$ for the underflow and overflow fractions ....................................... 19
Table 5.8: Comparison of SVI$_5$ and SVI$_{30}$ for plant aeration basin mixed liquor based prior to and subsequent to hydrocyclone operation at the JRWWTP ...................................................... 24
Table 5.9: Manufacturer B 10 m$^3$ hr$^{-1}$ ISV, mass, and hydraulic percent for underflow and overflow ................................................................................................................................. 29
Table 5.10: Manufacturer D: 5 m hr$^{-1}$ and 10 m hr$^{-1}$ ISV, mass and hydraulic ......................... 34
List of Figures

Figure 1.1: JRWWTP Process Overview................................................................. 1-2
Figure 1.2: Ferric salt addition to primaries and secondary clarifiers ......................... 1-5
Figure 1.3: Ferric salt addition and final effluent concentrations.................................. 1-5
Figure 1.4: SVIs & SVI30 before and after IFAS upgrade indicating poor settleability at the JRWWTP ................................................................. 1-6
Figure 1.5: Plant influent flow, final effluent TSS and polymer addition to the secondary clarifiers.................................................................................................. 1-6
Figure 2.1: Essential components of a hydrocyclone (drawing courtesy of Robert A. Jones II, HRSD, 2017)............................................................................. 2-11
Figure 4.1: 20 m³ hr⁻¹ James River WWTP mainstream configuration (drawing courtesy of Robert A. Jones II, HRSD, 2017).................................................................. 2
Figure 4.2: JRWWTP Process Overview with inDENSE™ ........................................... 2
Figure 4.3: Demonstration testing manifold (drawing courtesy of Robert A. Jones II, HRSD, 2017)......................................................................................... 4
Figure 4.5: Density bead tube and mixed liquor comparison (drawing courtesy of Robert A. Jones II, HRSD, 2017) ................................................................. 6
Figure 4.6: Phosphorus release and uptake rates methodology schematic (drawing courtesy of Robert A. Jones II, HRSD, 2017)................................................................. 7
Figure 4.7: Ammonia and nitrite oxidizing rate methodology schematic (drawing courtesy of Robert A. Jones II, HRSD, 2017)................................................................. 8
Figure 5.1: Overflow and underflow hydraulic percent................................................. 11
Figure 5.2: Initial settling velocities (m hr⁻¹) at 2.5 g L⁻¹ ........................................... 11
Figure 5.3: Underflow percent return to total inventory of mixed liquor solids in the aeration basins. .......................................................................................... 13
Figure 5.4: Underflow MLSS versus underflow hydraulic percent return ..................... 13
Figure 5.5: Density measurements for the overflow and underflow fractions and the aeration basin mixed liquor................................................................. 15
Figure 5.6. ISV measurements for the aeration basin normalized to a 3.5-day SRT during an evaluation of shutting the hydrocyclones off. ......................................................... 16
Figure 5.7: Feed/RAS mixed liquor intrinsic settling class percent bins....................... 17
Figure 5.8: Overflow mixed liquor intrinsic settling class percent bins ....................... 18
Figure 5.9: Underflow mixed liquor intrinsic settling class percent bins ..................... 18
Figure 5.10: Aeration basin mixed liquor intrinsic settling class percent bins ............... 19
Figure 5.11: Biological phosphorus release and uptake activity measurements for underflow and overflow. .............................................................................. 20
Figure 5.12: Biological phosphorus release and uptake activity uptake data for the underflow and sieve fractions................................................................. 21
Figure 5.13: AOB and NOB activity measurements underflow, overflow, and aeration basin mixed liquor .................................................................................. 21
Figure 5.14: Initial settling velocities the overflow and underflow from the 18 mm and 15 mm nozzles.................................................................................. 22
Figure 5.15: Biological phosphorus release and uptake activity for the plant aeration basin, overflow and underflow from the 18 mm and 15 mm nozzles. ................. 23
Figure 5.16: AOB and NOB activity for the plant aeration basin, overflow and underflow from the 18 mm and 15 mm nozzles ................................................................. 23
Figure 5.17: Plant aeration basin MLVSS ............................................................... 24
Figure 5.18: Influent and final effluent TSS concentrations and polymer addition to the secondary clarifiers with continuous hydrocyclone use ........................................ 25
Figure 5.19: Biological phosphorus release and uptake measurements at JRWWTP .................. 26
Figure 5.20: Biological phosphorus release and uptake measurements from WWTPs in the region ........................................................................................................... 26
Figure 5.21: Total phosphorus removal and ferric salt addition to primary and secondary clarifiers ........................................................................................................... 26
Figure 5.22: Increased ferric salt addition to maintain low final effluent concentrations not required with stabilization and increased Bio-P with sidestream load management .......... 27
Figure 5.23: Manufacturer A 5 m$^3$ hr$^{-1}$ ISV, mass, and hydraulic percent .......................... 28
Figure 5.24: Manufacturer B 5 m$^3$ hr$^{-1}$ ISV, mass, and hydraulic percent ............................ 28
Figure 5.25: Manufacturer C 5 m$^3$ hr$^{-1}$ mass and hydraulic percent for underflow and overflow 29
Figure 5.26: Manufacturer C 5 m$^3$ hr$^{-1}$ ISV for underflow and overflow ............................ 30
Figure 5.27: Manufacturer C 5 m$^3$ hr$^{-1}$ ISV for underflow and overflow per operating feed ...... 30
Figure 5.28: Manufacturer C 5 m$^3$ hr$^{-1}$ ISV for underflow and overflow with the 15-mm nozzle 31
Figure 5.29: Manufacturer C 5 m$^3$ hr$^{-1}$ ISV for underflow and overflow the 12.5 mm nozzle ... 31
Figure 5.30: Manufacturer C 5 m$^3$ hr$^{-1}$ ISV for underflow and overflow with the 10mm nozzle 32
Figure 5.31: Manufacturer C 10 m$^3$ hr$^{-1}$ ISV, mass and hydraulic percent for underflow and overflow per nozzle size with HRT 0.63 of seconds ............................................. 33
Figure 5.32: Manufacturer C 10 m$^3$ hr$^{-1}$ ISV, mass and hydraulic percent for underflow and overflow per nozzle size with HRT of 0.97 seconds ............................................. 33
Figure 5.33: Manufacturer C 10 m$^3$ hr$^{-1}$ underflow mass return per HRT for each nozzle .... 34
## List of Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS</td>
<td>Aerobic granular sludge</td>
</tr>
<tr>
<td>AM</td>
<td>AnitaMox™</td>
</tr>
<tr>
<td>AOB</td>
<td>Ammonia oxidizing bacteria</td>
</tr>
<tr>
<td>BioP</td>
<td>Biological phosphorus removal</td>
</tr>
<tr>
<td>BOD</td>
<td>Biochemical oxygen demand</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical oxygen demand</td>
</tr>
<tr>
<td>CSV</td>
<td>Critical settling velocities</td>
</tr>
<tr>
<td>DCS</td>
<td>Distributed Control System</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>dPAO(s)</td>
<td>Denitrifying phosphate accumulating organism(s)</td>
</tr>
<tr>
<td>FNE</td>
<td>Final effluent</td>
</tr>
<tr>
<td>GAO</td>
<td>Glycogen accumulating organism</td>
</tr>
<tr>
<td>GBTs</td>
<td>Gravity belt thickeners</td>
</tr>
<tr>
<td>GT</td>
<td>Gravity thickener</td>
</tr>
<tr>
<td>HRSD</td>
<td>Hampton Roads Sanitation District’s</td>
</tr>
<tr>
<td>HRT</td>
<td>Hydraulic Retention Time</td>
</tr>
<tr>
<td>IFAS</td>
<td>Integrated fixed-film activated sludge</td>
</tr>
<tr>
<td>IMLR</td>
<td>Internal mixed liquor recycles</td>
</tr>
<tr>
<td>ISC</td>
<td>Intrinsic Settling Classes</td>
</tr>
<tr>
<td>ISV</td>
<td>Initial settling velocity</td>
</tr>
<tr>
<td>JRWWTP</td>
<td>James River Wastewater Treatment Plant</td>
</tr>
<tr>
<td>KOH</td>
<td>Potassium hydroxide</td>
</tr>
<tr>
<td>MLSS</td>
<td>Mixed liquor suspended solids</td>
</tr>
<tr>
<td>MLVSS</td>
<td>Mixed liquor volatile suspended solids</td>
</tr>
<tr>
<td>NaCl</td>
<td>Sodium chloride solution</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>Ammonia as nitrogen</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>NO₂⁻N</td>
<td>Nitrite as nitrogen</td>
</tr>
<tr>
<td>NO₃⁻N</td>
<td>Nitrate as nitrogen</td>
</tr>
<tr>
<td>NOB</td>
<td>Nitrite oxidizing bacteria</td>
</tr>
<tr>
<td>OHO</td>
<td>Ordinary heterotrophic organism</td>
</tr>
<tr>
<td>OP</td>
<td>Orthophosphate</td>
</tr>
<tr>
<td>PAO(s)</td>
<td>Phosphate accumulating organism(s)</td>
</tr>
<tr>
<td>PCE</td>
<td>Primary clarifier effluent</td>
</tr>
<tr>
<td>PFR</td>
<td>Plug flow configurations</td>
</tr>
<tr>
<td>RAS</td>
<td>Return activated sludge</td>
</tr>
<tr>
<td>rbCOD</td>
<td>Readily biodegradable COD</td>
</tr>
<tr>
<td>SBRs</td>
<td>Sequencing batch reactors</td>
</tr>
<tr>
<td>sCOD</td>
<td>Soluble chemical oxygen demand</td>
</tr>
<tr>
<td>SIP</td>
<td>Stock isotonic Percoll</td>
</tr>
<tr>
<td>SRT</td>
<td>Solids retention time</td>
</tr>
<tr>
<td>SSV₅</td>
<td>Settled sludge volume after at 5 minutes</td>
</tr>
<tr>
<td>SSV₃₀</td>
<td>Settled sludge volume after at 30 minutes</td>
</tr>
<tr>
<td>tCOD</td>
<td>Total COD</td>
</tr>
<tr>
<td>TKN</td>
<td>Total Kjeldahl Nitrogen</td>
</tr>
<tr>
<td>TP</td>
<td>Total phosphorous</td>
</tr>
<tr>
<td>TS</td>
<td>Total solids</td>
</tr>
<tr>
<td>TSS</td>
<td>Total suspended solids</td>
</tr>
<tr>
<td>UASB</td>
<td>Upflow anaerobic sludge blanket</td>
</tr>
<tr>
<td>VFA</td>
<td>Volatile fatty acids</td>
</tr>
<tr>
<td>WAS</td>
<td>Waste activated sludge</td>
</tr>
<tr>
<td>WWTP</td>
<td>Wastewater treatment plants</td>
</tr>
<tr>
<td>WWW</td>
<td>World Water Works</td>
</tr>
<tr>
<td>ZSV</td>
<td>Zone Settling Velocity</td>
</tr>
</tbody>
</table>
1. Introduction

