Inducing granulation within a full-scale activated sludge system to improve settling

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ABSTRACT

Most cold-climate biological nutrient removal facilities experience poor settling mixed liquor during winter, resulting in treatment capacity throughput limitations. The Metro Wastewater Reclamation District in Denver, Colorado, operated two full-scale secondary treatment trains to compare the existing biological nutrient removal configuration (Control) to one that was modified to operate with an anaerobic selector and with hydrocyclone selective wasting (Test) to induce granulation. Results from this evaluation showed that the Test achieved significantly better settling behaviour than the Control. The difference in the mean diluted SVI_{30} between the Test and Control were statistically significant ($P < 0.05$), with values of 77 ± 17 and 135 ± 25 mL/g observed for the Test and Control respectively. These settling results were accompanied by differences in the particle size distribution, with notably higher settling velocities commensurate with increasing particle size. The degree of granulation observed in the Test train was between 32 and 56% of the mass greater than $\geq 250\ \mu m$ in particle size whereas 16% of the mixed liquor in the Control was $\geq 250\ \mu m$ over the entire study period. The improved settling behaviour of the Test configuration may translate into an increase of secondary treatment capacity during winter by 32%.

Key words | aerobic granular sludge, continuous flow reactor, full-scale, granules, hydrocyclone, settleability

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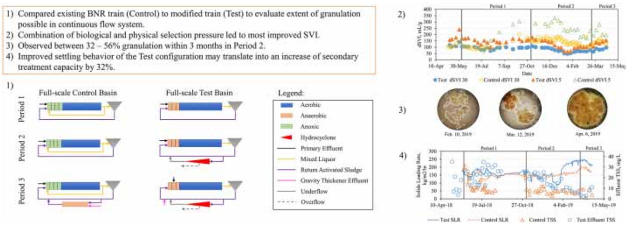
HIGHLIGHTS

- Inducing granulation in a full-scale continuous flow activated sludge system was possible with the application of both biological and physical selection pressures.
- Observations in this study could translate to a cost effective intensification solution versus traditional expansion for WRRFs evaluating capacity needs.

GRAPHICAL ABSTRACT



1) Compared existing BNR train (Control) to modified train (Test) to evaluate extent of granulation possible in continuous flow system.
2) Combination of biological and physical selection pressure led to most improved SVI.
3) Observed between 32 – 56% granulation within 3 months in Period 2.
4) Improved settling behavior of the Test configuration may translate into an increase of secondary treatment capacity by 32%.

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INTRODUCTION

The Robert W. Hite Treatment Facility (Hite treatment facility) is an 833 million litre per day (MLD) water resource recovery facility (WRRF) owned and operated by the Metro Wastewater Reclamation District (District) that serves a 2.0 million population equivalent in metropolitan Denver, Colorado. The Hite treatment facility has two parallel liquid treatment complexes (North and South), and a centralized solids treatment complex (Figure 1). The North Complex, which is the focus area of this paper, uses a side-stream anaerobic reactor as a biological selector for phosphorus accumulating organisms (PAOs), which supplements the mainstream Modified Ludzack-Ettinger (MLE) process to achieve nitrogen and enhanced biological phosphorus removal (EBPR).

The North Complex was constructed in the late 1960s to accomplish basic secondary treatment. The clarifier side water depth is 3.05 metres, which is shallow compared to typical design depths of 4.3 to 4.9 metres (Ahuja & Griborio 2017). These shallow North Complex clarifiers must operate consistently around their maximum rated design capacity of 147 kg/m^2/d to sustain the plant-rated 833 MLD capacity and operate at the solids retention time needed for year-round nitrogen removal.

There has been a growing interest in aerobic granular sludge (AGS) given the reported improvements in settleability in laboratory-scale studies with sequencing batch reactors (SBR) (Kreuk *et al.* 2005; Ji *et al.* 2009; Gao *et al.* 2011). However, few pilot studies on both SBR and continuous flow configurations have been performed (Pishgar *et al.* 2019), and full-scale application of AGS is limited to predominantly SBR configurations (Kent *et al.* 2018). Due to the lack of continuous flow full-scale applications of AGS, the authors opted to evaluate the impact of selective pressures in a full-scale trial. While there are configuration

