Metropolitan Water Reclamation District of Greater Chicago

Welcome to the May Edition of the 2021 M&R Seminar Series

NOTES FOR SEMINAR ATTENDEES

- All attendees' audio lines have been muted to minimize background noise.
- A question and answer session will follow the presentation.
- Please use the "Chat" feature to ask a question via text to "All Panelists".
- The presentation slides will be posted on the MWRD website after the seminar.
- The ISPE has approved this seminar for one PDH, and the IEPA has approved this seminar for one TCH. Certificates will only be issued to participants who attend the entire presentation.

Belinda Sue McSwain Sturm, Ph.D.

Associate Vice Chancellor for Research
Professor of Civil, Environmental & Architectural Engineering
The University of Kansas
Lawrence, Kansas

Dr. Belinda Sturm is a Professor in the Department of Civil, Environmental & Architectural Engineering at the University of Kansas. She also serves as an Associate Vice Chancellor for Research. Belinda currently serves as Vice-Chair of the Water Environment Federation's Municipal Design Symposium and as Chair of the International Water Association's USA National Committee Executive Board. Belinda earned her bachelor of science in Public Health from the University of North Carolina at Chapel Hill and her Ph.D. in Civil Engineering and Geological Sciences from the University of Notre Dame.

Recent Advances in Aerobic Granular Sludge Processes

Belinda Sturm, PhD
University of Kansas

Steady Progression of Design for Settleability

1970s

Selector zone concept introduced to control bulking
(Choduba et al. 1973)

Filaments shown to dominate based on bioreactor design and operation (Eikelboom, 1975)

Unified theory of filaments developed (Sezgin et al, 1978)

1980s

DO shown to impact selection of filaments versus flocs (Palm et al. 1980)

1990s

SVI correlations for settling curves became more standardized (Wahlberg and Keinath, 1998; Daigger, 1995; Ozinsky and Ekama, 1995)

2000s

Selector zone design became more formal (Marten and Daigger, 1997) and better understood (Martins et al, 2004)

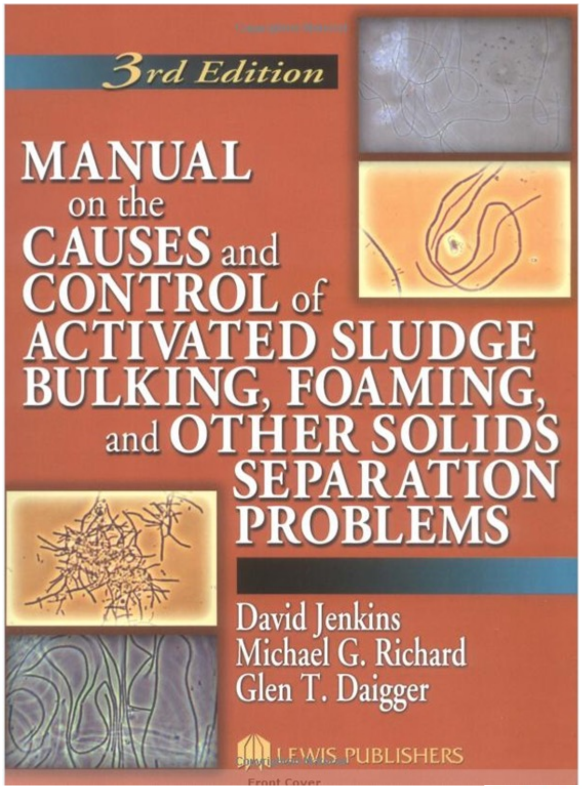
WE&RF report on selector zone design guidelines (Gray et al, 2008)

2010s

Is aerobic granular sludge the natural evolution of good settling sludge development?

Five decades of settling theory evolution has been summarized in one key manual for operations

- Focus: settleability
- Select for good settling
  - Low SVI
  - Larger floc
  - Limit filamentous growth
- Operating parameters
  - SRT control
  - F/M gradients
  - Selector zones and plug flow



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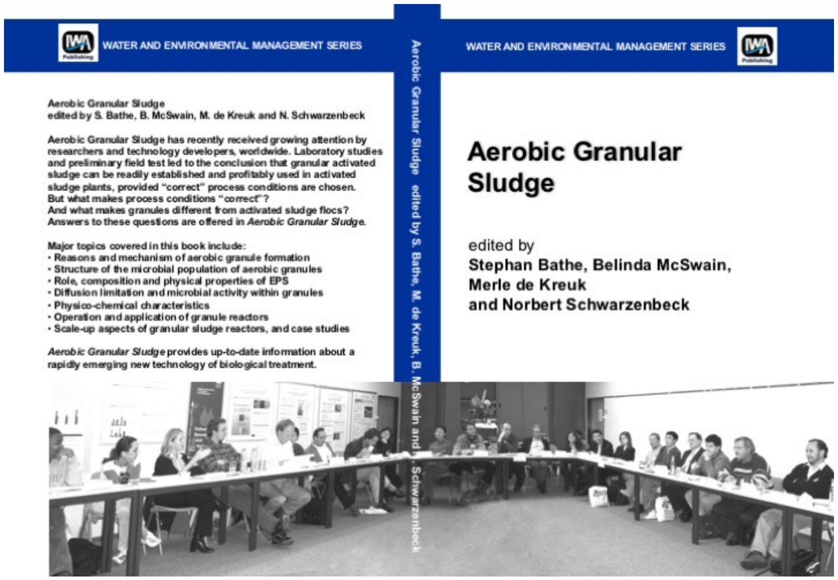
IWA Granule Workshop 2004

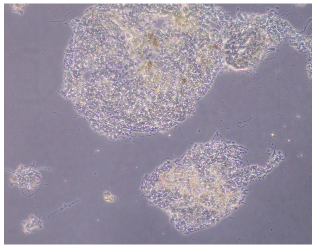


Granules making up aerobic granular activated sludge are to be understood as aggregates of microbial origin, which do not coagulate under reduced hydrodynamic shear, and which subsequently settle significantly faster than activated sludge flocs.

- $SVI_{30} < 60$ mL/g
- $SVI_5 = SVI_{30}$ or $SVI_5 / SVI_{30} = 1$
- Settling velocities > 9 m/hr
- Particle diameter > 200 µm

How Does Densified Activated Sludge Compare with Granular Sludge?

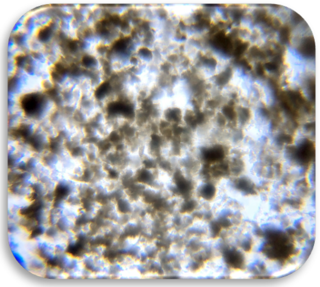
Compact AS (non-granular)



SVI_{30} 80 to 120 mL/g

non-patented AS
Conventional Selector Design

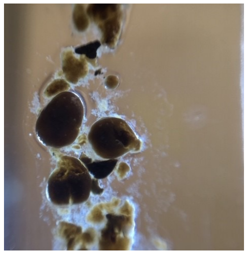
Densified AS (non-granular)



SVI_{30} < 80 mL/g

non-patented AS*

Densified AS (granular)



SVI_{30} < 50 mL/g

AquaNEREDA™
inDENSE™

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Different types of aerated granules have been formed

Parameter	NIT Granules	OHO Granules	NDN-OHO Granules	NDN-PAO Granules*
Processes	Nitrification (low COD/N feed)	COD oxidation (and possibly Nitrification)	Nitrification + Denitrification	Nitrification + Denitrification + EBPR[1]
Feeding condition	Aerobic	Aerobic	Anoxic	Anaerobic
Denitrifying bacteria	N/A	OHOs[2]	OHOs[2]	PAOs[3] and GAOs[4]
Nitrogen removal method	N/A	Assimilation w/ limited denitrification	Sequential anoxic and aerobic periods	Simultaneous nitrification and denitrification (SND) in aerobic period
Demonstrated	Lab-scale	Lab-scale	Lab-scale	Lab- and Full-scale

1. EBPR – Enhanced biological phosphorus removal
2. OHOs – Ordinary heterotrophic organisms
3. PAOs – Phosphorus accumulating organisms
4. GAOs – Glycogen accumulating organisms – may also grow

Figdore, B.A., Stensel, H.D., Winkler, M.K.H., Neethling, J.B. (2017) *Aerobic Granular Sludge for Biological Nutrient Removal*. Project No. NUTR5R14h. Water Environment and Reuse Foundation: Alexandria, VA.