1.1 Motivation

The secondary treatment process is a focus of substantial intensification efforts by using microorganism metabolic kinetics to achieve optimal utilization of influent parameters and internal recycle streams, resulting in negligible usage of chemical addition, reduced dissolved oxygen requirements, and a net decrease of energy while utilizing minimal reactor volume. Increased MLSS concentration could lead to a reduction in required tank volume; however, secondary clarification design failures are often the limiting factor for wastewater treatment capacity (Ekama et al. 1997).

Secondary clarifiers/settling tanks function as solid-liquid separators allowing for the removal of secondary treatment biological flocs/mixed liquor from the liquid stream while producing an effluent with low total suspended solids (TSS). Secondary clarifiers also function as thickeners, resulting in concentrated MLSS through compression, and source of the return activated sludge (RAS ) (WEF, 2005). Lastly, secondary clarifiers function as temporary sludge holding basins to minimize process disruptions during increased flow events. Sludge settleability is often the limiting factor in secondary clarifiers; however, discerning the grounds for poor settleability is problematic at best. The root of the issue may have foundations in nutrient deficiencies, low dissolved oxygen, excessive sulfide loading, excessive monovalent/divalent cation ratios, poor management of solids retention time, low pH, high organic loading without the utilization of a metabolic selector, low organic loading, and excessive extracellular polymeric substances production. Research on improving settleability is widespread and has given rise to numerous process applications such as anaerobic/anoxic selectors, inert ballast addition, selective wasting of poor settling microorganisms, and process operation to select for granular sludge.

Intensification through granular sludge is by no means a novel concept with applications of anaerobic granulation being utilized in upflow anaerobic sludge blanket (UASB) reactors to promote the aggregation of methanogenic and acetogenic organisms to effectively reduce organic material to methane, carbon dioxide, hydrogen gas, and volatile fatty acids (Young and McCarty, 1969; Lettinga et al., 1980). The microorganism community shifting through anaerobic granulation laid the foundation for extensive research on metabolic and physicochemical pathways for the stratified microbiome and improvements in settling.

Aerobic granular sludge (AGS) observations began in the early 1990s (Mishima and Nakamura, 1991) with extensive research conducted by Delft University of Technology, Netherlands which gave rise to the Nereda® process in which carbon, nitrogen, and enhanced biological phosphorus removal (EBPR) occur with granules being formed within sequencing batch reactors (Beun et al. 1999; de Kreuk, 2006). The implementation of the technology has been successful and is continuing to grow. However, plug flow reactors (PFR) are a common configuration for wastewater treatment plants (WWTP) and subsequently face capacity challenges when subjected to increasingly stringent permits due to limitations of costly reactor modifications. This situation led to a desire to promote intensification through external selection allowing for microorganism community changes through specified retainment. Hydrocyclones have been utilized in wastewater process applications for grit removal, inert ballast retrieval, and side stream deammonification. An evaluation of hydrocyclones as a low capital cost installation as an external
selector for improving settleability and enhancing biological phosphorus removal was the focus of this research.

1.2 Project Background

1.2.1 James River Wastewater Treatment Plant

The Hampton Roads Sanitation District’s (HRSD) James River Wastewater Treatment Plant (JRWTP) operates under permit number: VA0081272, and is hydraulically rated for an annual average of 20 mgd (75,700 m$^3$ day$^{-1}$) (Figure 1.1). Domestic waste, with approximately 10% industrial waste, travels by means of a gravity/force main collection system leading to mild septicity and a medium strength wastewater (Table 1.1).
JRWWTP operates a 4-stage Bardenpho configuration with integrated fixed-film activated sludge (IFAS) in the first aerobic zone, utilizing approximately 45% fill of AnoxKaldnes K3 plastic media with a specific surface area of 500 m² m⁻³. In order to achieve denitrification and to prevent media migration, two internal mixed liquor recycles (IMLR) discharge to the first cell of the anoxic zone. Supplemental carbon addition to the second anoxic zone does not occur, thus, its primary function is to serve as a zone to reduce oxygen, rather than for denitrification.

Five circular secondary clarifiers which are, peripheral feed, center wells with organ style sludge removal, have poor hydraulic splits and require manual gate adjustments to prevent excessive discharge of suspended solids in the final effluent. Each of the clarifiers have flat bottoms except for clarifier number 5, which has a cone depth of 1.35 ft. The design parameters for the secondary clarifiers are listed in Table 1.2.

| Table 1.1: JRWWTP influent characteristics based on yearly average (2013-2015). |
|---------------------------------|-----|-----|-----|-----|-----|-----|-----|
|                                | BOD | tCOD | sCOD | TS  | TSS | TKN | TP  |
|                                | mg L⁻¹ | mg L⁻¹ | mg L⁻¹ | mg L⁻¹ | mg L⁻¹ | mg L⁻¹ | mg L⁻¹ | CaCO₃ |
| 2013                           | 232 | No Data | No Data | 582 | 171 | 38  | 5.0 | 171  |
| 2014                           | 261 | 547    | 281    | 598 | 174 | 39  | 5.1 | 171  |
| 2015                           | 238 | 517    | 258    | 580 | 166 | 39  | 5.0 | 173  |

| Table 1.2: Physical characteristics for JR WWTP's secondary clarifiers |
|-----------------------------|-----|-----|
| Secondary Clarifier         | Diameter | Side Water Depth |
| #                           | ft. | ft.  |
| 1                           | 75  | 8.8  |
| 2                           | 75  | 8.8  |
| 3                           | 105 | 8.8  |
| 4                           | 105 | 8.8  |
| 5                           | 130 | 11.9 |

Primary solids and secondary solids are sent to a gravity thickener (GT) and gravity belt thickener (GBT), respectively. Two anaerobic digesters operating in parallel stabilize the thickened solids. After centrifuging, the centrate is diverted to sidestream treatment where AnitaMox™ (AM) manages the ammonia load. Ferric sulfate can be added to the primary clarifier influent, the AM effluent, or the influent of the secondary clarifiers to manage the phosphorus load.
1.2.2 Operational Challenges

The influent wastewater characteristics of a high VFA: rbCOD ratio promotes successful Bio-P treatment without a formal anaerobic selector (Table 1.3). However, these benefits were not consistent, driving the necessity for metal salt addition to achieve acceptable phosphorus removal (Figure 1.2). In addition, if the sidestream phosphorous concentration was not managed properly, excessive loading transpired which subsequently increased the addition of metal salts to the primary clarifiers and/or secondary clarifiers leading to a destabilization of Bio-P (Figure 1.3). Poor settleability and compressibility in the secondary clarifiers has been a historic affliction generating hydraulic and biological treatment capacity limitations (Figure 1.4). Capacity limitations were compounded during wet weather events when flows increase above 20 mgd causing increased final effluent turbidity, TSS, and total phosphorous (TP). In an attempt to combat undesired solids discharge, cationic polymer addition to the secondary clarifier was utilized (Figure 1.5).

Table: 1.3: JRWWTP’s operational and influent characteristics promoting Bio-P.

<table>
<thead>
<tr>
<th></th>
<th>Total SRT</th>
<th>Aerobic SRT</th>
<th>rbCOD: tCOD</th>
<th>VFA: rbCOD</th>
<th>VFA: P</th>
<th>rbCOD: P</th>
<th>tCOD: P</th>
<th>sCOD: P</th>
</tr>
</thead>
<tbody>
<tr>
<td>JRWWTP</td>
<td>4 - 6</td>
<td>1.5 - 3.0</td>
<td>0.26</td>
<td>0.66</td>
<td>14</td>
<td>22</td>
<td>66</td>
<td>38</td>
</tr>
</tbody>
</table>
Figure 1.2: Ferric salt addition to primaries and secondary clarifiers

Figure 1.3: Ferric salt addition and final effluent concentrations.
Figure 1.4: SVI₅ & SVI₃₀ before and after IFAS upgrade indicating poor settleability at the JRWWTP.

Figure 1.5: Plant influent flow, final effluent TSS and polymer addition to the secondary clarifiers
1.3 Research Objectives

The objectives of this project were to: (1) investigate hydrocyclone operation based on nozzle diameter and operating pressure, (2) evaluate hydrocyclones as external selectors for selectively wasting poor settling flocs while retaining dense particles for improved settleability, (3) examine the influence of hydrocyclone operation on Bio-P performance and metal salt and caustic addition, and (4) elucidate the extent of metabolic selection utilizing a hydrocyclone on a treatment process without a formal anaerobic selector to enhance Bio-P performance.
2. Literature Review

2.1 Aerobic Granular Sludge

2.1.1 Structure

Aerobic granular sludge (AGS) is a spherical stratified microorganism biome with diameters of 0.2 to 5 mm (de Kreuk, 2006; Liu, 2007; McSwain et al., 2004a; Mishima and Nakamura, 1991). In general terms, they are composed of an inner core which can be composed of inert materials, active biomass, and inactive biomass with varying levels of degraded cells (McSwain et al., 2005; Wang et al., 2005a). The outer layer and potential middle layer are composed of active biomass, extra cellular polymeric substances, and small fractions of enmeshed inert materials (McSwain et al., 2005; Toh et al., 2003; Wang et al., 2005a; Wang et al., 2005b). The depth of the inner layer can range from 0.2 – 0.8 mm based on the substrate provided for growth (Figadore at al., 2017; McSwain et al., 2005; Tay et al., 2002a).