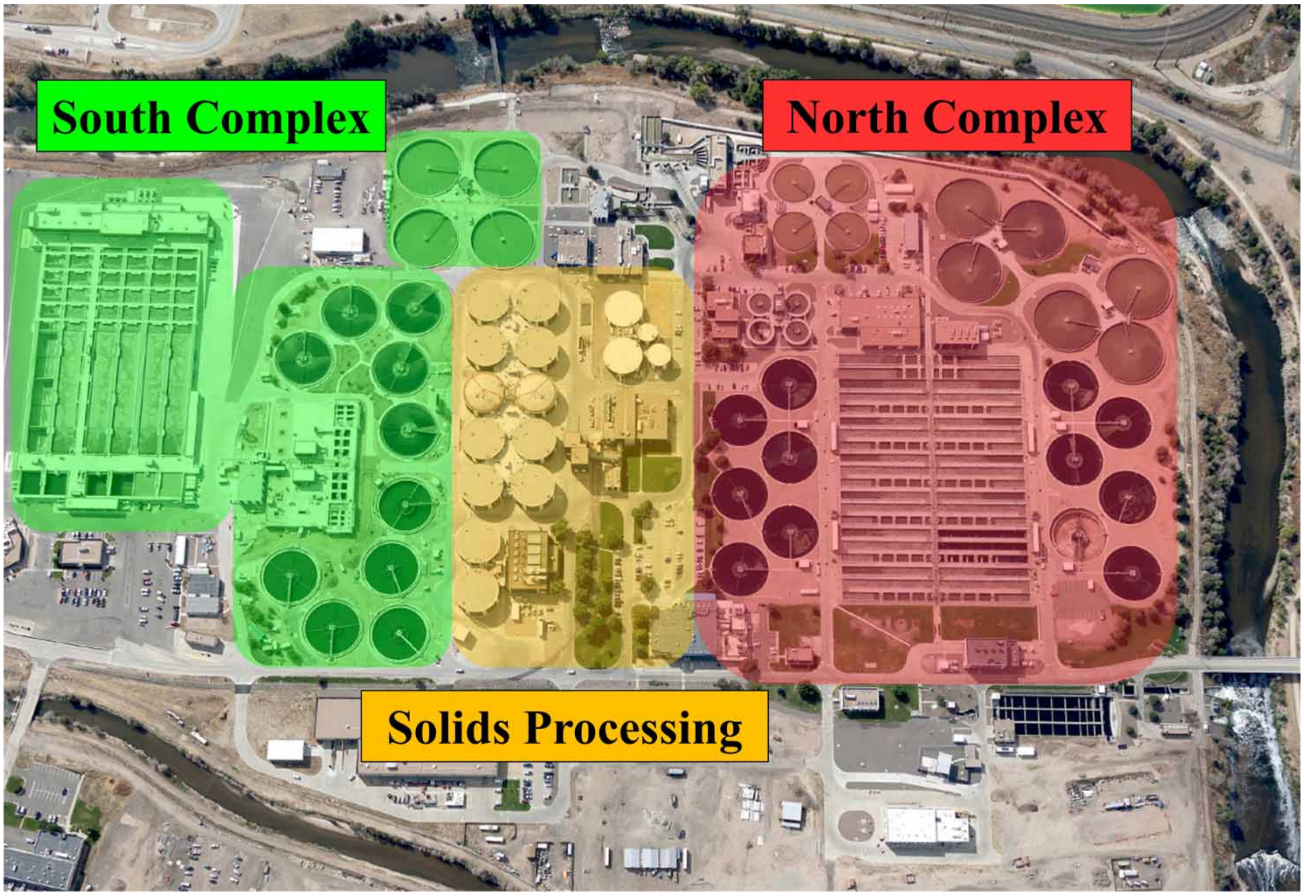

Figure 1 | The Robert W. Hite treatment facility.

differences between AGS and a continuous flow system, fundamental control mechanisms learned from AGS research are applied in this study.

Granules are distinguished from floc by being defined as particles larger than 0.2 mm in diameter. To form smooth and compact granules, typically higher shear is required to maintain a smooth granule structure. Granular sludge settles significantly faster than activated sludge, and typically an AGS SVI_5 is comparable to SVI_{30} in conventional activated sludge (Kreuk *et al.* 2005). Key selective pressures documented to promote granule formation and retention are as follows: (1) High fraction of readily biodegradable chemical oxygen demand (rbCOD) in the influent stream. A compact granular particle is dependent on the degree of extracellular polymeric substance (EPS) production (Mcswain *et al.* 2005). In a pilot study evaluating the impact of food to micro-organism (F/M) ratio on EPS production in AGS, it was observed that EPS content and settling velocity linearly increases with increasing F/M ratio (Sturm *et al.* 2017). It was reported by Sturm *et al.* that EPS production and the intrinsic settling velocity was maximized at an F/M ratio of ~0.2 mg rbCOD/mg VSS/d. At these higher F/Ms, the resulting carbon gradient results in fully penetrating substrate conditions into the granule structure and avoids diffusion limiting conditions. Floc and filamentous bacteria can typically out-compete granules under rbCOD-limited conditions due to mass transfer limitations, which can result in granule instability, causing elevated effluent total suspended solids (TSS) and worsening settleability (Layer *et al.* 2019). (2) A physical selection pressure for larger, denser solids such as hydrocyclones. As granules begin to form, physical selection becomes possible due their increased density relative to more buoyant floc particles. It has been reported that selectively wasting flocs reduces competition between granules and floc particles for the rbCOD (Loosdrecht *et al.* 2005). (3) Granule growth requires the presence of electron acceptors such as oxygen, nitrate, and nitrite, and they must be present in quantities great enough to fully diffuse into the granule structure. Electron acceptor-limited conditions can lead to granule instability (Kreuk *et al.* 2007). (4) Elevated hydrodynamic shear must be present in order to maintain smooth and compact granule structures, which has been reported to facilitate settling and substrate diffusion into the granule (Kreuk *et al.* 2005; Figdore 2017).

Due to reported successful uses of hydrocyclones to gravimetrically retain granules in deammonification systems (Klein *et al.* 2012; Wett *et al.* 2015), the authors opted for this technology for selective wasting. Hydrocyclones operate with no moving parts, and achieve separation through centrifugal forces and their shape. Return activated sludge (RAS) is fed tangentially into the hydrocyclone at a target feed pressure. As the fluid velocity increases within the body of the hydrocyclones, the denser particles are forced towards the outer perimeter of the hydrocyclone before exiting in the underflow. The lighter solids remain in the inner vortex of the hydrocyclone, and are forced upwards to exit in the overflow (Bradley 1965).

One of the 12 three-pass North Complex secondary aeration basins (i.e. Test) was configured for the study independent and yet parallel to the rest of the North Complex secondary treatment system. The Test train receives its proportion of the same primary effluent as is received by the remaining basins. To promote granulation, modifications to the Test basin include: (1) incorporation of a front-end zone where the RAS and hydrocyclone underflow recycle is introduced to primary effluent, creating a high gradient F/M condition, and (2) installation of hydrocyclones to facilitate a physical selective pressure towards retention of granules and wasting out of floc particles. The purpose of this paper is to share observations from this effort to induce granulation in a full-scale activated sludge system.