Implementation of Aerobic Granular Sludge in Continuous Flow Activated Sludge (CFAS) Plants

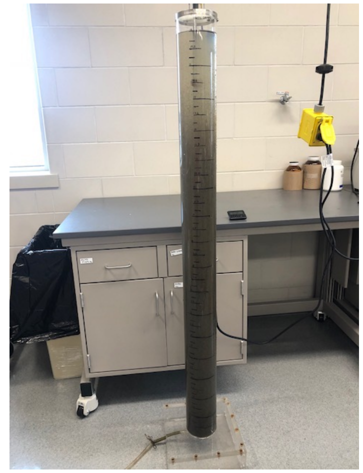
Aerobic granular sludge SBRs
- Sequencing batch operations
- High anaerobic F/M Ratio
- Short settling time

Conventional activated sludge
- Continuous flow
- Can have high anaerobic F/M with selector
- No settling selection

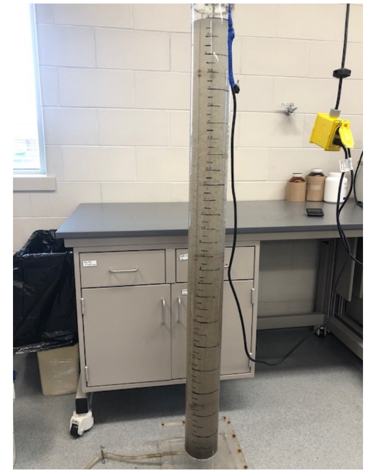
Densifying Activated Sludge Is Key to Increasing Capacity at WRRFs

Lawrence WWTP
Granular Sludge Pilot (70 L)

WERF U1R14 Project

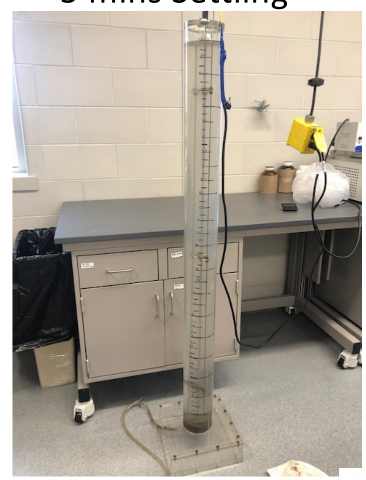


Flocculent Sludge
– 5 mins Settling



Granular Sludge
– 5 mins Settling

Flocculent Sludge
– 30 mins Settling



Granular Sludge
– 30 mins Settling

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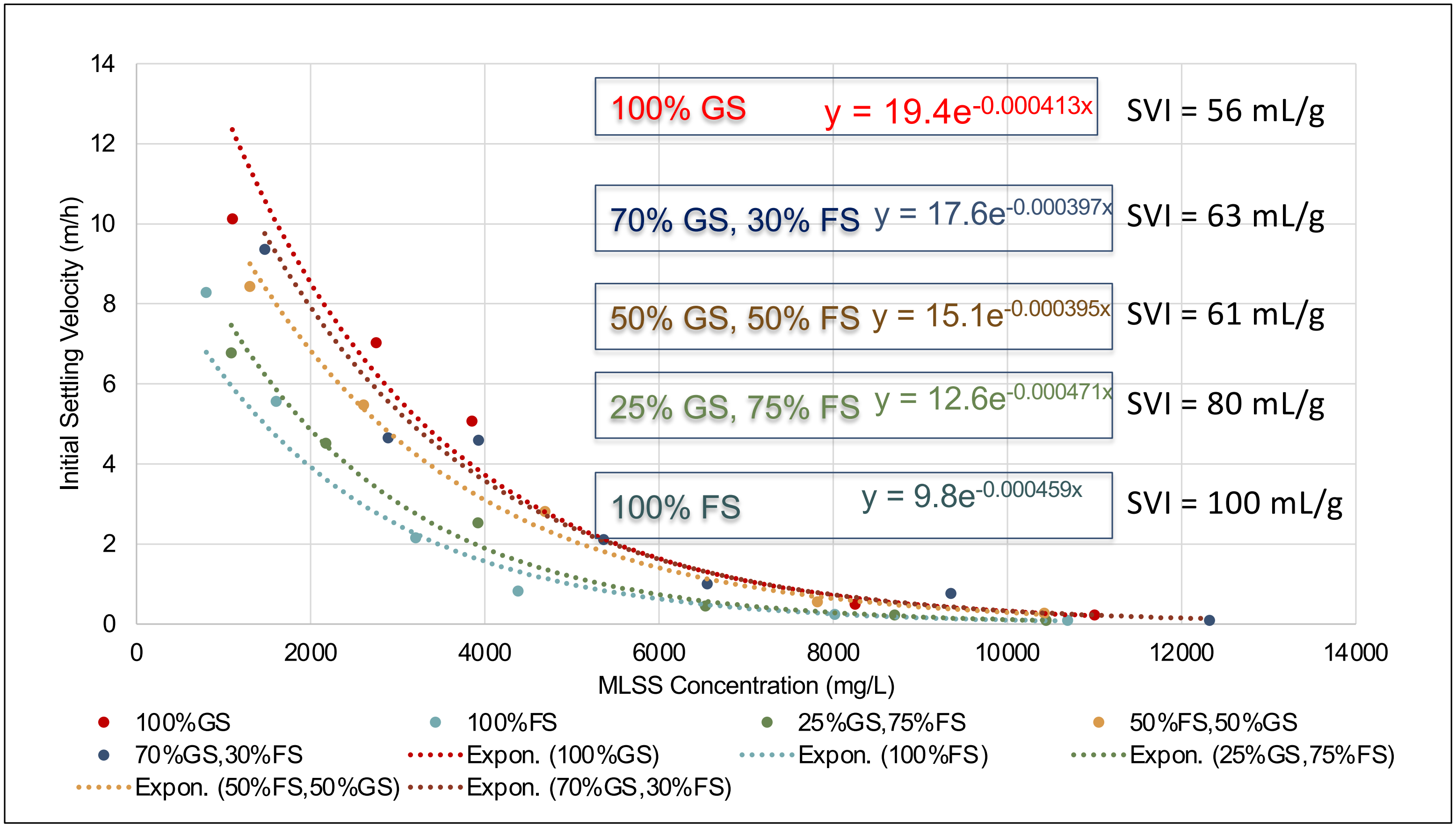
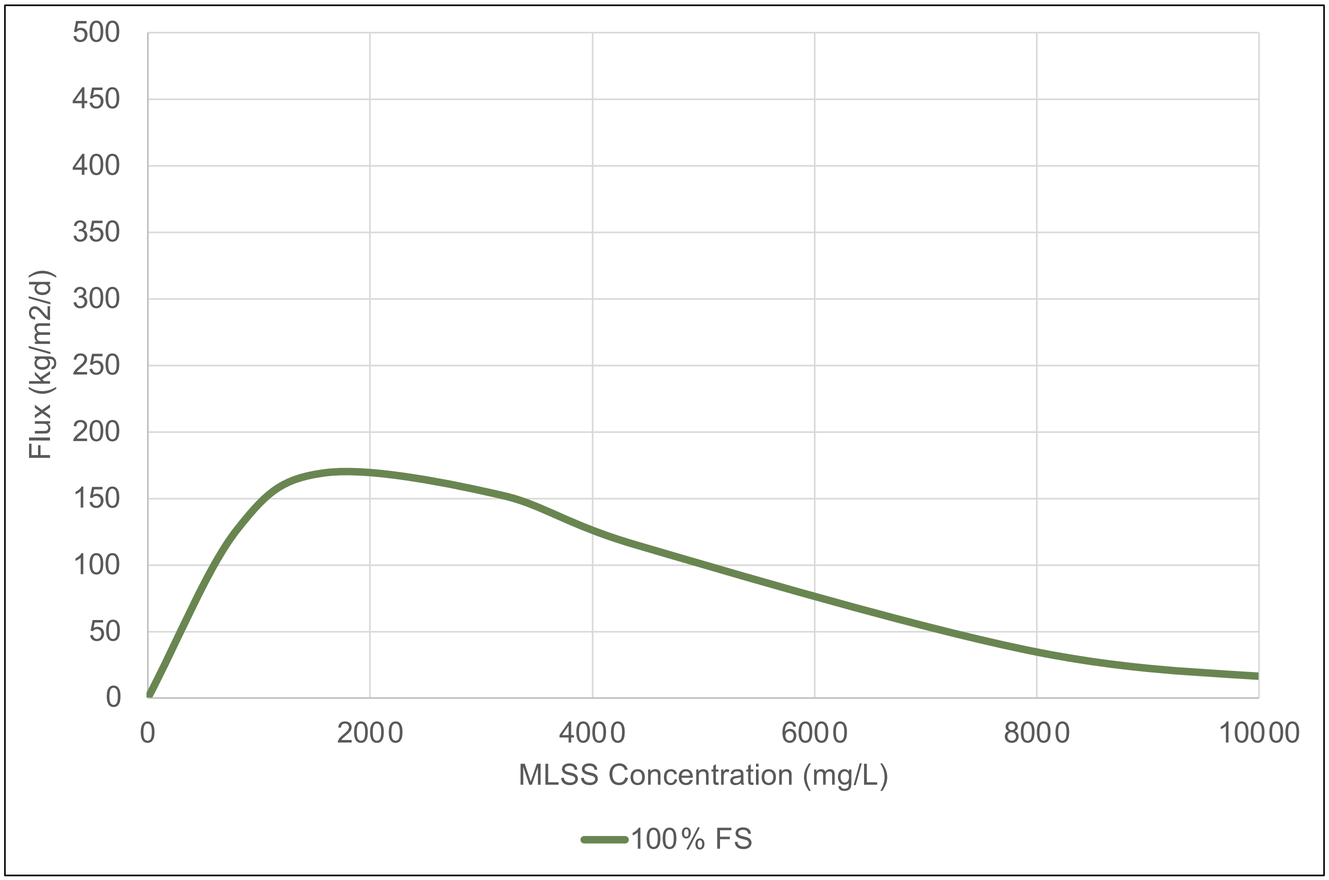
Lawrence WWTP AGS Pilot Results - Settling Parameters