2.1.2 Morphology

The metabolic structure of the aerobic granules differs based upon the substrate diffusion and subsequent microorganism community. Carbon based aerobic granules achieve nitrogen removal through assimilation (Figadore at al., 2017; Tay et al., 2002b). Nitrification-based aerobic granules successfully perform the stepwise processes during aerobic conditions with non-organic carbon substrates (Figdore et al., 2015; Tay et al., 2002c). Carbon-based, nitrification and denitrification by aerobic granules utilize mostly OHOs and nitrogen removal is through assimilation (Figadore et al., 2017; Wang et al., 2012). Carbon-based, nitrification, denitrification, and biological phosphorus removal aerobic granules have an anaerobic core which promotes Bio-P, nitrification and phosphorus uptake is achieved in the outer aerobic layer, and denitrification is achieved through OHOs and PAOs (de Kreuk et al., 2005; Winkler et al., 2012). The key to achieving all forms of nutrient removal in this application of aerobic granular sludge is the accessibility to rbCOD.

Denitrification through means of PAOs occurs when nitrate or nitrite is used as the electron acceptor by denitrifying phosphorous accumulating organisms (dPAOs) for phosphorus uptake. The establishment of dPAOs is not limited to aerobic granular sludge but occurs in suspended growth applications as well and most of the comprehension on the metabolic functions are from these type applications. The removal of nitrate by dPAOs has been reported as 4 - 5 g NO$_3$-N per g of P removal (Brdjanovic et al. 1998; Lee & Yun, 2014). Nitrite serving as the electron acceptor would be most ideal since short cut nitrogen removal techniques in mainstream processes lead to a reduction in sludge production and aeration cost. However, it has been found NO$_2$-N concentrations above 6 mg/L can lead to inhibition of aerobic phosphorus uptake and anoxic phosphorus removal is reduced by 35% if concentrations of NO$_2$-N are elevated above 12 mg/L (Ahn et al., 2001a; Meinhold et al., 1999a; Saito et al., 2004; Sin et al., 2008). The percent of dPAO versus PAO uptake varies in the literature and has been found to range from 20-60% (Kuba et al., 1994, 1997; Liu et al., 2015; Meinhold et al., 1999b). Studies show variation in sCOD concentrations do not impact the removal efficiencies of phosphorus, indicating a mixed population of facultative dPAOs.
using oxygen, nitrate or nitrite, obligatory dPAOs using only nitrate, and obligatory PAOs using only oxygen, allows for competition in substrate limiting environments leading to a more robust biological phosphorus removal system (Ahn et al., 2001b; Lee and Yun, 2014).

2.1.3 Substrate

Substrate diffusion impacts the structure and the morphology of AGS. Research indicates elevated concentrations of rbCOD promotes the formation of AGS by limiting low substrate growth of filamentous bacteria which promotes biological activity, and promotes metabolic selection of microorganism that favor AGS formation with superior settling characteristics (Chudoba et al., 1985; Figdore et al., 2017; Lopez-Vazquez et al., 2009; Mino et al., 1998; van Loosdrecht et al., 1995). Faraj et al. (2017) found low rbCOD wastewater could successfully promote the growth of AGS but recommend an external selector to retain the granules and mitigate elevated TSS in the effluent.

2.1.4 Shear

Shear stress is an essential parameter on the structure and morphology of aerobic granular sludge. Shear stabilizes the granule and maintains the firm, compact, smooth shape by sloughing off filaments, produces extra cellular polymeric substances, and promotes the selection of a desired microorganism community (Tay et al., 2001; Liu & Tay 2002; McSwain et al., 2005; van Loosdrecht et al., 2005). Full-scale, pilot-scale, and bench-top studies report different requirements which range from 0.5 to 2.0 cm s\(^{-1}\) (de Kreuk and van Loosdrecht, 2006; McSwain et al., 2004b; Wang et al., 2004, 2009).

2.1.5 Density

The metabolic function of the microorganisms is an influential factor determining density and settleability. Density of activated sludge is typically 1.02 – 1.06 g mL\(^{-1}\) which should yield settling velocities of 1.0 to 1.5 m hr\(^{-1}\) (Dammel and Schroeder, 1990; Li & Pagilla, 2017). Biological nutrient removal organisms exhibit better settleability than ordinary heterotrophic organisms (Schuler et al., 2001, 2002, 2007a Winkler et al., 2013). In particular, PAOs exhibit superior settling characteristics with reported densities of 1.08 to 1.23 g mL\(^{-1}\) (Friedberg and Avigad, 1968, Dawes and Senior., 1972, Schuler et al., 2001, Winkler et al. 2013). Organic material within the cell is a source of increased density within the microorganism cells with the average density of carbohydrates 1.37 g mL\(^{-1}\), proteins 1.35 g mL\(^{-1}\), and nucleic acid 1.70 g mL\(^{-1}\) (Scott and Still, 1970; Quillin and Matthews, 2000; Smialek et al., 2013; Li & Pagilla, 2017). The structure of aerobic granular sludge would suggest an elevated density; however, literature indicates a range of 1.02 to 1.09 g mL\(^{-1}\) (Etterer and Wildere, 2001; Winkler et al., 2013a).

2.1.6 Settling Characteristics

The structure of aerobic granule sludge promotes discrete settling characteristics over hindered settling rates. High initial settling velocities of greater than 9.0 m hr\(^{-1}\) are often reported (McSwain et al., 2004b; Tay et al., 2002b; Winkler et al., 2012a). In addition, low SVIs of 25 to 50 mL g\(^{-1}\) are typical while well settling activated sludge flocs’ SVI\(_{30}\) of 70 -120 mL g\(^{-1}\) are desired (de Kreuk & Van Loosdrecht, 2004,
Tay et al., 2004a). Comparison of SVI5:SVI30 finds granules have a ratio typical of 1.0 whereas in activated sludge flocs the value is closer to 2.0 (van Haandel and van der Lubbe, 2012).

2.1.7 Existing Technologies Utilizing Aerobic Granular Sludge

The development of the aerobic granular sludge technology gave rise to the Nereda® process in which sequencing batch reactors (SBRs) through proprietary wasting and bottom feeding regiments provide substrate gradients which promote granule formation (de Kreuk, 2006). Aeration provides the necessary shear for the formation of the compact granular shape and substrate diffusion for nitrification. SBRs with incorporated selective wasting allows for an enrichment of microorganisms with superior settling that promote granulation (Winkler et al., 2011, 2012a, 2012b, 2012c). Pilot and full-scale SBRs have led to applications of aerobic granular sludge in which successful treatment of carbon, nitrogen, and phosphorus coupled with superior settling benefits have occurred. New construction and retrofits of existing facilities are options for the implementation of the Nereda® process.

2.2 Hydrocyclones

During the late 1800s and early 1900s, hydrocyclones were designed mostly for the pulp and coal industries and focused on classification, thickening, and gravity separation (Bradley, 1965). Over time, modification patents for operational optimization have been assigned as the technology continues to develop.

2.2.1 Structure

Hydrocyclones are typically composed of a tangential feed inlet, vortex finder, conical shaped body, spigot/nozzle, underflow spout, overflow spout and in some applications, a body extension (Figure 2.1). Though hydrocyclones are relatively low cost and simply operated, selection optimization can be difficult as a result of the feed characteristics and impacts of the components on the fluid mechanics.
2.2.2 Operation

Hydrocyclones receive a pressurized liquid stream through a tangential inlet and because the outer and inner fluid layers move in oppositional rotation, a low-pressure center along the vertical axis, known as the air core, forms (Bradley, 1965). The equilibrium orbit theory explains that opposing drag and centrifugal forces promote the separation of particles. The equality of the opposing forces, or terminal velocity, is the foundation for classification. The centrifugal force accelerates the settling rate of the particles; therefore, they separate based on particle size, density, and shape prompting the denser, coarser particles to migrate to the sidewalls allowing them exit via the apex/underflow. The viscous drag force created within the hydrocyclone causes the poorer settling particles to move to the low energy zone within the axis, being discharged as part of the overflow (Bradley, 1965; Kawatra et al., 1996a, 1996b; Tripathy et al., 2015). It has been noted that sufficient hydraulic retention time (HRT) is necessary to provide adequate particle separation based on the opposing forces (Hwang K. and Chow S., 2017; Vakamalla et al., 2017).

2.2.3 Air Core

The air core, which if created due to the oppositional rotation of the fluid, formation is an indicator of hydrocyclone geometry and vortex stability based upon feed rate and subsequent pressure drop due to the width of the air core diameter having a linear relationship with the overflow diameter and cone angle (Bradley, 1965). Poor air core formation negatively impacts the particle separation efficiency. Low flow entry prevents the overflow from discharging, hence leading to an increase in underflow reporting.
Volume split ratios are impacted by high flow entry if the air core exceeds the diameter of the nozzle, as minimal reporting to the underflow occurs (Bradley, 1965).