MATERIALS AND METHODS

Operations

Two identically sized basins (a Test and Control) were operated from May 7, 2018 to April 19, 2019. The Test basin was modified to be completely isolated from the remainder of the North Complex, including a separate primary effluent pumping station designed to mimic full-scale diurnal flow patterns. Both the Control and Test basins were operated according to the conditions summarized in Table 1 across three operating periods.

From May 7, 2018 until June 5, 2018, both the Test and Control basins were operated using commingled solids in a MLE configuration with surface wasting, which is wasting solids from the surface of the aeration basin versus traditional wasting from the clarifier. Period 1: The goal of Period 1 was to compare the Control to the Test basin configured with a biological selector. On June 5, 2018 the Test basin solids were isolated from the rest of the commingled North Complex solids and operated in an anaerobic-oxic (AO) process configuration with traditional wasting. The Control basin remained in the MLE configuration. Period

Table 1 | Key operating conditions for test and control secondary treatment trains

	Phase	**Period 1**		**Period 2**		**Period 3**	
	Testing Goals	**Evaluate impact of biological selector**		**Evaluate impact of biological and physical selector**		**Stress testing clarifier**	
	Start Date	**6/5/2018**		**11/5/2018**		**3/18/2018**	
	Basin	**Test**	**Control**	**Test**	**Control**	**Test**	**Control**
Parameter	***Process configuration***	***Anaerobic – Oxic (AO)***	***Modified Ludzack-Ettinger (MLE)***	***AO – Hydro cyclone***	***MLE***	***Modified AO – Hydrocyclone***	***MLE – EBPR***
Design capacity	*Million Litres per Day (MLD)*	33	33	33	33	33	33
Influent flow	*MLD*	26.5 ± 2	24.3 ± 4.2	21.1 ± 2	22.1 ± 2.9	23.1 ± 2.1	27.5 ± 1.7
Gravity thickener effluent flow	*MLD*	–	–	–	–	1.15 ± 0.13	–
Dissolved oxygen	*mg O_2/L*	0.53 ± 0.17	0.94 ± 0.4	0.83 ± 0.24	1.13 ± 0.26	0.9 ± 0.2	1.31 ± 0.15
Mixed liquor suspended solids	*mg/L*	3,526 ± 435	2,826 ± 475	4,219 ± 1,038	3,492 ± 361	5,227 ± 607	3,985 ± 513
Mixed liquor volatile suspended solids ratio	%	85.5 ± 2.1	84.1 ± 1.3	83.5 ± 1.2	84.6 ± 2.0	84.4 ± 4.5	85.9 ± 1.8
F/M ratio	*mg rbCOD/mg VSS/d*	0.19 ± 0.02	0.2 ± 0	0.18 ± 0.03	0.23 ± 0.03	0.13 ± 0.02	0.19 ± 0
Aerobic solids retention time	*days*	4.6 ± 0.4	6.3 ± 1.6	5.8 ± 0.8	6.8 ± 2.7	6.2 ± 0.6	6.3 ± 1
RAS recycle	*% of influent flow*	130 ± 10	150 ± 20	160 ± 30	160 ± 20	160 ± 20	130 ± 10
Mixed liquor recycle	*% of influent flow*	0	310 ± 50	0	340 ± 50	0	270 ± 20
% Anaerobic volume	*% of basin volume*	16.1	0	16.1	0	16.1	5.5
% Anoxic volume	*% of basin volume*	0	21.5	0	21.5	0	20.3
%Aerobic volume*	*% of basin volume*	83.9	70.2	83.9	70.2	83.9	66.3
Total basin volume	*Million litres*	7.76	7.76	7.76	7.76	7.76	7.76
Hydrocyclone hydraulic ratio	*OF/UF*	–	–	85/15	–	87/13	–
Hydrocyclone mass flow ratio	*OF/UF*	–	–	66/34	–	69/31	–
Total mass wasted	*Metric tons per day*	4.3 ± 0.7	4.0 ± 1.1	4.2 ± 0.9	4.0 ± 0.7	5.5 ± 0.7	4.7 ± 0.7

*Difference in % aerobic volume is due to all North Complex secondary basins (including Control) having unaerated zones at the end of the aerobic zone to reduce dissolved oxygen in recycle to anoxic zones. All Test basin aerobic zones were fully aerated as there was no mixed liquor recycle.

2: The goal of Period 2 was to compare the Control to the Test basin configured with both a biological and physical selector. On November 5, 2018, an InDense™ (World Water Works, Oklahoma) hydrocyclone skid comprised of eight 10 m^3/h hydrocyclones was placed in service for selective wasting on the Test basin, and was operated in an AO-Hydrocyclone configuration until March 18, 2019. Period 3: The goal of Period 3 was to stress test the clarifier on the Test basin by operating at increasing solids loading rates while comparing clarifier performance to the Control. On March 18, 2019, the sidestream anaerobic reactor in the North Complex was placed into service, changing the configuration of the Control basin to include a formal anaerobic selector for EBPR at the full scale. This system was placed in service independent of the study, so the process configurations had to be modified to account for this system being placed in service. Operation of the sidestream anaerobic reactor changes the flow distribution of gravity thickener effluent (GTE) in the North Complex such that it is added directly to the sidestream anaerobic reactor. During Period 1 and Period 2, GTE was mixed in with the primary effluent upstream of the Test basin's pump station. Modifications were made to the Test basin to allow for the GTE to be added directly to the anaerobic zone when the sidestream anaerobic reactor is in operation to account for the GTE not being mixed in with the primary effluent. This modified AO-Hydrocyclone process flow configuration was implemented to reintroduce GTE to an anaerobic solids contact zone in the Test basin. Stress testing of the Test clarifier was achieved by reducing wasting rates to increase the solids inventory, thus increasing the clarifier solids loading rate. Process flow configurations tested throughout all study periods are summarized in Figure 2. The piloting period ended abruptly during Period 3 due to mechanical failure of an aeration grid in the Test basin requiring the system be drained and cleaned for repairs.