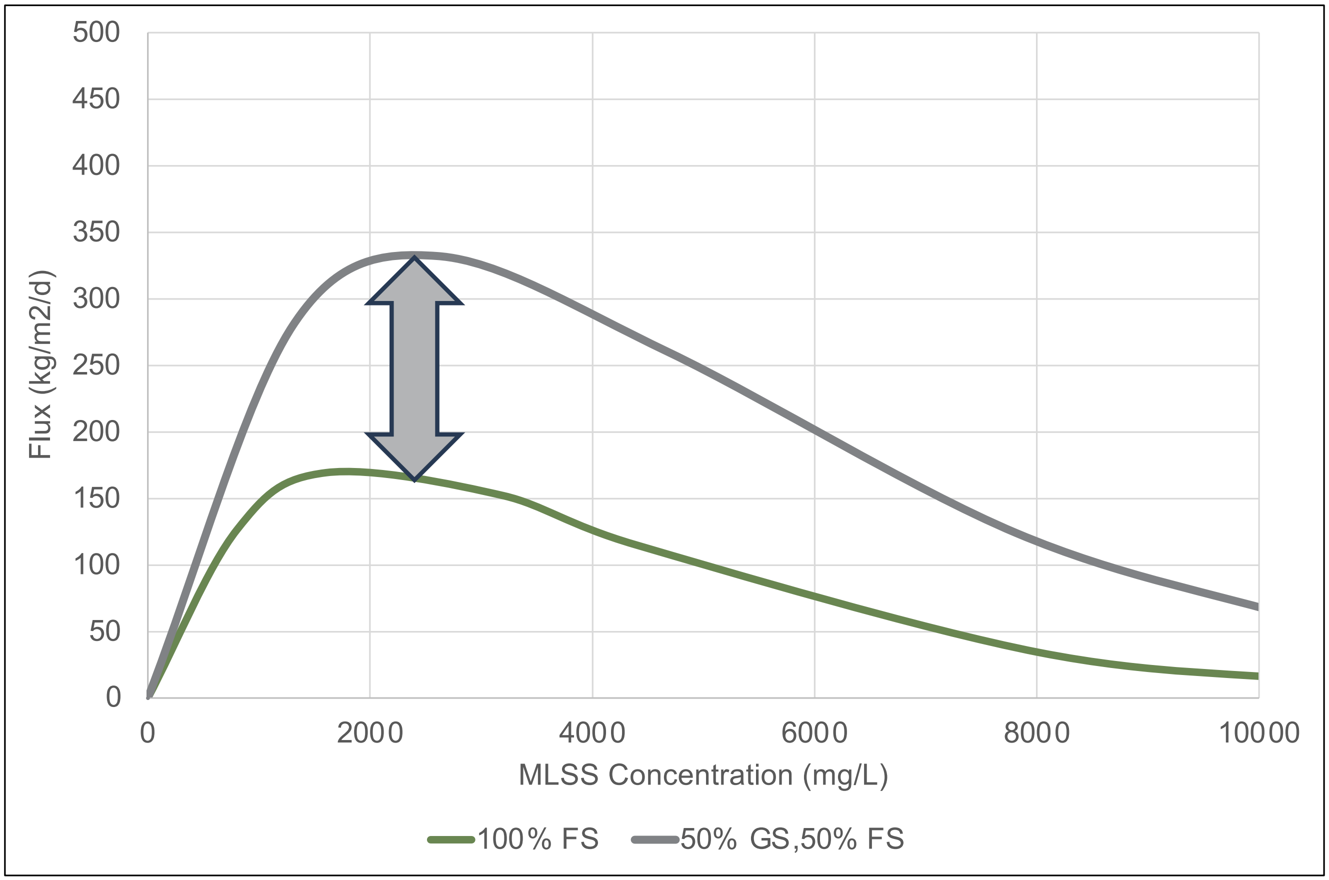
$$V_S = V_0 \cdot e^{(-K \cdot X_{TSS})}$$



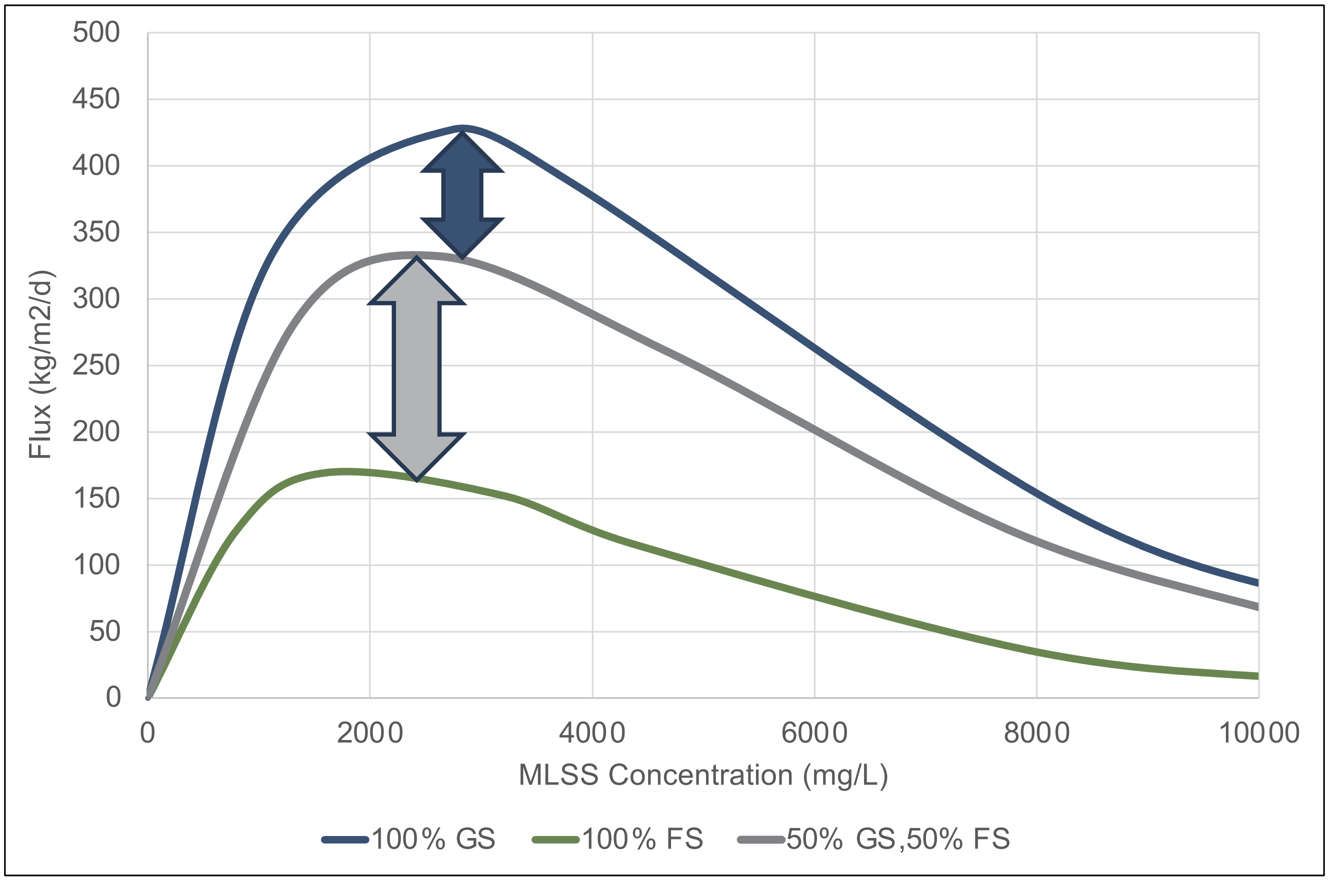
Flux Curves for different levels of granulation