### 2.2.4 Separation

The $d_{50}$, also known as cut point or cut diameter, is the separation point in which a particle has a 50% chance of reporting to the underflow or overflow. It is formed when the centrifugal and drag forces are equal and form a zero-vertical velocity plane which is the point when the drag force and the centrifugal force are equal (Bradley, 1965; Kawatra et al., 1996a). The position of the plane is the determining factor for the particle underflow or overflow discharge preference. Empirical formulas have been developed to determine the placement of the plane allowing for predicking the $d_{50}$ (Bradley, 1965). Hydrocyclones used for classification require a correct, sharp $d_{50}$ (Bradley, 1965). Changes to the $d_{30}$ can be affected by operating feed pressure, feed density/solids concentration, size restriction within the hydrocyclone, and viscosity. An increase in feed pressure, increases the centrifugal force which decreases the $d_{50}$ allowing for a better selection of heavy particles reporting to the underflow; however, if the feed pressure is too high, the vortex could be short circuited allowing for dense particles to leave via the overflow (Bradley, 1965; Kaung et al., 2012; Sabbagh et al., 2017). The feed solids concentration impacts the classification efficiency by increasing the viscous drag force and hindering the heavier particles from migrating to the sidewalls; however, literature indicates this occurrence is only problematic when the solid concentrations are above 2% (Bradley, 1965; Kawatra et al., 1996b; Kaung et al., 2012; Sabbagh et al., 2017). In wastewater applications, the feed/ RAS falls below this value, and therefore, should not be a hindering factor. The most efficient separation by hydrocyclone is for particle sizes ranging from 5 to 200 µm, if particle sizes are smaller either a large density gradient or small feed inlet diameter is needed (Bradley, 1965; Sabbagh et al., 2017). A decrease in the diameter of a nozzle or vortex finder, which control the zero-vertical velocity plane, forces a sharper $d_{50}$ by increasing the pressure of the vortex consequently classification for the better settling materials is increased and the underflow particles are denser. The $d_{50}$ decreases with increasing temperature because of decreasing viscosity (Cilliers et al., 2004; Kawatra et al., 1988). Furthermore, increased viscosity suppresses the tangential velocity thus reducing the settling rate in the underflow (Bradley, 1965)

### 2.2.5 Shear

The shear produced within the hydrocyclone serves to classify particles. Consequently, proper shear rates must be selected when flocculation based solids are considered for classification (Bradley, 1965). The highest potential for floc breakage is located at the feed inlet or overflow/underflow outlets due to the increased shear rates (Williams and Roldan-Villasana, 1991). Non-Newtonian fluids, which decrease in viscosity with increased shear rate, are well suited for classification by a hydrocyclone; however detrimental impacts can occur if the proper shear rate is not established. Increased viscous drag forces a reduction in centrifugal speed within the hydrocyclone, leading to an increase in the unprocessed feed fraction reporting to underflow (Kawatra et al., 1996a, Vakamalla et al., 2017). In addition, denser particles located within the vicinity of the vortex finder due to eddies, or obstructions of flow pattern can be swept into the overflow stream leading to misdirection of particles with superior settling characteristics (Bradley, 1965, Vakamalla et al., 2017).
2.2.6 Existing Technologies within Wastewater Treatment Utilizing Hydrocyclones

Hydrocyclones have been previously used to enhance wastewater treatment with classification of grit for removal, high rate clarification, and microorganism metabolic selection for side stream treatment.

2.2.6.1 Grit Classifiers

Grit removal from influent wastewater is essential to minimize excessive wear/abrasion of pumps and reduce deposition in channels, basins, clarifiers, and digesters. Hydrocyclones can serve as a classifier wherein the inorganic is separated from organic material and influent wastewater via the underflow because of the density gradient.

2.2.6.2 High Rate Clarification

High rate clarification utilizes a ballast material and typically a chemical aid to form flocs which enhance settleability. The applications can function for primary, secondary, or tertiary settlers. The ballast material can consist of sand, magnetite, or a microcarrier and is separated from the floc after clarification via a hydrocyclone to be recycled to the start of the process.

2.2.6.3 Deammonification Sidestream Treatment

Patent US: 0198284 was filed August 2007 and granted August 2011 (Nyhuis, 2011). This patent applies hydrocyclones as external selectors for the development and retainment of granules for de-ammonifying activated sludge systems in which a portion of ammonia is converted to nitrite by AOBs, and then anaerobic ammonia oxidizing bacteria (anammox) convert the remaining ammonia and the nitrite to nitrogen gas. The hydrocyclones retain the anammox granules in the underflow.

3. Patent Associated with Mainstream Hydrocyclone Technology

3.1 Method and Apparatus for Wastewater Treatment Using External Selection

Patent: US 9,670,083 B2 was filed in June 2015 and granted June 2017 (Wett et al. 2017). The patent is based on utilizing a density-based gravimetric selector to promote or enhance Bio-P through intensification or granulation in an activated sludge process. The gravimetric selector is used for biological or physical selection. The activated sludge processes can be comprised of either anaerobic, anoxic, aerobic, or a combination.

3.2 Method and Apparatus for Wastewater Treatment Using Gravimetric Selection

Patent: US 0144836 A1 was filed November 2013 and granted May 2014 (Nyhuis et al., 2014). The patent is based on a gravity selector which retains solids with superior settling characteristics and reintroduces them to an activated sludge process. The activated sludge processes could be a membrane
bioreactor, suspended growth, granular sludge, integrated fixed-film, biological nutrient removal, aerobic digestion, anaerobic digestion, or a combination.
4. Methods

4.1 Hydrocyclone Installations at James River Wastewater Treatment Plant

4.1.1 Hydrocyclone Mainstream Operation

The mainstream inDENSE™ process provided by World Water Works (WWW) included eight 20 m³/hr hydrocyclones which were installed and continuously operated from June 2015 to February 2017 (Figures 4.1, 4.2). The hydrocyclone feed/RAS pumping system comprised of two Goulds 3656 centrifugal pumps controlled by variable frequency drives (VFD), two Dwyer digital pressure gauges, and two Rosemount magnetic flowmeters. Each pumping system fed a manifold consisting of four hydrocyclones, each with an isolation valve, allowing them to be placed in and out of service. The hydrocyclone pressure was monitored via a diaphragm analog gauge with ± 0.5 psi. Pressure would be changed by increasing or decreasing the pump speed. The adjustments could be performed manually or through automation controlled through the Emerson Ovation Distributed Control System (DCS). The underflow from the hydrocyclone was returned to the aeration tank influent channel where it combined with primary clarifier effluent (PCE) and RAS, and then distributed to the eight aeration basins. The overflow, which served as the WAS, discharged into a holding tank. The overflow was pumped from the holding tank to the GBTs for thickening. Alarms were established to shut the RAS feed pumps off if there was a high feed pressure reading or if the holding tank level increased beyond the established setpoint. To ensure proper fraction separation and operating efficiency for the hydrocyclones, the underflow and overflow mixed liquor were allowed to free flow into their respective basins to eliminate back pressure. The feed/RAS line and overflow/WAS line had flow meters therefore the underflow volumetric flow rate was the calculated difference. The number of cyclones in operation was dependent on the desired waste rate. The facility typically operated at a desired SRT of 2.8 to 5.0 days therefore; the minimum and maximum wasting rate of 0.30 and 0.55 MGD, respectively. To maintain the waste rate the hydrocyclones were placed in and out of service. Usually three to five hydrocyclones were in service while the others remained idle.
Figure 4.1: 20 m³ hr⁻¹ James River WWTP mainstream configuration (drawing courtesy of Robert A. Jones II, HRSD, 2017).

Figure 4.2: JRWWTP Process Overview with inDENSE™

Four nozzles with internal diameters of 25, 20, 18, and 15 mm were evaluated in conjunction with varying the feed pressures with initial short duration testing of an hour followed by continuous operation of at least two weeks to evaluate impact on overall plant performance. In Tables 4.1 and 4.2
the nozzle size and operating pressures for the short duration testing and continuous evaluation are listed. During the continuous operation evaluation, with the exception of a two-week study of concurrently operating the 15 and 18 mm nozzle, the nozzle sizes and operating pressures were the same.

**Table 4.1: Feed pressures and nozzle size evaluation grid for 20 m³ hr⁻¹ short duration testing**

<table>
<thead>
<tr>
<th>Nozzle (mm)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>20,23,25,27,30</td>
</tr>
<tr>
<td>20</td>
<td>20,23,25,27,30</td>
</tr>
<tr>
<td>18</td>
<td>20,23,25,27,30</td>
</tr>
<tr>
<td>15</td>
<td>20,23,25,27,30</td>
</tr>
</tbody>
</table>

**Table 4.2: Feed pressures and nozzle size evaluation grid for 20 m³ hr⁻¹ continuous operation.**

<table>
<thead>
<tr>
<th>Nozzle (mm)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>15</td>
<td>27</td>
</tr>
<tr>
<td>15</td>
<td>29</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

**4.1.2 Hydrocyclone Demonstration Manifold Operation**

A demonstration manifold was built to test multiple hydrocyclones simultaneously (Figure 4.3). The feed/RAS was pumped using one of the Goulds 3656 centrifugal pumps and the hydrocyclones would be placed into service by opening the isolation valves. Pressure was monitored utilizing a diaphragm analog gauge with ± 0.5 psi and was changed manually by increasing or decreasing the pump speed. The overflow and underflow mixed liquor from the hydrocyclones were separately isolated into 1.32 m³ totes marked with volume gradation lines.
Table 4.3 lists the hydrocyclones provided by WWW with nominally volumetric flow rate provided by the manufacturer, available nozzles, and operating feed pressures. The nozzle for the 10 m³ hr⁻¹ from manufacturer B was equipped with a soft nipple, which increased and decreased in diameter as the screw conical bottom was adjusted. Due to the internal design, measurements could not be taken of the actual diameter. Therefore, during the evaluation, the nozzle was opened half-way.