Wastewater characterization

The Test and Control basins both receive municipal wastewater treated through bar screens, grit screening, and primary sedimentation. The primary effluent, GTE, and clarified secondary effluent were characterized for nutrients, carbon, and solids according to Baird *et al.* (2017). Floc-filtered chemical oxygen demand (ffCOD) was measured according to the method outlined in Mamais *et al.* (1993), and is used as a surrogate for rbCOD. Influent feed characteristics for the Test and Control are provided in Tables 2 and 3.

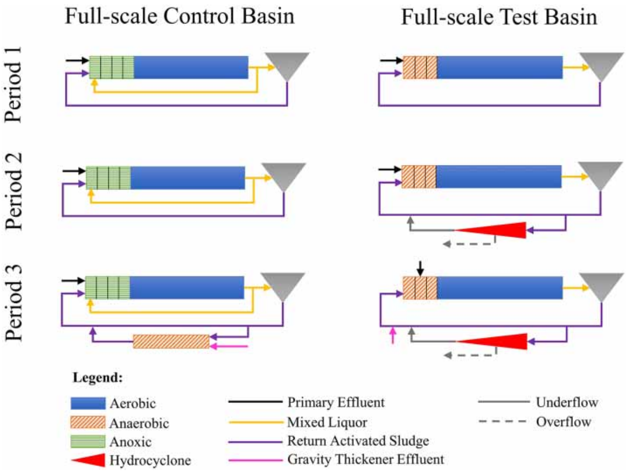

Figure 2 | Process flow configurations for the Test and Control basin throughout study.

Settling and particle characterization

Sieve analysis and dilute Sludge Volume Index (dSVI) were performed according to methods outlined in van Loosdrecht *et al.* (2016). Cole Parmer (Vernon Hills, Illinois) standard sieve model numbers 35 (500 μm), 60 (250 μm), and 120 (125 μm) were used to estimate particle size distribution. Qualitative microscopy was performed on mixed liquor using an Olympus Life Sciences (Waltham, Massachusetts) BH-2 phase contrast microscope. Where applicable, basic statistics were calculated using a two-tailed Student's t-test to evaluate whether any differences observed between the means of paired datasets were statistically different. For the t-test, the variances were assumed unequal for each paired test.

Operational challenges

There are inherent challenges associated with operation of a full-scale system. Equipment failure and limited control over certain operational variables can impact testing. This section provides a summary of the main issues experienced.

On January 7, 2019, the RAS volumetric recycle rates were reduced from 160% to 71% of the influent flow to observe if this change would help reduce clarifier effluent TSS. Shortly after the RAS rate was intentionally reduced, the gear box of a mixer in the Test basin anaerobic zone broke and was out of service from January 10, 2019 to February 27, 2019. From January 10, 2019 to January 19, 2019, the mixed liquor suspended solids concentration in the Test

Table 2 | Primary effluent characteristics

Parameter	Phase Date	Period 1 6/5/2018	Period 2 11/5/2018	Period 3 3/18/2018
Total suspended solids	*mg/L*	86 ± 13	110 ± 20	103 ± 16
Total alkalinity	*mg $CaCO_3$/L*	238 ± 10	241 ± 5	241 ± 2
COD	*mg/L*	372 ± 26	484 ± 30	418 ± 58
Soluble COD	*mg/L*	–	235 ± 25	229 ± 36
rbCOD	*mg/L*	–	228 ± 11	168 ± 10
Ammonia	*mg n/L*	32 ± 13	34 ± 3	32 ± 3
Total Kjedal nitrogen	*mg N/L*	40 ± 3	47 ± 3	48 ± 3
Orthophosphorus	*mg P/L*	3.1 ± 0.2	3.6 ± 0.3	3.9 ± 0.6
Total phosphorus	*mg P/L*	4.7 ± 0.6	5.7 ± 0.4	6.1 ± 0.1
Temperature	*Celsius*	21.6 ± 0.9	16.7 ± 1.5	15.8 ± 0.5
COD:total nitrogen	*mg/mg N*	9.1 ± 0.5	10.1 ± 0.4	8.5 ± 1.3

Table 3 | Gravity thickener effluent characteristics

Parameter	Phase *Date*	Period 1 *6/5/2018*	Period 2 *11/5/2018*	Period 3 *3/18/2018*
Total alkalinity	*mg $CaCO_3$/L*	–	270 ± 18	272 ± 3
COD	*mg/L*	–	614 ± 152	604 ± 30
Soluble COD	*mg/L*	–	254 ± 27	241 ± 18
rbCOD	*mg/L*	–	209 ± 23	178 ± 3

basin dropped from 3,479 mg/L to 2,778 mg/L, a 20% reduction. Two theories for what caused the decline in mixed liquor suspended solids are related to the low dSVIs occurring during this period. The reduced RAS flow led to lower fluid velocity in the RAS recycle channel, causing solids deposition in the channel, and solids were settling in the unmixed anaerobic zone. The volumetric RAS recycle rate was increased back to 160% of the total influent flow on January 31, 2019, and the gear box to the mixer was finally repaired on February 27, 2019. Additional measures were taken to mitigate the solids loss: (1) the wasting rate from the Test basin was reduced, and (2) a temporary pumping system was implemented to pump any settled solids from anaerobic zone 3 into the next zone. After all of the issues were corrected, the mixed liquor suspended solids increased to 4,800 mg/L. It was decided to move forward with stress testing the clarifier on the Test basin, which was originally targeted to be done during Period 3. Stress testing the clarifier in the Test train began on February 28, 2019. The operational challenges experienced are summarized in Table 4.