Flux Curves for different levels of granulation



Flux Curves for different levels of granulation

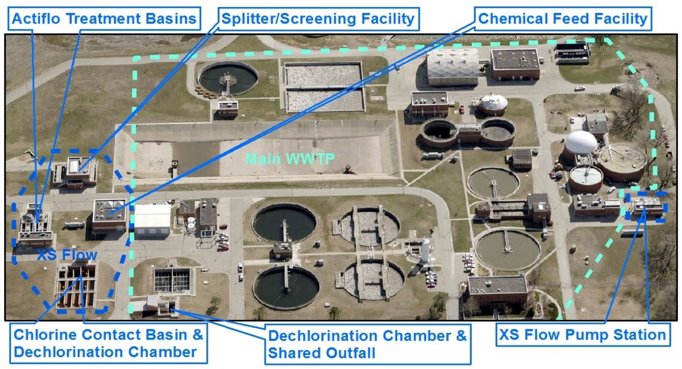


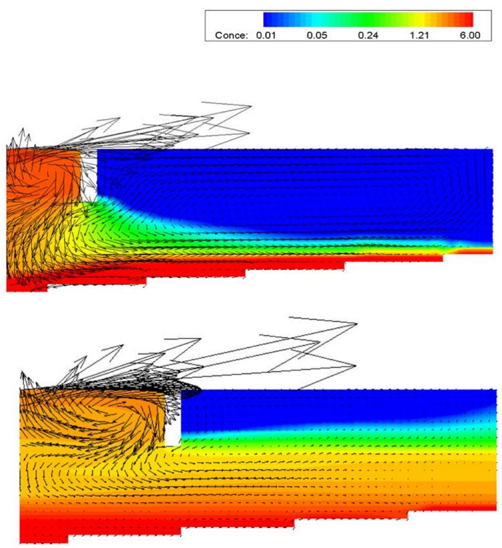
Clarifier Capacity Modeling

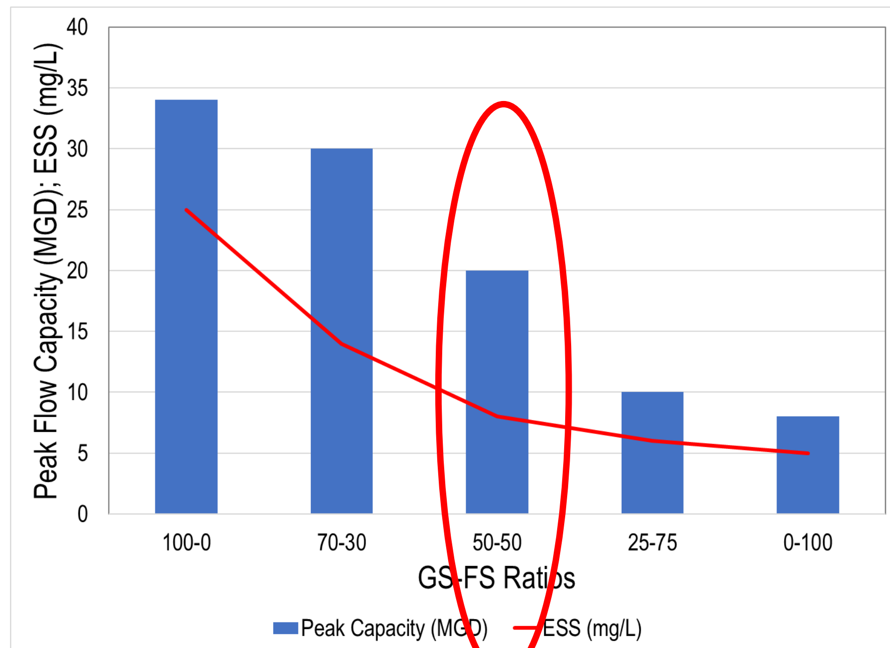
Hazen

Brown AND Caldwell

Performed by Dr. José Jimenez and Dr. Alonso Griborio







Note: Modeling assumed equal biomass concentrations for all ratios

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Sludge Densification extends the same principles we learned from preventing bulking sludge

Five decades of settling theory evolution has been summarized in one key manual for operations

- Focus: settleability
- Select for good settling
  - Low SVI
  - Larger floc
  - Limit filamentous growth
- Operating parameters
  - SRT control
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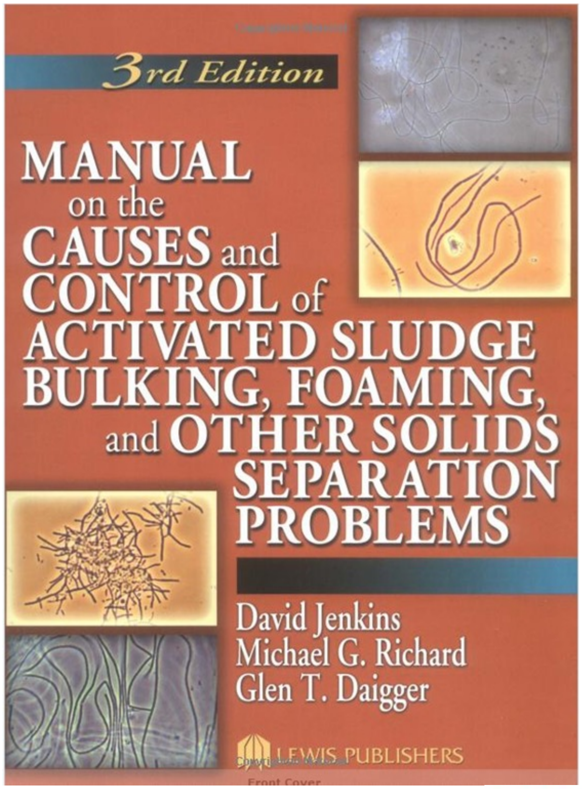

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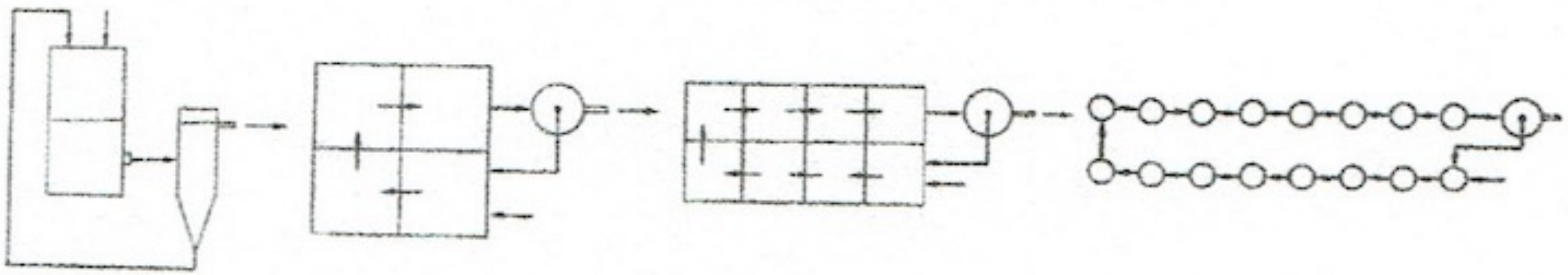
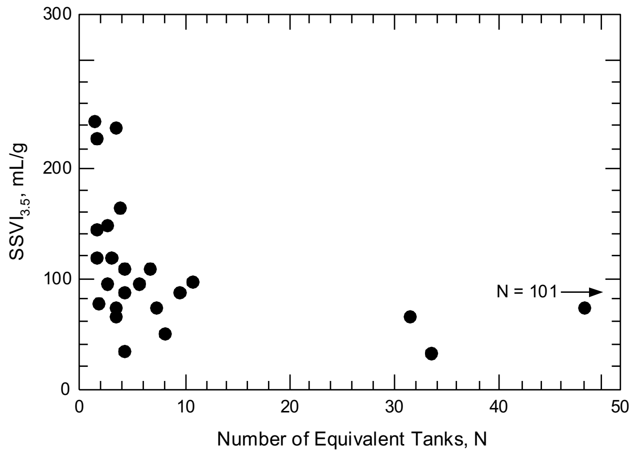
Floc Selection Theory and Filament Out-Selection



SVI, mL/g			
517	300	91	51

Chudoba, Ottova and Madera (1973) *Water Research*, 7, 1163.

What are our key parameters for selecting for good settling activated sludge?



From E. J. Tomlinson and B. Chambers, The effect of longitudinal mixing on the settleability of activated sludge. Technical Report TR 122, Water Research Centre, Stevenage, England, 1978. Reprinted by permission of the Water Research Centre.)

1. Plug Flow Conditions

Slide courtesy of Dr. Leon Downing, Black & Veatch

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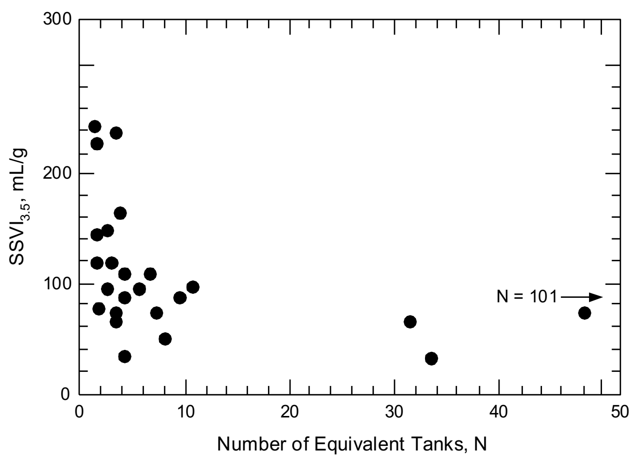

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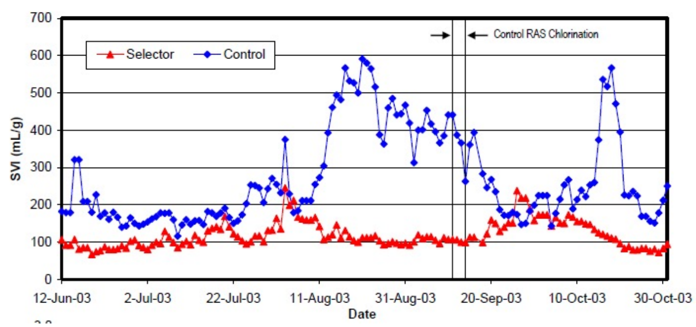


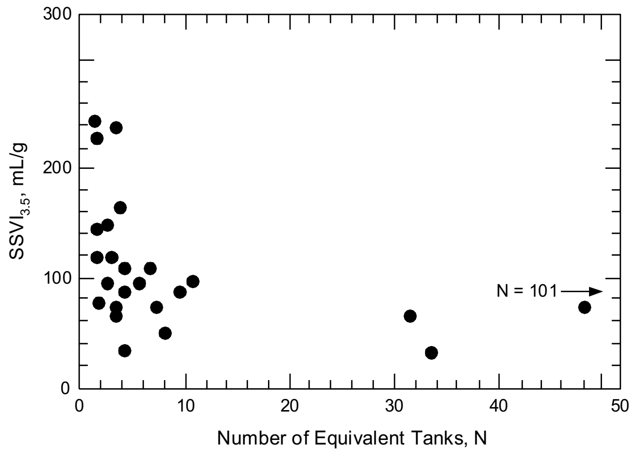
From Gray et al (2006) Develop and Demonstrate Fundamental Basis for Selectors to Improve Activated Sludge Settleability

1. Plug Flow Conditions

2. Anaerobic/Anoxic feed

Slide courtesy of Dr. Leon Downing, Black & Veatch

What are our key parameters for selecting for good settling activated sludge?