**Table 4.3: Hydrocyclones with volumetric flow rates, nozzle sizes, and operating pressures tested on the demonstration manifold.**

<table>
<thead>
<tr>
<th>Volumetric Rate m³ hr⁻¹</th>
<th>Nozzle Sizes mm</th>
<th>Operating Pressure psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer A</td>
<td>5</td>
<td>14, 13, 11, 9</td>
</tr>
<tr>
<td>Manufacturer B</td>
<td>5</td>
<td>4.8</td>
</tr>
<tr>
<td>Manufacturer B</td>
<td>10</td>
<td>Manually Adjustable</td>
</tr>
<tr>
<td>Manufacturer C</td>
<td>5</td>
<td>25, 22.5, 20, 17.5, 15, 12.5, 10, 8, 7, 5</td>
</tr>
<tr>
<td>Manufacturer C</td>
<td>10</td>
<td>25, 22.5, 20, 17.5, 15, 12.5, 8</td>
</tr>
<tr>
<td>Manufacturer D</td>
<td>5</td>
<td>6.5</td>
</tr>
<tr>
<td>Manufacturer D</td>
<td>10</td>
<td>6.5</td>
</tr>
</tbody>
</table>
4.1.3 Data Collection

Initial / Zone Settling Velocity Measurements (ISV / ZSV)

Measurements were conducted on the underflow, overflow, and feed fractions of the hydrocyclones as well as on the plant aeration basin effluent. The mixed liquor from each sample point was either diluted or concentrated to 2500 mg L\(^{-1}\) MLSS, which represents typical secondary treatment operating values at JRWWTP. The adjusted sample was settled in a 2 L graduated cylinder. A centimeter measuring tape was used to record height measurements of the settled sludge interface. The most linear slope determined by the entire data set was used to determine the ISV/ZSV in cm min\(^{-1}\) and m hr\(^{-1}\). In addition, SSV\(_5\) and SSV\(_{30}\) were used to find SVI\(_5\) and SVI\(_{30}\) for each mixed liquor fraction following the method of Mohlman, 1943.

Intrinsic Settling Classes (ISC) Analysis

The ISC method, developed by Mancell-Egala et al., 2014, was performed at discrete settling MLSS values for underflow, overflow, and feed fractions of the hydrocyclones and on plant aeration basin effluent. The sampling apparatus consisted of a 4L settling column with two sample collection ports each at 5 cm depth (Figure 4.4). The mixed liquor was diluted to approximately 100 to 300 mg L\(^{-1}\) using secondary clarifier effluent, poured into the settling apparatus, and allowed to settle for 20, 60, 120, or 300 seconds which correspond to critical settling velocities (CSV) of 9, 3, 1.5, 0.6 m hr\(^{-1}\) respectively. The difference between the initial and settled MLSS determined the percent removal based upon the different CSV.

Floc Density Measurements

Floc density measurements for aeration, underflow, and overflow samples were performed utilizing a methodology developed by Dammel and Schroeder (1991) in which a media gradient solution is created by diluting Percoll, a silica colloid solution, with a weak salt solution to mimic the ionic strength of the secondary clarifier effluent. A density gradient from 1.05 to 1.3 g mL\(^{-1}\) is formed when centrifuged at high g-forces. The stock isotonic Percoll (SIP) solution was created by diluting the concentrated Percoll with 1.5 M sodium chloride solution (NaCl) to a target osmolality of 525 mOsm kg H\(_2\)O\(^{-1}\). The solution was placed in two 15 mL tubes in which one of them had density marker beads and then centrifuged for 90 minutes at 17,000 x g. Upon completion, mixed liquor was added to a blank tube and was further centrifuged for 30 minutes at 400 g. The densities of the marker beads were: 1.02, 1.04, 1.06, 1.08, 1.09, and 1.13 g mL\(^{-1}\) which encompassed the typical span of mixed liquor and aerobic granular sludge densities (Sears et al., 2006). The density of the mixed liquor was determined by linear interpolation, comparing the height of the density marker beads to the isopycnic position of the mixed liquor band (Figure 4.5).
Biological Phosphorus Release and Uptake Rates

Kinetic activity batch experiments for PAO, GAO, dPAO were conducted on the underflow, overflow, and feed fractions of the hydrocyclones and on plant aeration effluent at ambient wastewater temperatures. In addition, a series of experiments was performed on sieved fractions of the underflow. The underflow was passed sequentially through 300, 106, and 53 μm sieves and the retainment captured was rehydrated with secondary clarifier effluent. A phosphorus release and uptake rates methodology was developed following guidance from WERF (2005) (Figure 4.6). For all test pH was maintained between 6.5 and 7.5. During aerobic testing, dissolved oxygen (DO) was provided with an air pump and diffuser stone targeting between 2 - 4 mg DO L⁻¹. Anaerobic conditions were established by thoroughly interspersing the mixed liquor on a stir plate and sparging with nitrogen and argon gas to ensure maximum release and uptake measurements; the mixed liquor was dosed with 10 mg L⁻¹ of PO₄³⁻-P solution and preaerated for 120 minutes. Then after anaerobic conditions were established through sparging, 100 mg L⁻¹ of COD solution was added, and testing conducted for 120 minutes. Samples were collected every 15 minutes for OP and sCOD analysis. The mixed liquor was then split in two aliquots where one was treated aerobically and the other dosed with 10 mg NO₃-N L⁻¹ solution to establish anoxic conditions. Samples were immediately filtered through 0.45μm cellulose membrane filters and analysis was performed with Test in Tubes (TNT) (HACH Company, Loveland, Colorado) and a spectrophotometer for NH₄-N, NO₃-N, NO₂-N, and OP.
Ammonia Oxidizing Bacteria and Nitrite Oxidizing Bacteria Uptake Rates

Kinetic activity batch experiments for AOBs and NOBs were conducted on the underflow, overflow, and feed fractions of the hydrocyclones and on plant aeration effluent at ambient wastewater temperatures. The mixed liquor was dosed with 20 mg L\(^{-1}\) of NH\(_4\)-N and 5 mg L\(^{-1}\) of NO\(_2\)-N solution and aerated for 60 minutes (Figure 4.7). For all test pH was maintained between 6.5 and 7.5. During aerobic testing, dissolved oxygen (DO) was provided with an air pump and diffuser stone targeting between 2 - 4 mg DO L\(^{-1}\). Samples were immediately filtered through 0.45µm cellulose membrane filters and analysis was performed with Test in Tubes (TNT) (HACH Company, Loveland, Colorado) and a spectrophotometer for NH\(_4\)-N, NO\(_3\)-N, and NO\(_2\)-N.
Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS) Analysis

Total suspended solids and volatile suspended solids analysis was performed following standard method 2540D and 2540E, respectively.

Total Phosphorus (TP) Analysis

Total phosphorus analysis was performed using HACH Test’N Tube (TNT) 845 with a range of 5.0 – 20.0 mg L⁻¹ PO₄-P. The TNT follows standard method 4500 in which the inorganic and organic phosphates are converted to orthophosphates through hydrolysis and digestion with heat, acid addition, and persulfate, respectively. The phosphomolybdenum blue method is used for the orthophosphates. Antimony phosphomolybdate complexes are formed by the ions reacting in an acidic solution with molybdate and antimony. The samples are analyzed at 880 nm on a spectrophotometer.

Orthophosphate (OP) Analysis

Orthophosphate analysis was performed using HACH Test’N Tube Plus 846 with a range of 1.6 – 30.0 mg L⁻¹ PO₄-P. The TNT follows standard method 4500 where vanadate-molybdate regent reacts with phosphate ions and then the samples are analyzed at 435 nm on a spectrophotometer.

Figure 4.7: Ammonia and nitrite oxidizing rate methodology schematic (drawing courtesy of Robert A. Jones II, HRSD, 2017).
**Ammonia (NH\textsubscript{4}-N) Analysis**

Ammonia analysis was performed using Hach Test’N Tube Plus 830, 831, and 832 with ranges of 0.015 – 2.0 mg L\textsuperscript{-1}, 1.0 – 12.0 mg L\textsuperscript{-1}, and 2.0 – 47.0 mg L\textsuperscript{-1} NH\textsubscript{4}-N, respectively. The TNT used EPA method 10205 where hypochlorite ions and salicylate ions react with ammonium ions in the presence of sodium nitroprusside to form indophenol blue which is analyzed at 690 nm on a spectrophotometer.

**Nitrate (NO\textsubscript{3}-N) Analysis**

Nitrate analysis was performed using the HACH Test’N Tube Plus 835. The range for analysis was 0.23 – 13.5 mg NO\textsubscript{3}-N L\textsuperscript{-1}. The TNT used EPA method 10206 where sulfuric and phosphoric acids react with nitrate ions. 2, 6-dimethylphenol forms 4-nitro-2, 6-dimethylphenol and was analyzed at 345 nm on a spectrophotometer. Nitrite concentration was measured before nitrate analysis. If detection was above 2.0 mg L\textsuperscript{-1}NO\textsubscript{2}-N, then approximately 10 mg of sulfamic acid was added to a 5.0 mL sample and allowed to react for 10 minutes to prevent nitrite being oxidized and causing interference on the nitrate analysis.

**Nitrite (NO\textsubscript{2}-N) Analysis**

Nitrite analysis was performed using the HACH Test’N Tube Plus 840. The range was 0.6 – 6.0 mg L\textsuperscript{-1} NO\textsubscript{2}-N and used EPA method 10237. In an acidic solution, aromatic amine reacts with nitrite ions to form diazonium salt where the colored complex are analyzed at 515 nm on a spectrophotometer.

**Chemical Oxygen Demand (COD)**

COD analysis was performed using HACH Test’N Tube 821 and 822. The ranges used where 3.0 - 150 mg L\textsuperscript{-1} and 0.0 - 1500 mg L\textsuperscript{-1}. The results from this method are reported as mg of O\textsubscript{2} consumed per liter of sample following EPA method 10211. Potassium dichromate reacts with the sample during the 2 hour 150 °C digestion period. Dichromate ion Cr\textsubscript{2}O\textsubscript{7}\textsuperscript{2-} reduces to chromic ion Cr\textsuperscript{3+}. The remaining yellow Cr\textsuperscript{6+} are measured at 348 nm on a spectrophotometer to determine the COD concentration in mgL\textsuperscript{-1}. Since the sample is filtered through 0.45 μm cellulose membrane filters, the value represents soluble COD (sCOD) concentration.
5. Results and Discussion

5.1 20 m$^3$ hr$^{-1}$ Hydrocyclone Mainstream Operation

5.1.1 Short Duration Nozzle and Pressure Evaluation

The short duration nozzle and pressure evaluation was conducted to alleviate the paucity of performance data for the 20 m$^3$ hr$^{-1}$ hydrocyclones on mainstream activated sludge. A performance evaluation to elucidate the balance of the maximum flow return with selection of active mixed liquor particles with the highest velocities was the strategy. The short duration testing consisted of one set of experiments in which hydrocyclones were operated at each nozzle size and pressure for one hour.