RESULTS AND DISCUSSION

Effluent quality

Average effluent quality for both the Test and Control basins across all three testing periods is summarized in Table 5, and all values were below facility discharge limits. Until Period 3 the Control basin had lower effluent TSS. Particulate COD in the effluent was higher in the Test than in the Control. Nitrogen removal efficiency in the Control was higher than the Test, which is predominantly attributed to the lack of a dedicated anoxic zone in the Test, and potentially due to partial conversion of particulate COD (Wagner *et al.* 2015a, 2015b). Phosphorus removal in both the Test and Control were comparable across all three testing periods. It is

Table 4 | Summary of operational challenges that occurred during testing

Operational change	Start date	Impact	Correctional change	Date corrected
Reduced RAS rate to 71% of influent flow	1/7/2019	Possible solids loss in RAS recycle channel	Increased RAS rate to 160% of influent flow	1/31/2019
Anaerobic zone mixer gear box malfunction	1/10/2019	Possible solids loss in unmixed anaerobic zone	Gear box replaced in mixer and mixer placed back in service. Temporary pumping of settled solids.	2/27/2019

Table 5 | Summary of Test and Control clarified effluent

	Phase	**Period 1**		**Period 2**		**Period 3**	
	Date	**6/5/2018**		**11/5/2018**		**3/18/2018**	
Parameter	***Basin***	***Test***	***Control***	***Test***	***Control***	***Test***	***Control***
TSS	*mg/L*	22.7 ± 7.1	13.8 ± 12.7	15 ± 6.0	7.1 ± 2.2	5.6 ± 3.7	6.4 ± 3.2
Alkalinity	*mg/L*	127 ± 18	124 ± 11	118 ± 2	136 ± 5	125 ± 12	143 ± 3
COD	*mg/L*	60 ± 20	38 ± 6	47 ± 8	38 ± 10	80 ± 31	40 ± 7
Soluble COD	*mg/L*	22 ± 7	22 ± 1	24 ± 12	33 ± 16	25 ± 4	32 ± 4
Ammonia	*mg N/L*	3.4 ± 3.7	0.3 ± 0.1	0.9 ± 1.5	0.9 ± 0.8	0.2 ± 0	0.3 ± 0.2
Nitrate	*mg N/L*	5.5 ± 2.1	3.7 ± 1.9	6 ± 1.5	0.2 ± 0.3	5.4 ± 3.8	0.5 ± 0.2
Nitrite	*mg N/L*	0.31 ± 0.23	0.06 ± 0.09	0.46 ± 0.54	0.17 ± 0.1	0.2 ± 0	0.25 ± 0.1
TKN	*mg N/L*	5.1 ± 3.7	3 ± 2	2.7 ± 1.7	2.1 ± 0.8	1.6 ± 0.1	1.6 ± 0.4
Ortho-phosphorus	*mg P/L*	0.00 ± 0.00	0.07 ± 0.07	0.22 ± 0.55	0.11 ± 0.15	0.09 ± 0.08	0.02 ± 0.01
Total phosphorus	*mg P/L*	0.77 ± 0.32	0.47 ± 0.25	0.39 ± 0.18	0.29 ± 0.07	0.74 ± 0.63	0.27 ± 0.08

noted that EBPR has occurred in the North Complex despite the lack of a dedicated anaerobic zone. While effluent quality is not a focus of this paper, this information is provided for completeness.

Settling performance

The Test and Control basins began operation in the same configuration using common mixed liquor inventory. The mean $dSVI_{30}$ observed in the Test and Control was 117 ± 6.1 and 113 ± 16.2 mL/g respectively (Figure 3). After Period 1 began, the $dSVI_5$ and $dSVI_{30}$ in the Test began to diverge from values observed in the Control basin. The $dSVI_{30}$ observed in the Control basin increased to values relatively similar to the $dSVI_5$ observed in the Test basin. The differences in the mean $dSVI_{30}$ values observed during Period 1 were statistically significant ($P < 0.05$), with values of 93 ± 10 and 107 ± 29 mL/g observed for the Test and Control respectively. Higher abundance of PAOs have been attributed to greater biomass density due to the increase in internal polyphosphate content (Schuler & Jang 2007). As shown in Table 5, EBPR was occurring throughout the study. Two months into Period 2 of testing, the $dSVI_5$ and $dSVI_{30}$ in the Test basin decreased to a low of 64 and 48 mL/g respectively. While the $dSVI_5$ and $dSVI_{30}$ in the Test were observed to increase from the low observed in January to values of 97 and 155 mL/g respectively. The differences in the mean $dSVI_{30}$ between the Test (76 ± 18 mL/g) and the Control (137 ± 28 mL/g) during Period 2 of testing remained statistically significant ($P < 0.05$). Period 3 of testing lasted one month, during which the $dSVI_{30}$ in both the Test and Control increased. During Period 3, the differences in the mean $dSVI_{30}$ between the Test (83 ± 12) and Control (127 ± 11) remained statistically significant ($P < 0.05$). These results suggest that having an anaerobic biological selector in the Test basin initially lowered the dSVI in the Test as compared