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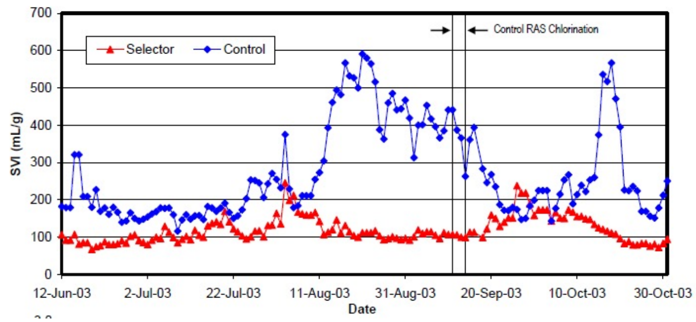

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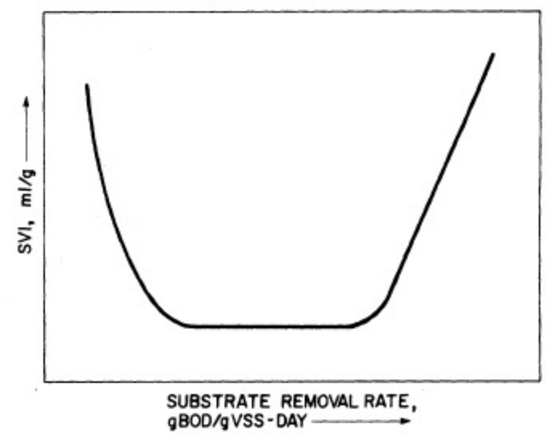


FIGURE 15. Effect of substrate removal rate on sludge volume index.

From Sezgin et al (1978) A Unified theory of activated sludge bulking, Journal of Water Pollution Control Federation 50(2)

1. Plug Flow Conditions

2. Anaerobic/Anoxic feed

3. Loading rate matters

Slide courtesy of Dr. Leon Downing, Black & Veatch

High F/M and Metabolic Selection

$$q_s = q_s^{\max} \frac{C_s}{K_s + C_s}$$

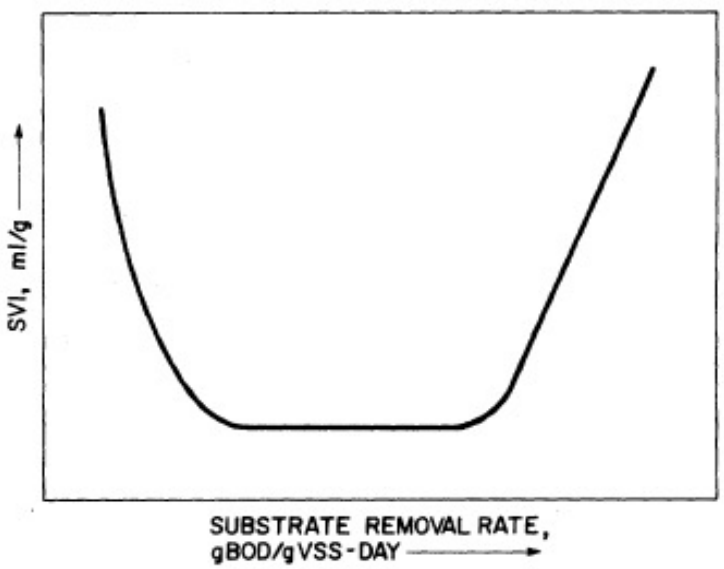
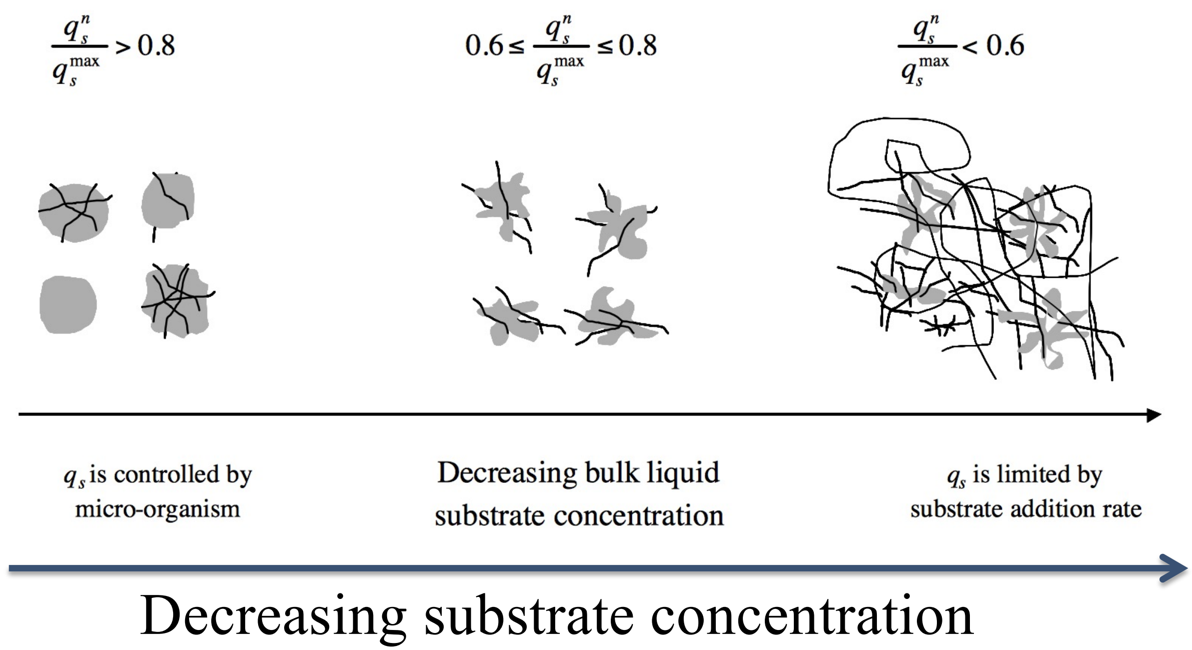


FIGURE 15. Effect of substrate removal rate on sludge volume index.



From Sezgin et al (1978) A Unified theory of activated sludge bulking, Journal of Water Pollution Control Federation 50(2)

Martins et al. (2003) *Water Research* 37, p.2555–2570

A high F/M anaerobic feeding regime is important to drive diffusion into granule and achieve metabolic selection

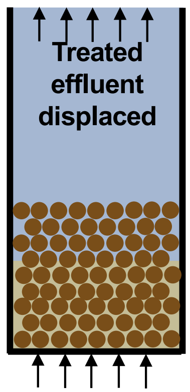
Contacting with high rbCOD drives diffusion to granule interior

-Allows interior to be biologically active

Anaerobic feeding selects for PAOs for EBPR

Slow upflow feeding widely used in lab and full-scale SBRs

Slug feeding has also been used in lab systems



Slow upflow plug-flow feeding through settled sludge bed

Figdore, B.A., Stensel, H.D., Winkler, M.K.H., Neethling, J.B. (2017) *Aerobic Granular Sludge for Biological Nutrient Removal*. Project No. NUTR5R14h. Water Environment and Reuse Foundation: Alexandria, VA.

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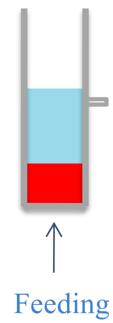
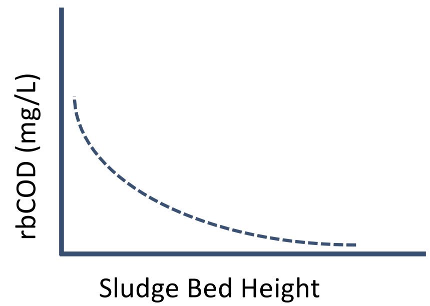
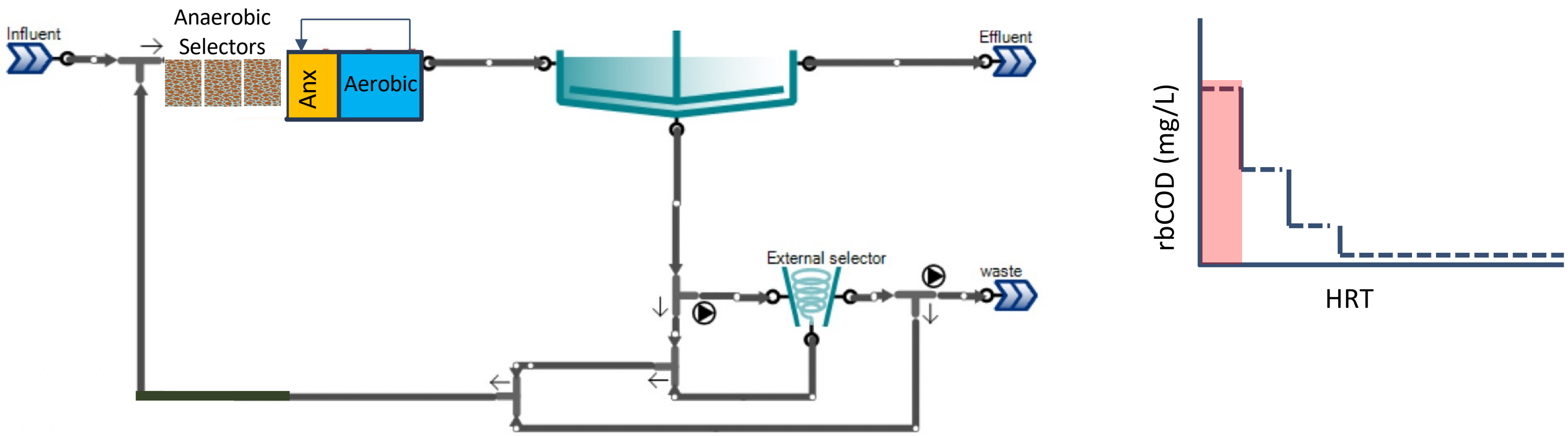
Substrate Utilization in SBR vs Plug Flow