5.1.1.1 Hydraulic Percent and Initial/Zone Settling Velocities (ISV or ZSV) for the Overflow and Underflow Fractions.

The underflow volumetric return lessened with decreasing nozzle size at a constant feed pressure. In addition, the underflow volumetric return decreased with increasing pressure (Figure 5.1). The ISV for the underflow increased with decreasing nozzle size and moreover, the deviation from the overflow increased (Figure 5.2).
Changes to the sludge characteristics overtime and the subsequent impacts on the plant process could not be extrapolated from the short duration testing data set. Therefore, continuous hydrocyclone operation of at least two weeks with the different nozzle sizes and pressures was conducted.
5.1.2.1 Hydraulic and Mass Percent for the Overflow and Underflow Fractions

The underflow volumetric hydraulic based continuously monitored flow and mass split based in mixed liquor concentration decreased with decreasing nozzle size (Table 5.1). Overall, the mass percent of underflow returned when compared to the total inventory of bulk liquid mixed liquor in the aeration basins did not exceed 10% (Figures 5.3 and 5.4). The low percent return may have resulted in limited settling improvements in the low SRT system.

Table 5.1: Hydraulic and mass percent for hydrocyclone fractions from continuous operation nozzle and pressure evaluation.

<table>
<thead>
<tr>
<th>Nozzle mm</th>
<th>Pressure psi</th>
<th>Time Days</th>
<th>Underflow Hydraulic %</th>
<th>Overflow Hydraulic %</th>
<th>Underflow Mass %</th>
<th>Overflow Mass %</th>
<th>Underflow Mass: Hydraulic</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>23</td>
<td>180</td>
<td>17</td>
<td>83</td>
<td>21</td>
<td>79</td>
<td>1.24</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>150</td>
<td>18</td>
<td>82</td>
<td>21</td>
<td>79</td>
<td>1.17</td>
</tr>
<tr>
<td>20</td>
<td>23</td>
<td>90</td>
<td>6.1</td>
<td>94</td>
<td>8.5</td>
<td>92</td>
<td>1.39</td>
</tr>
<tr>
<td>18</td>
<td>25</td>
<td>30</td>
<td>4.4</td>
<td>96</td>
<td>9.3</td>
<td>91</td>
<td>2.11</td>
</tr>
<tr>
<td>15</td>
<td>25</td>
<td>60</td>
<td>5.1</td>
<td>95</td>
<td>18</td>
<td>82</td>
<td>3.53</td>
</tr>
<tr>
<td>15</td>
<td>27</td>
<td>30</td>
<td>2.4</td>
<td>98</td>
<td>17</td>
<td>83</td>
<td>7.08</td>
</tr>
<tr>
<td>15</td>
<td>29</td>
<td>180</td>
<td>2.4</td>
<td>98</td>
<td>13</td>
<td>87</td>
<td>5.42</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>180</td>
<td>2.5</td>
<td>98</td>
<td>9.3</td>
<td>91</td>
<td>3.72</td>
</tr>
</tbody>
</table>
Results and Discussion

Figure 5.3: Underflow percent return to total inventory of mixed liquor solids in the aeration basins.

Figure 5.4: Underflow MLSS versus underflow hydraulic percent return
5.1.3 Mixed Liquor Total Suspended Solids and Volatile Suspended Solids

The smaller nozzle diameters and higher pressure allowed for increased selection of particles in the underflow fraction (Table 5.2). The MLVSS decreased from ~ 73 % to 47 % in the underflow (Table 5.3); however, the Feed/RAS MLVSS concentrations did not decrease.

Table 5.2: Mixed liquor suspended solids for hydrocyclone fractions

<table>
<thead>
<tr>
<th>Nozzle mm</th>
<th>Pressure psi</th>
<th>Feed MLSS g L⁻¹</th>
<th>Underflow MLSS g L⁻¹</th>
<th>Overflow MLSS g L⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>23</td>
<td>4.82 ± 0.71</td>
<td>5.79 ± 1.10</td>
<td>4.59 ± 0.72</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>4.55 ± 0.83</td>
<td>5.30 ± 0.89</td>
<td>4.33 ± 0.73</td>
</tr>
<tr>
<td>20</td>
<td>23</td>
<td>4.33 ± 0.59</td>
<td>6.10 ± 1.40</td>
<td>4.29 ± 0.60</td>
</tr>
<tr>
<td>18</td>
<td>25</td>
<td>4.41 ± 0.43</td>
<td>10.0 ± 3.60</td>
<td>4.29 ± 0.63</td>
</tr>
<tr>
<td>15</td>
<td>25</td>
<td>4.24 ± 0.45</td>
<td>17.3 ± 5.15</td>
<td>4.08 ± 0.55</td>
</tr>
<tr>
<td>15</td>
<td>27</td>
<td>4.01 ± 0.65</td>
<td>20.1 ± 6.91</td>
<td>3.6 ± 0.71</td>
</tr>
<tr>
<td>15</td>
<td>29</td>
<td>4.45 ± 1.26</td>
<td>30.9 ± 8.00</td>
<td>4.08 ± 1.01</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>4.36 ± 0.28</td>
<td>36.1 ± 10.6</td>
<td>4.23 ± 0.24</td>
</tr>
</tbody>
</table>

Table 5.3: Mixed liquor volatile suspended solids for hydrocyclone fractions from nozzle and pressure evaluation

<table>
<thead>
<tr>
<th>Nozzle mm</th>
<th>Pressure psi</th>
<th>Feed/RAS MLVSS %</th>
<th>Underflow MLVSS %</th>
<th>Overflow MLVSS %</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>23</td>
<td>78 ± 2.0</td>
<td>73 ± 2.4</td>
<td>81 ± 2.6</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>76 ± 4.2</td>
<td>72 ± 4.0</td>
<td>71 ± 4.4</td>
</tr>
<tr>
<td>18</td>
<td>25</td>
<td>81 ± 1.4</td>
<td>54 ± 5.4</td>
<td>83 ± 0.8</td>
</tr>
<tr>
<td>15</td>
<td>25</td>
<td>79 ± 1.0</td>
<td>42 ± 0.5</td>
<td>82 ± 1.5</td>
</tr>
<tr>
<td>15</td>
<td>27</td>
<td>80 ± 0.5</td>
<td>40 ± 2.9</td>
<td>82 ± 0.5</td>
</tr>
<tr>
<td>15</td>
<td>29</td>
<td>77 ± 2.8</td>
<td>44 ± 5.5</td>
<td>79 ± 2.4</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>78 ± 0.9</td>
<td>47 ± 3.4</td>
<td>78 ± 1.3</td>
</tr>
</tbody>
</table>
5.1.4 Mixed Liquor Density Measurements

The aeration basins mixed liquor density before startup of the hydrocyclone operation was ~ 1.03 g mL\(^{-1}\) (Welling, 2015). With continued operation, the density increased to 1.05 – 1.06 g mL\(^{-1}\) (Figure 5.4). The overflow fraction was less dense with consistent values of 1.03 g mL\(^{-1}\). The underflow fraction was more dense and changing to the 15 mm nozzle, two distinct bands formed. The first band was similar to aeration basin mixed liquor in appearance and with an average density of 1.06 g mL\(^{-1}\) while the second band appeared to be particles with values of with an average density 1.10 g mL\(^{-1}\).

![Graph of density measurements for the overflow and underflow fractions and the aeration basin mixed liquor.](image)

**Figure 5.5:** Density measurements for the overflow and underflow fractions and the aeration basin mixed liquor.

5.1.5 Initial/Zone Settling Velocities (ISV or IZV)

The ISVs for the underflow, overflow, and aeration basin mixed liquor are listed in Table 5.4. During the hydrocyclone evaluation, the overflow remained below the typical secondary clarifier solids settling design of 1.0 m hr\(^{-1}\). The underflow exhibited good settling of 1.5 to 4.0 m hr\(^{-1}\) with the 25 and 18 mm nozzle. Extremely good settling of 25 m hr\(^{-1}\) occurred with the 15-mm nozzle and increased feed operation pressure of 29 psi. The mainstream process settling improved with a 1.0 to 1.5 m hr\(^{-1}\) increase with the operation of the 15-mm nozzle. The increase in ISV corresponded to the decrease in MLVSS. In order to test if the improvements were due to the hydrocyclone operations, the hydrocyclones were shut off for 30 days from December 2016 to January 2017. ISV measurements were normalized to average SRT at the time by dividing the number of days passed by 3.5 days. In less than one SRT period, the aeration basin settling declined (Figure 5.5). Within 2.3 SRTs, the ISVs observed had decreased to below 1.0 m hr\(^{-1}\). Once the hydrocyclones were restarted, the ISV improved to above 1.0 m hr\(^{-1}\) within 2.7 SRTs.
Table 5.4: Initial/Zone settling velocities for underflow, overflow, and aeration basin mixed liquor from the nozzle and pressure evaluation.