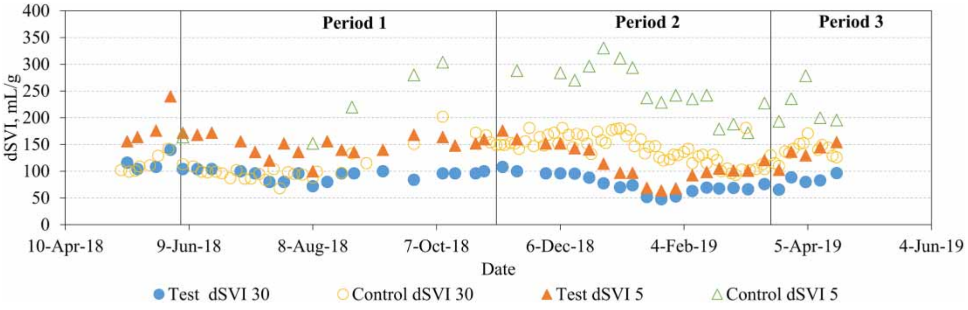

Figure 3 | Comparison of $dSVI_5$ and $dSVI_{30}$ between the Test and Control.

to the Control, and that the addition of a physical selection pressure with hydrocyclones further separated the dSVI between the Test and Control.

Clarifier effluent TSS in the Test was variable and higher than the Control during Period 1 (Figure 4). During the summer months, algae growth in the clarifier effluent launders is a known problem at the Hite treatment facility, and contributes to elevated effluent TSS during the summer. The average clarifier solids loading rates to the Test and control clarifiers were 162 ± 14 and 152 ± 19 $kg/d/m^2$. After the hydrocyclones were placed in service during Period 2 of testing, the effluent TSS from the Test clarifier began to decline; however, as summarized in earlier in Table 4, a series of intentional and unintentional operational changes occurred. The RAS was reduced to see if a reduced solids loading rate would lower effluent TSS. This reduced the solids loading rate to the Test clarifier from 162 $kg/d/m^2$ to 100 $kg/d/m^2$. The loss of the anaerobic zone mixer during Period 2 further reduced the solids loading rate to the Test clarifier due to a decline in mixed liquor suspended solids. Even at a reduced clarifier solids loading rate, the effluent TSS was observed to increase from below 4 mg/L to above 7 mg/L. The RAS volumetric recycle ratio in the Test was increased back to 160%, which elevated the solids loading rate to the Test clarifier, and also began increasing the blanket depth in the clarifier. Prior to these changes, the average blanket depths in the Test and Control clarifiers were 0.9 ± 0.1 and 1.2 ± 0.2 metres respectively. After these operational issues were corrected and the solids inventory in the Test was increased, the blanket depths in the Test and Control clarifiers averaged 1.7 ± 0.5 and 1.3 ± 0.4 metres respectively. The effluent TSS from the Test clarifier declined to levels equal to or below effluent TSS from the Control clarifier, even with the Test clarifier operating at solids loading rate that was 32 ± 9% greater than that of the Control. These results suggest that the extent of granulation achieved was sufficient to allow operation at a higher solids inventory, while maintaining comparable effluent TSS to the existing system.

Particle size

Size distribution analysis using sieves began near the end of Period 1 (October 2018) for the Test basin mixed liquor suspended solids, followed by the Control basin during Period 2 of testing (December 2018). Analysis of the Control basin revealed that the total fraction of biomass greater than 250 μm remained relatively consistent at around 16% over the entire testing period. Conversely, results from the size distribution analysis of the test basin showed that the total fraction of biomass ≥250 μm (the sum of solids retained on the 250 and 500 μm sieves) began to increase within one month after the start of Period 2, and reached a peak of 56% after three months into Period 2 (Figure 5). After this maximum was reached, the total fraction of biomass ≥250 μm began to decline, reaching a value of around 40% by the end of Period 3. Granules within the size range of 250 to 500 μm began to decline during the period where operational issues forced the change in wasting, thus driving the mixed liquor suspended solids concentration higher. Particle sizes ≥500 μm in the Test basin were steady at approximately 2% of the total population until around three months into Period 2, at which time there was a steady increase until the end of Period 3, reaching a maximum of 20%. In spite of the declining total fractionation of particles above 250 μm, the mature and established larger particles continued to increase while the smaller granules decreased.

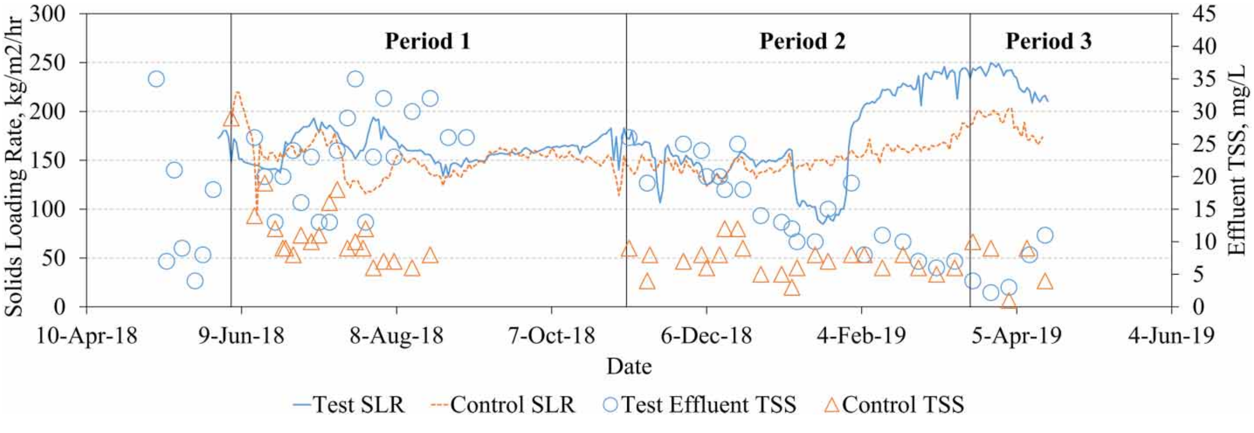

Figure 4 | Clarifier solids loading rate and effluent TSS.