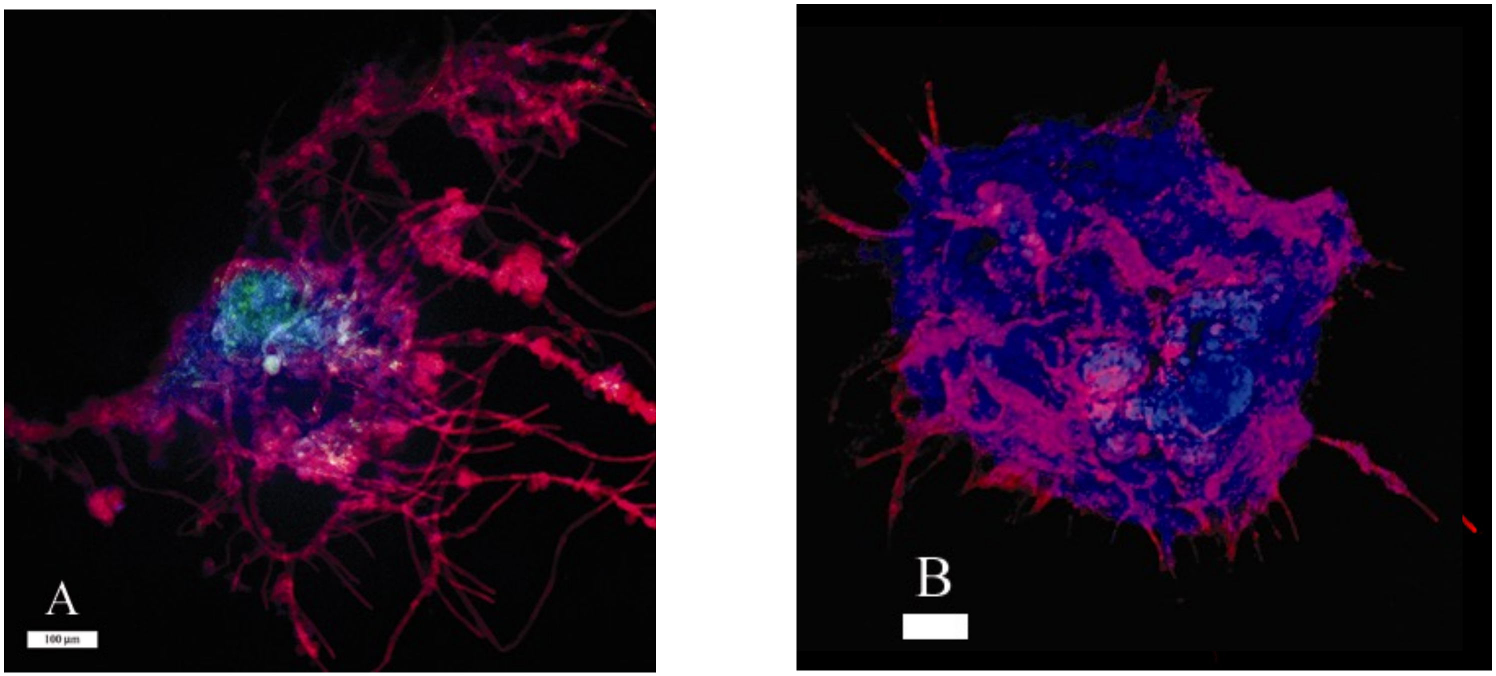




Continuous Flow configuration with high F/M selector



Effect of F/M on EPS Formation

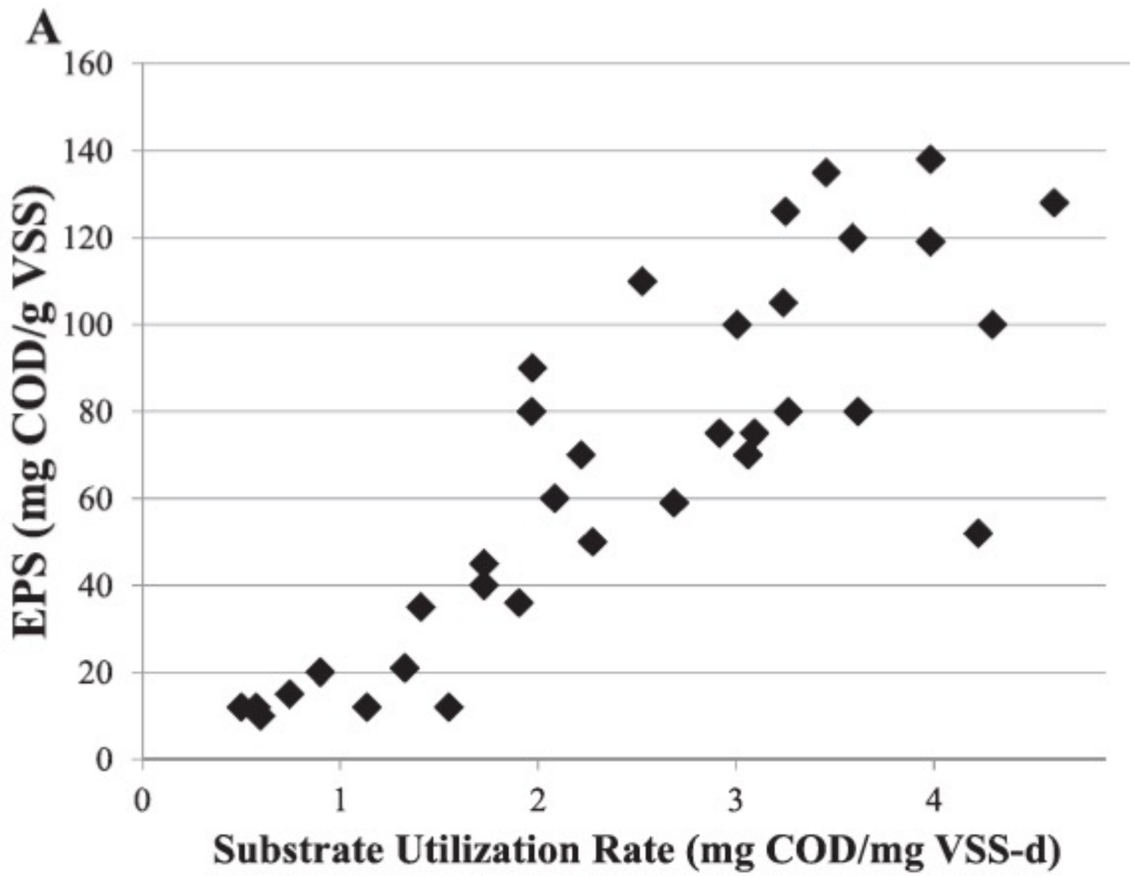


Scale = 100 µm

Cells Polysaccharides - Bl oteins Gre

McSwain et al. (2005). *Applied and Environmental Microbiology*, *71*(2), 1051-1057.