<table>
<thead>
<tr>
<th>Nozzle mm</th>
<th>Pressure psi</th>
<th>Underflow ISV m hr⁻¹</th>
<th>Overflow ISV m hr⁻¹</th>
<th>Mainstream Aeration Effluent m hr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>23</td>
<td>2.79 ± 1.28</td>
<td>0.69 ± 0.55</td>
<td>1.85 ± 0.77</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>1.65 ± 0.71</td>
<td>0.34 ± 0.17</td>
<td>1.23 ± 0.60</td>
</tr>
<tr>
<td>18</td>
<td>25</td>
<td>3.87 ± 0.51</td>
<td>0.11 ± 0.07</td>
<td>2.14 ± 0.49</td>
</tr>
<tr>
<td>15</td>
<td>25</td>
<td>9.68 ± 0.62</td>
<td>0.24 ± 0.20</td>
<td>2.29 ± 0.39</td>
</tr>
<tr>
<td>15</td>
<td>27</td>
<td>14.8 ± 1.96</td>
<td>0.19 ± 0.18</td>
<td>3.36 ± 0.71</td>
</tr>
<tr>
<td>15</td>
<td>29</td>
<td>25.2 ± 2.23</td>
<td>0.49 ± 0.34</td>
<td>2.59 ± 0.56</td>
</tr>
</tbody>
</table>

Figure 5.6. ISV measurements for the aeration basin normalized to a 3.5-day SRT during an evaluation of shutting the hydrocyclones off.
5.1.6 Intrinsic Settling Class Analysis

The intrinsic settling classes are separated into six settling velocity bins to include flocs, aggregates, and large aggregates/granules. The RAS/feed was well distributed across all the settling class bins (Figure 5.6). 70% of the overflow was classified into the less than 1.0 m hr\(^{-1}\) settling class (Figure 5.7). 50% of underflow initially was classified into the greater than 3.0 m hr\(^{-1}\), and with continued operation the percent increased to greater than 75% with the large portion in the greater than 9 m hr\(^{-1}\) indicating an increase in retention of floc forming organisms (Figure 5.8). The aeration effluent was similar in to the RAS/Feed in distribution in the settling class bins (Figure 5.9).

![Intrinsic Settling Class Analysis Chart]

Figure 5.7: Feed/RAS mixed liquor intrinsic settling class percent bins.
Results and Discussion

Figure 5.8: Overflow mixed liquor intrinsic settling class percent bins.

Figure 5.9: Underflow mixed liquor intrinsic settling class percent bins.
5.1.7 Five and Thirty Minute Sludge Volume Index

Table 5.6 lists the underflow and overflow SVI$_5$ and SVI$_{30}$ during the nozzle and operating feed pressure evaluation. The overflow exhibited poor settling regardless of nozzle size or pressure. The 15-mm nozzle produced an underflow fraction with superior settling characteristics and at higher pressures the SVI$_5$ and the SVI$_{30}$ were comparable signifying selection of well settling particles.

Table 5.6: SVI$_5$ and SVI$_{30}$ for the underflow and overflow fractions

<table>
<thead>
<tr>
<th>Nozzle Size</th>
<th>Operating Pressure</th>
<th>Underflow SVI$_5$</th>
<th>Underflow SVI$_{30}$</th>
<th>Overflow SVI$_5$</th>
<th>Overflow SVI$_{30}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>psi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>23</td>
<td>187 ± 74</td>
<td>82 ± 44</td>
<td>343 ± 44</td>
<td>211 ± 77</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>306 ± 66</td>
<td>158 ± 92</td>
<td>376 ± 92</td>
<td>274 ± 88</td>
</tr>
<tr>
<td>18</td>
<td>25</td>
<td>144 ± 28</td>
<td>64 ± 5.0</td>
<td>391 ± 5.0</td>
<td>335 ± 30</td>
</tr>
<tr>
<td>15</td>
<td>25</td>
<td>28 ± 10</td>
<td>16 ± 13</td>
<td>385 ± 13</td>
<td>289 ± 75</td>
</tr>
<tr>
<td>15</td>
<td>27</td>
<td>19 ± 4.0</td>
<td>10 ± 5.0</td>
<td>382 ± 5.0</td>
<td>278 ± 58</td>
</tr>
<tr>
<td>15</td>
<td>29</td>
<td>10 ± 1.0</td>
<td>5.0 ± 4.0</td>
<td>353 ± 4.0</td>
<td>262 ± 112</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>8.0 ± 1.0</td>
<td>5.0 ± 2.0</td>
<td>349 ± 22</td>
<td>251 ± 98</td>
</tr>
</tbody>
</table>

Figure 5.10: Aeration basin mixed liquor intrinsic settling class percent bins.
5.1.8 Kinetic Activity Measurements

Biological phosphorus release and uptake activity measurements did not indicate a selectivity to either the overflow or underflow fraction on a consistent basis (Figure 5.10). From December 2015 to August 2016 BioP was sluggish at the facility due to excessive ferric salt addition and ongoing construction activities that impacted overall process. Sieve analysis was performed for three different experiments occurring July through August 2016. The underflow did not demonstrate a particle size correlation to higher PAO activity which could indicate larger cluster of PAOs exist along with dispersed growth (Figure: 5.11). AOB and NOB activity measurements did not suggest a selectivity to either the overflow or underflow fraction; therefore, hydrocyclones do not waste nitrifying biomass in an IFAS configuration (Figure 5.12). OHO measurements also demonstrated a lack of selectivity for either overflow or underflow reporting.

![Graph showing biological phosphorus release and uptake activity measurements for underflow and overflow.](image_url)

**Figure 5.11:** Biological phosphorus release and uptake activity measurements for underflow and overflow.
Results and Discussion

Figure 5.1: Biological phosphorus release and uptake activity uptake data for the underflow and sieve fractions

Underflow or Sieve Size (μm)

Figure 5.12: Biological phosphorus release and uptake activity uptake data for the underflow and sieve fractions

Figure 5.13: AOB and NOB activity measurements underflow, overflow, and aeration basin mixed liquor
5.1.9 Simultaneous Operation Comparative Study Between the 18 mm and 15 mm Nozzle

A simultaneous comparison study between the 18 and 15-mm nozzle was conducted to determine the extent of external and metabolic selection based on nozzle diameter while being fed the same RAS to reduce ambiguity.

The 18-mm nozzle, when compared to the 15-mm nozzle, doubled the ISV for the underflow fraction indicating superior external selection (Figure 5.13). Biological phosphorus release and uptake activity was slightly greater with the 15 mm nozzles indicating the potential for beneficial changes in PAO metabolic selection (Figure 5.14). AOB and NOB activity was slightly greater with the 18 mm nozzles indicating the probability for positive changes in metabolic selection (Figure 5.15).

Figure 5.14: Initial settling velocities the overflow and underflow from the 18 mm and 15 mm nozzles
Figure 5.15: Biological phosphorus release and uptake activity for the plant aeration basin, overflow and underflow from the 18 mm and 15 mm nozzles.

Figure 5.16: AOB and NOB activity for the plant aeration basin, overflow and underflow from the 18 mm and 15 mm nozzles.
5.1.10 Mainstream Hydrocyclone Operation Impact on Overall Plant Process

The aeration basin MLVSS remained within typical operation concentrations signifying that an accrual of inert materials did not occur (Figure 5.16).

![Graph showing plant aeration basin MLVSS.](image)

**Figure 5.17: Plant aeration basin MLVSS.**

The 5 and 30-minute SVI did not improve with the continuous operation of the 25 mm nozzles when compared to the yearly average for 2013 and 2014; however, usage of the 15-mm nozzle led to an ~30 g mL\(^{-1}\) decrease (Table 5.8).

**Table 5.8: Comparison of SVI\(_5\) and SVI\(_{30}\) for plant aeration basin mixed liquor based prior to and subsequent to hydrocyclone operation at the JRWWTP.**

<table>
<thead>
<tr>
<th>Nozzle Size</th>
<th>SVI(_5)</th>
<th>SVI(_{30})</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>g mL(^{-1})</td>
<td>g mL(^{-1})</td>
</tr>
<tr>
<td>Pre-cyclone 2013</td>
<td>268 + 53</td>
<td>141 + 34</td>
</tr>
<tr>
<td>Pre-cyclone 2014</td>
<td>281 + 48</td>
<td>145 + 28</td>
</tr>
<tr>
<td>25</td>
<td>281 + 51</td>
<td>145 + 22</td>
</tr>
<tr>
<td>18</td>
<td>260 + 38</td>
<td>130 + 16</td>
</tr>
<tr>
<td>15</td>
<td>223 + 21</td>
<td>118 + 11</td>
</tr>
</tbody>
</table>

Results and Discussion
Improvements in SVI prompted the elimination of polymer addition to the secondary clarifiers while still maintaining low effluent TSS concentrations unless plant influent flows were elevated due to wet weather events (Figure 5.17).

![Graph](image)

**Figure 5.18:** Influent and final effluent TSS concentrations and polymer addition to the secondary clarifiers with continuous hydrocyclone use.

Welling, 2015 indicted a loss of BioP prior to the implementation of hydrocyclones; however, continuous operation led to stabilized performance (Figure 5.18). Furthermore, activity measurements revealed ~ 25 to 35% of the phosphorus uptake was attributed to dPAOs based on the anoxic uptake to total uptake determined during the kinetic activity measurements, which was slightly higher than formal Bio-P treatment facilities in the region based on a single kinetic activity measurement (Figures 5.18 and Figures 5.19). Stabilization of Bio-P led to an overall reduction of ferric addition to the secondary clarifiers while maintaining a high total phosphorus removal efficiency with sidestream management (Figure 5.20, Figure 5.21).
Results and Discussion

Figure 5.19: Biological phosphorus release and uptake measurements at JRWWTP

Figure 5.20: Biological phosphorus release and uptake measurements from WWTPs in the region

Figure 5.21: Total phosphorus removal and ferric salt addition to primary and secondary clarifiers.
5.2 Hydrocyclone Demonstration Manifold

The assessment of the 20 m hr\(^{-1}\) cyclone suggested the underflow portion, while exhibiting improved settling characteristics and the potential for stabilization of Bio-P, did not have sufficient volumetric mass return of the underflow to greatly improve SVI\(_{30}\), thus prohibiting a comprehensive evaluation of the full benefits of hydrocyclones on a plug flow, short SRT IFAS system. Since it was hypothesized that different cyclone geometries would provide an increase in the underflow return, a technology evaluation of hydrocyclones from various manufactures was performed. All the testing was short duration focusing on mass and hydraulic percent fractions and ISV measurements. From these data, the number of hydrocyclones needed to maintain the average waste rate of 0.45 MGD and the percent of underflow volumetric return to total aeration basin mixed liquor was predicted.