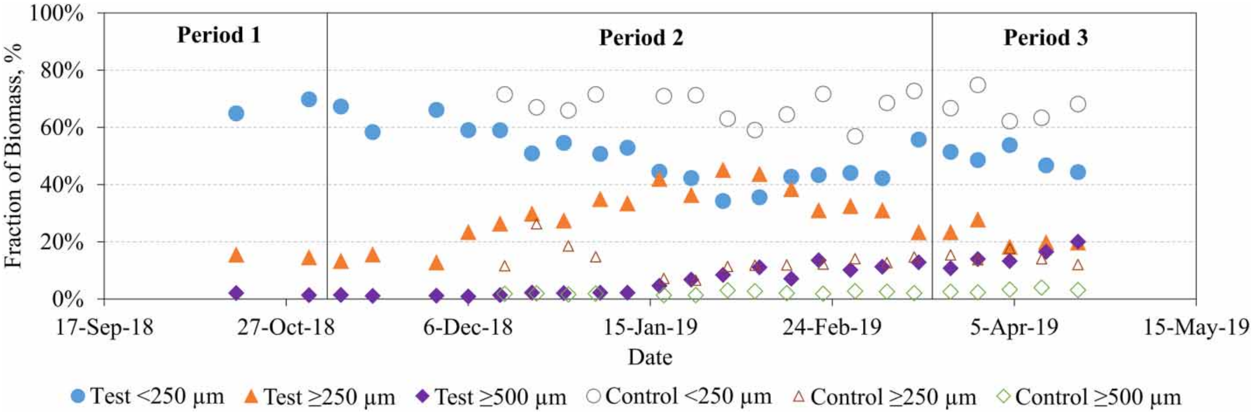

Figure 5 | Particle size distribution of mixed liquor suspended solids from the Test and Control basin.

During Period 1, the F/M ratios for the Test and Control systems were similar, ~0.2 mg rbCOD/mg VSS/d, which is within the range of values reported to be adequate for achieving 60% granulation in an SBR (Sturm *et al.* 2017). However, without a strong physical selection pressure, only a low fraction of the biomass was of granular fraction. The low degree of granulation observed in the Test basin during Period 1 and the Control Basin during Period 2 and Period 3 could be attributed to having an appropriate F/M ratio, plug flow conditions in a continuous flow system creating a gradient feast/famine condition, and a physical selection pressure from the surface wasting strategy employed at the Hite treatment facility, which are suggested to be the reasons granules have been observed in other full-scale continuous flow systems (Downing *et al.* 2017; Wei *et al.* 2020). Upon implementation of the hydrocyclones in the Test basin during Period 2, the granular fraction began to increase which suggests that the addition of the physical selection pressure from the hydrocyclones was enough to drive the granular fraction to the degrees observed during this study. The decline of the fraction of biomass ≥250 µm during the latter part of Period 2 and into Period 3 could be a combination of these smaller granules transitioning to larger sized granules, and potential instability due to operational challenges that occurred during Period 2. It has been reported that granules display less stability during maturation and growth as operating conditions are more complex (Pishgar *et al.* 2019), which could explain the dynamics in size distribution observed in this work given the operational challenges experienced during testing. However, the long-term stability of granular sludge in a continuous flow system will need to be determined in future evaluations.

There was a direct correlation with $dSVI_{30}$ between the fraction of biomass in the range of 125 to 250 µm. However, an inverse correlation with $dSVI_{30}$ is suggested when considered with the fraction of biomass greater than 250 µm (Figure 6). Maintaining a consistent degree of granulation

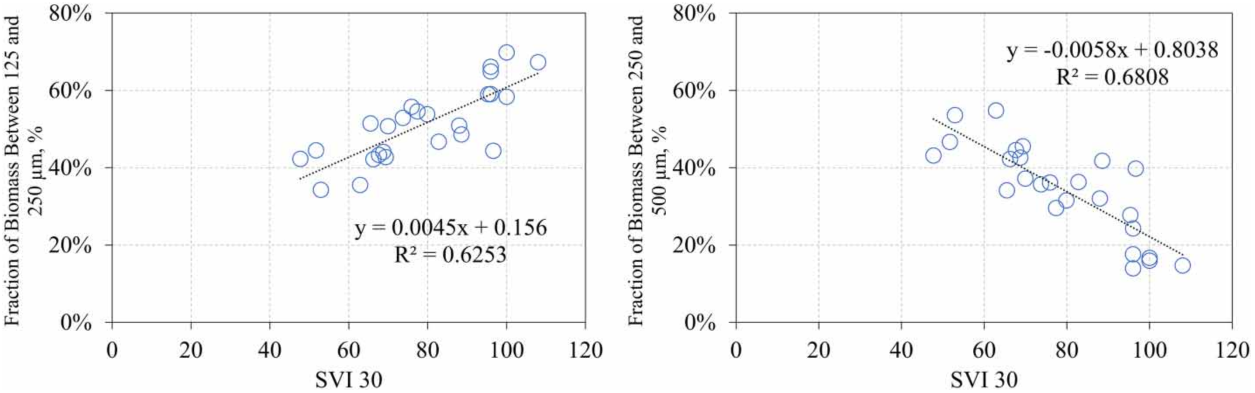

Figure 6 | $dSVI_{30}$ as a function of the total fraction of biomass between 125 and 250 µm in Test (left graph), and as a function of the total fraction of biomass greater than 250 µm (right graph).