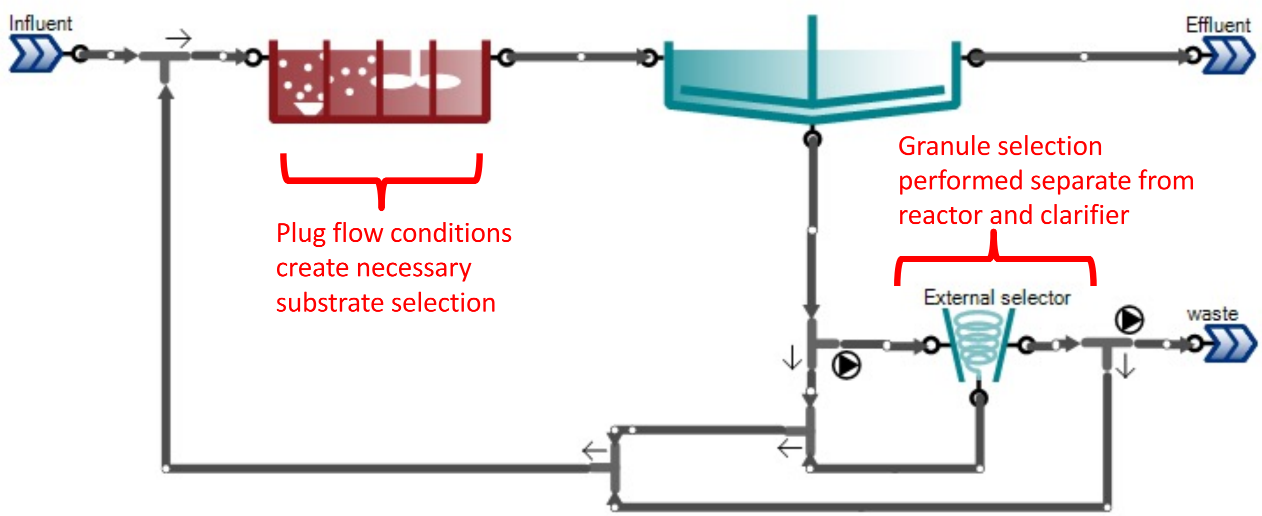
Effect of substrate utilization on EPS and granulation



Jimenez (2015). *Water research*, *87*, 476-482.

Sludge densification may utilize a combination of biological and physical selection mechanisms

WRF Study Purpose: Granule Application in Continuous-Flow Systems



Liquid-solids separation design must retain granules

Favor **retention** of larger, faster-settling granules over flocs

Short settling times <10 minutes widely applied in SBRs

-"Selective settling pressure"

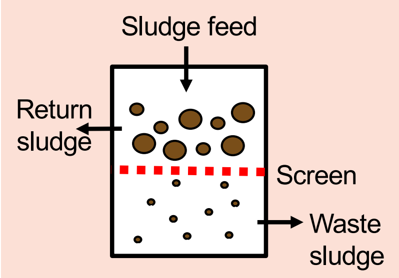
-"Hydraulic selection pressure"

Other approaches involving selective wasting

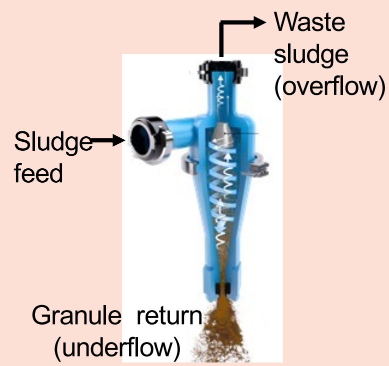
-Screens / Sieves (Liu et al., 2014)

-Hydrocyclones (Welling et al., 2015)

-Surface wasting (Barnard 2015)



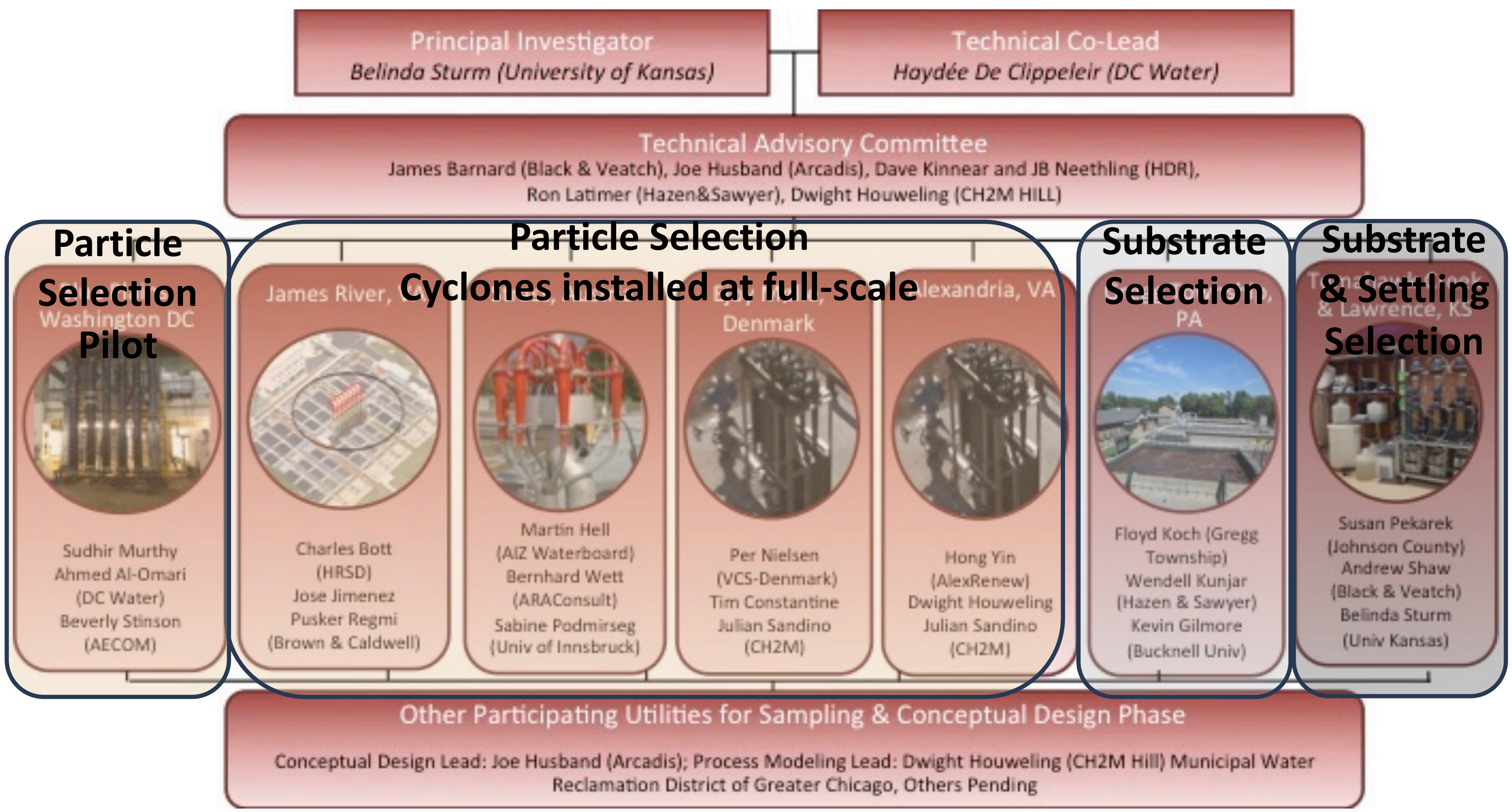
Selective wasting using screening



Selective wasting using hydrocyclones

Figdore, B.A., Stensel, H.D., Winkler, M.K.H., Neethling J.B. (2017) *Aerobic Granular Sludge for Biological Nutrient Removal*. Project No. NUTR5R14h. Water Environment and Reuse Foundation: Alexandria, VA.

Water Research Foundation Project Overview



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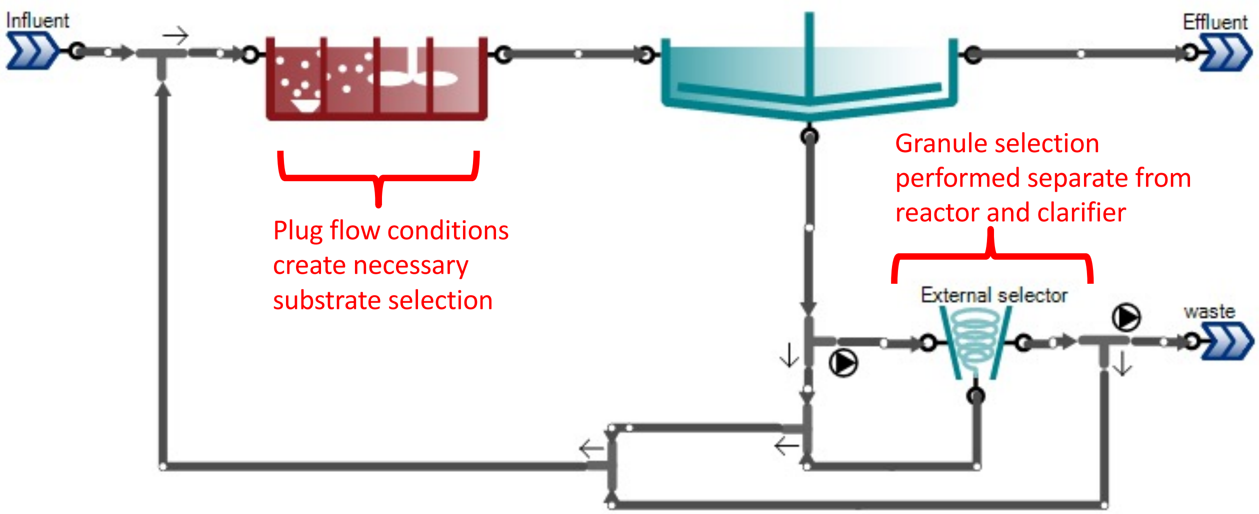

Pilot Studies Manipulating F/M with Wasting

Substrate Selection Only:

North Reactor

A target F/M is maintained by wasting mixed liquor daily (both granules and flocs wasted)

A mixture of granules and flocs are maintained in reactor

South Reactor

Substrate & Particle Selection:

Daily biomass wasting is performed through a 0.2 mm sieve, and granules are retained