5.2.1 Initial Settling Velocities, Hydraulic and Mass Split for the Overflow and Underflow Fractions for Each Manufacturer

Manufacturer A provided a 5 m\(^3\) hr\(^{-1}\), 0.60 L hydrocyclone with a 14, 13, 11, and 9 mm nozzle and a recommended feed operating pressure of 30 psi. In Figure 5.22 the hydraulic, mass, and ISV for the overflow and underflow are summarized. Based on the 14, 13, 11, and 9 mm nozzle the underflow volumetric percent return to total inventory would be ~ 31, 30, 24, and 13; respectively. The hydrocyclone provided good selection with the smaller nozzles.
Manufacturer B provided a 5 m$^3$ hr$^{-1}$, 0.90 L with a 4.8 mm nozzle. A recommended operating feed pressure was not provided therefore it was evaluated at 20, 30, and 40 psi. The 4.8 mm nozzle resulted in aggressive selection of fast settling particles but had low underflow hydraulic and mass percent (Figure 5.23). The various pressures did not cause significant changes to mass, hydraulics, or ISVs for the underflow or overflow.

Figure 5.24: Manufacturer B 5 m$^3$ hr$^{-1}$ ISV, mass, and hydraulic percent
Manufacturer B also provided a 10 m$^3$ hr$^{-1}$, 3.0 L with manually adjustable nozzle which was opened half-way during the evaluation. The recommended operating feed pressure was 30 psi. The mass, hydraulic, and ISVs for the underflow and overflow are listed in Table 5.9. The underflow mass return was low with poor particle selection.

Table 5.9: Manufacturer B 10 m$^3$ hr$^{-1}$ ISV, mass, and hydraulic percent for underflow and overflow.

<table>
<thead>
<tr>
<th>Nozzle Position</th>
<th>Underflow Mass %</th>
<th>Underflow Hydraulic %</th>
<th>Overflow Mass %</th>
<th>Overflow Hydraulic %</th>
<th>Underflow ISV m hr$^{-1}$</th>
<th>Overflow ISV m hr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-opened</td>
<td>12</td>
<td>10</td>
<td>88</td>
<td>90</td>
<td>2.28</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Manufacturer C provided a 5 m$^3$ hr$^{-1}$ with a 25, 22.5, 20, 17, 15, 12.5, 10, 8, 7, and 5 mm nozzle with a recommended operating pressure of 26 psi. The large selection of nozzles provided versatility allowing for a selection of hydraulic and mass percent return for the underflow (Figure 5.24). The 20, 17.5, 15, 12.5, and 10 mm nozzles were further evaluated at 20, 23, 26, and 30 psi with ISV measurements to discern if optimization was probably and as confirmation of hydraulic and mass percent return for the underflow. Figures 5.25, 5.26, 5.27, 5.28, and 5.29 for the 20, 17.5, 15, 12.5, and 10 mm, respectively, confirm the hydraulic and mass percent return for underflow and indicate an operating feed pressure from 23 – 26 psi provides a better selection for faster settling particles.

Figure 5.25: Manufacturer C 5 m$^3$ hr$^{-1}$ mass and hydraulic percent for underflow and overflow.
Figure 5.26: Manufacturer C 5 m³/hr ISV for underflow and overflow

Figure 5.27: Manufacturer C 5 m³/hr ISV for underflow and overflow per operating feed
Results and Discussion

Figure 5.28: Manufacturer C 5 m$^3$ hr$^{-1}$ ISV for underflow and overflow with the 15-mm nozzle

Figure 5.29: Manufacturer C 5 m$^3$ hr$^{-1}$ ISV for underflow and overflow the 12.5 mm nozzle.
Figure 5.30: Manufacturer C 5 m$^3$ hr$^{-1}$ ISV for underflow and overflow with the 10mm nozzle.

The 5 m$^3$ hr$^{-1}$ hydrocyclone from manufacture C could be converted to a 10 m$^3$ hr$^{-1}$ by switching the 18-mm vortex finder to a 25-mm and operating at 43 psi. In addition, a 205-mm extension piece was added and evaluated at an operating pressure of 41 psi to test the hypothesis whether increased HRT provides increased selection of particles. The 10 m$^3$ hr$^{-1}$ hydrocyclone demonstrated similar versatility as the 5 m$^3$ hr$^{-1}$ one regarding hydraulic and mass percent return and ISVs (Figure 5.30, 5.31). The extension piece increased the HRT by 0.34 seconds for the 10 m$^3$ hr$^{-1}$ hydrocyclone, which provided approximately an additional 5% of underflow mass return demonstrating increased HRT (Figure 5.32).
Figure 5.31: Manufacturer C 10 m$^3$ hr$^{-1}$ ISV, mass and hydraulic percent for underflow and overflow per nozzle size with HRT 0.63 of seconds.

Figure 5.32: Manufacturer C 10 m$^3$ hr$^{-1}$ ISV, mass and hydraulic percent for underflow and overflow per nozzle size with HRT of 0.97 seconds.
Manufacturer D provided a 5 m³ hr⁻¹ and a 10 m³ hr⁻¹ hydrocyclone with a 6.5 mm nozzle and a recommended operating feed pressure of 22 psi. The mass, hydraulic, and ISVs for the underflow and overflow are listed in Table 5.10. The small diameter caused a low underflow percent return. The 5 m³ hr⁻¹ style would require 10-20 units and would only provide a 2% underflow mass percent return to total inventory. The 10 m³ hr⁻¹ style would require 5-10 units for SRT control and would only provide 1% under volumetric percent return to total inventory.

Table 5.10: Manufacturer D: 5 m hr⁻¹ and 10 m hr⁻¹ ISV, mass and hydraulic

<table>
<thead>
<tr>
<th>Nozzle Size mm</th>
<th>Volumetric Rate m³ hr⁻¹</th>
<th>Underflow Mass %</th>
<th>Overflow Mass %</th>
<th>Underflow Hydraulic %</th>
<th>Overflow Hydraulic %</th>
<th>Underflow ISV m hr⁻¹</th>
<th>Overflow ISV m hr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>5</td>
<td>8</td>
<td>92</td>
<td>5</td>
<td>95</td>
<td>1.46</td>
<td>0.23</td>
</tr>
<tr>
<td>6.5</td>
<td>10</td>
<td>4</td>
<td>96</td>
<td>3</td>
<td>97</td>
<td>2.09</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The technology evaluation indicated a wide range of variation for ISVs, mass and hydraulic splits. The impact on selection based on hydrocyclone geometry and operating pressure is not well understood. Focusing on the data collected during the short duration evaluation indicates a smaller volumetric hydrocyclone with proper nozzle selection could potentially lead to a 30 – 40% percent mass return of good settling sludge. Long-term evaluation would be needed to assess the full impact on the metabolic selection and overall plant performance.
6. Conclusion and Engineering Significance

6.1 Conclusion and Engineering Significance

The 20 m³/hr hydrocyclones exhibited the ability to serve as a classifying external selector with a cut point which provides excellent selection for superior settling particles. Optimal selection of superior settling material required a small nozzle diameter which ultimately led to a minimal mass percent return due to reductions in the hydraulic percent reporting to the underflow. Because of the low mass return the percent of underflow inventory when compared to the total activated sludge rarely exceeded 10% consequently limiting the overall impact on a short SRT fixed film process. The larger nozzles provide an increased mass percent return; however, the selected solids for the underflow did not exhibit exceptional settling characteristics. Considering the potential destruction of flocs due to the shear created from the hydrocyclones, a balance of excellent selection and percent mass return is desirable.

The results from the demonstration manifold indicated either a 5 m³/hr or 10 m³/hr volumetric hydrocyclone could provide an increased underflow mass percent with good settling characteristics. Because of the volume required for wasting, a bank of 10 m³/hr hydrocyclones may be a better option cost and operation-wise because of fewer units would be needed for the installation. In addition, the demonstration manifold provided insight to the available hydrocyclone technologies and further enhanced the understanding of nozzle diameter, operating pressure, and HRT.

In addition, external selection the 20 m³/hr demonstrated a slight propensity for metabolic selection based upon nozzle diameter. While the hydrocyclones stabilized weak Bio-P when compared to data collect by Welling, 2015 before the implementation. The hydrocyclone may provide material that could be used as AGS core material, but they did not seem to form granules which would contain the much-needed formal anaerobic zone. A formal Bio-P process would allow for a more robust PAO population which could potentially allow for the foundation for aerobic granules through enhanced metabolic selection.

In the current configuration, substrate diffusion for the underflow is diminished due to intermingling with the RAS. Research indicates a 0.2 g rbCOD/g VSS-d F:M is essential for granule formation (Sturm et al., 2017) however the current design at JRWTTP provides an approximate 0.08 F:M g rbCOD/g VSS-d. In order to increase the potential for granulation, adequate contact time should be provided by allowing the underflow to mix with PCE before intermingling with the RAS. The increase in substrate gradient would penetrate deeper into the granule forming a more stable structure by minimizing internal hydrolysis and boost the metabolic selection by forming ideal conditions for PAOs and dPAOs.

The installation of the 20 m³/hr hydrocyclone was a low maintenance, low capital cost technology that provided marginal settling benefits which allowed for reductions in polymer addition to the secondary clarifiers, stabilized weak Bio-P leading to a decrease in ferric salt addition to the secondary clarifiers.
7. References


Dawes, E.A., Senior, P.J. (1972). The Role and Regulation of Energy Reserve Polymers in Microorganisms. Advance Microbiology Physiology (10) 135-266.


References


8. VITA

Education

- Virginia Wesleyan College, Virginia Beach, VA - Bachelors of Earth and Environmental Science, 2009
- North Carolina State University, Raleigh, NC - Certificate in GIS, 2013
- North Carolina State University, Raleigh, NC - Masters of Environmental Science, 2014
- Old Dominion University, Norfolk, VA - Master of Environmental Engineering, 2018

Publications/Presentations


Work History

- Dept. of Earth & Environmental Science, Virginia Wesleyan University; 2009 – 2017
- Hampton Roads Sanitation District; 2009 – 2017
- Hazen and Sawyer; 2017 – current