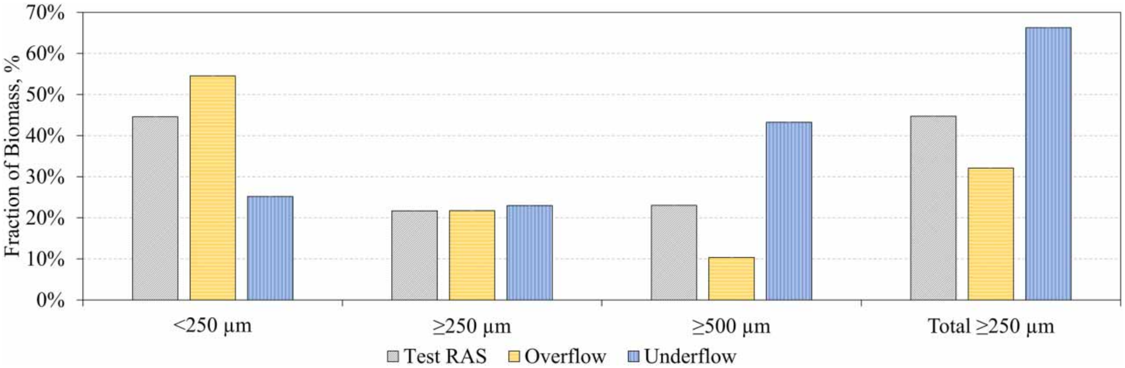

Figure 7 | Size distribution analysis of hydrocyclone RAS feed, underflow, and overflow.

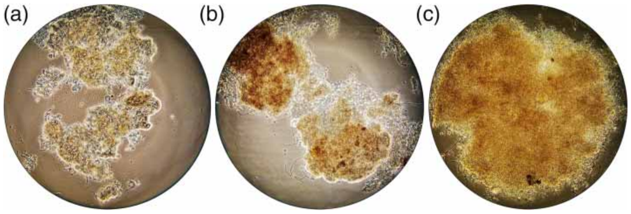

Figure 8 | Microscopic images from Test basin mixed liquor samples collected during Periods 2 and 3. All images at 100x total magnification. (a) Sample collected February 10, 2019. (b) Sample collected March 12, 2019. (c) Sample collected April 6, 2019.

might be an important consideration for achieving optimum settling behaviour in a continuous flow system.

A sieve mass balance was performed around the hydrocyclones during Period 3 of testing. The fraction of biomass ≥500 µm was observed to be greatest in the underflow stream from the hydrocyclones, while the majority of particles in the overflow are less than 250 µm (Figure 7). Qualitative microscopy performed confirmed the presence of granule-like structures (Figure 8). Given the operating conditions tested in this study, these results suggest that forming and retaining granular sludge was possible and occurred within three months, which is in line with timeframes reported in other AGS studies (Wagner *et al.* 2015a, 2015b; Pronk 2017).

CONCLUSIONS

- Inducing granulation in a continuous flow activated sludge system was possible with the application of both biological and physical selection pressures.
- For the Test basin, a negative correlation was observed between the fraction of biomass greater than 250 µm and $dSVI_{30}$, which suggests that maintaining a consistent fraction of granules in a continuous flow activated sludge system could be vital for increasing and maintaining intensified secondary treatment capacity through high mixed liquor concentrations and sustained high solids loading rates on secondary clarifiers.
- The reduction in dSVI in the Test basin allowed operation at a solids loading rate to the Test clarifier that was 32% greater than the Control while maintaining equivalent effluent TSS.
- Under the conditions tested in the study, granulation was observed to occur in a full-scale continuous flow system. The total fraction of biomass larger than 250 µm began to increase after one month of operation, and within three months peaked at 56%. The fraction of biomass within the range of 250 to 500 µm fluctuated over time, while the fraction ≥500 µm continually increased, peaking at 20% before piloting ceased. The long-term stability of granular sludge in a continuous flow activated sludge system is unknown and would need to be determined in future evaluations.
- Operating in an AO process configuration during Period 1 initially attenuated settleability as measured by $dSVI_{30}$, and the differences in the means observed between the Test and Control were statistically significant ($P < 0.05$), with values of 93 ± 10 and 107 ± 29 mL/g respectively. The differences in the mean $dSVI_{30}$ observed during hydrocyclone operation in Period 2 were statistically significant ($P < 0.05$), with values of 76 ± 18 and 137 ± 18 mL/g observed for the Test and Control respectively. These results suggest that having an anaerobic biological selector in the Test basin initially moderated the dSVI relative to the Control, and that the addition of a physical selection pressure with hydrocyclones further improved the dSVI.

SUMMARY AND OUTLOOK

The observations in this study suggest that through application of key biological and physical selection pressures, intentional granulation in a continuous flow activated sludge system is possible and could be a cost effective solution versus traditional expansion for other WRRFs with similar capacity needs. Some of the results presented, while not the focus of this paper, have potential design implications such as:

- The reduction in the mixed liquor suspended solids that occurred during Period 2 points to the need to evaluate mixing energy requirements throughout the system as part of design considerations for granulation in a continuous flow system.
- Operating at higher mixed liquor suspended solids in the Test basin during Periods 2 and 3 decreased total F/M ratios from 0.18 to 0.13 mg rbCOD/mg volatile suspended solids, which could possibly lead to reduced granule stability. Balancing optimal feed conditions with an appropriate solids inventory could be an important operational consideration to sustain optimal selective conditions.

This work has the potential to inform design guidelines for practitioners, as well as potentially supplement future academic research into key mechanistic principles.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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