Mainly granules are maintained in the reactor

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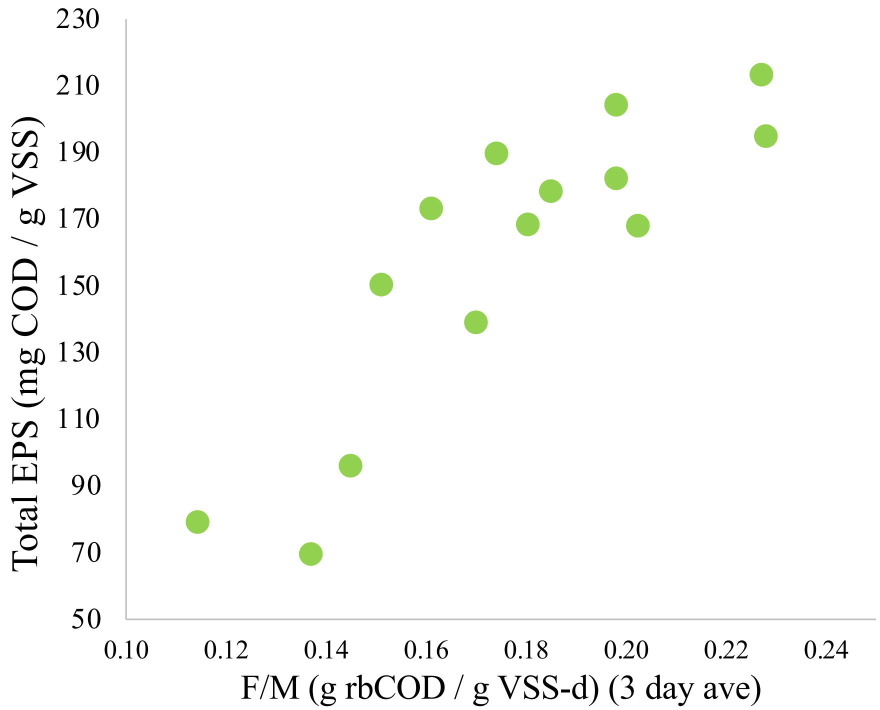
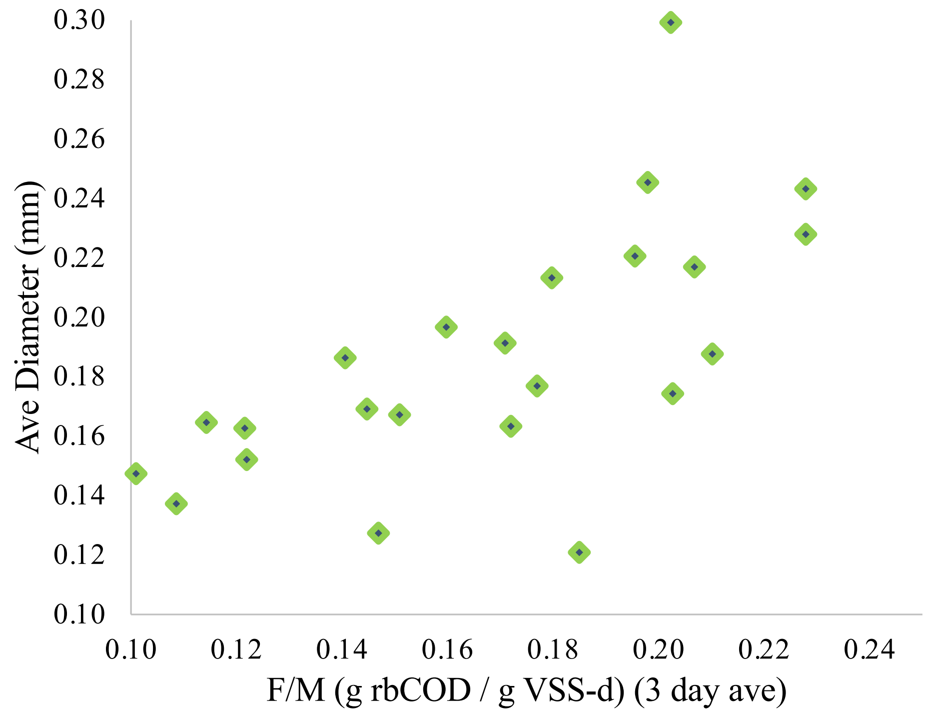
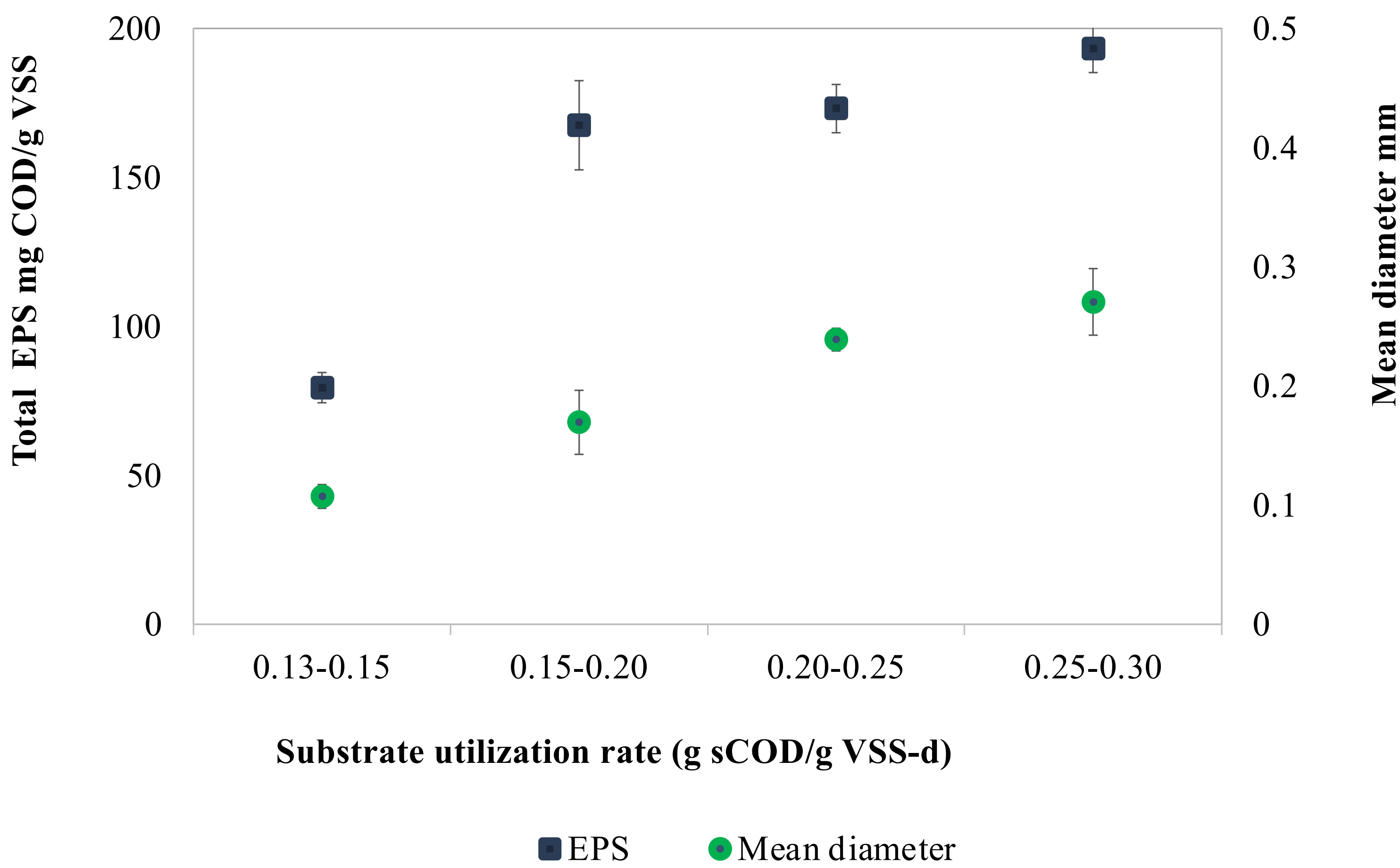
Effect of F/M on EPS and Granule Formation

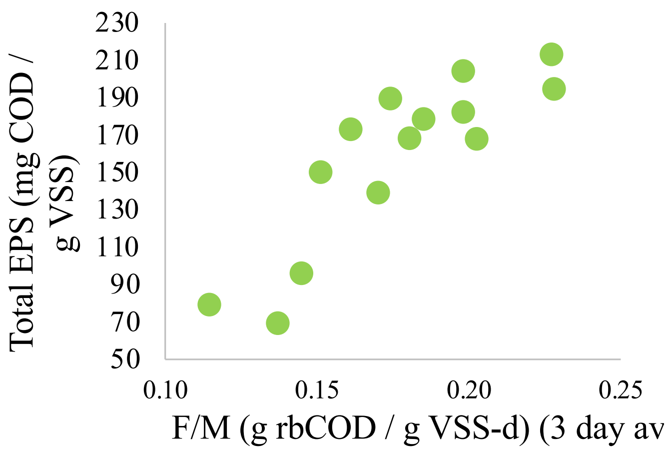


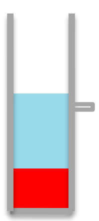


Effect of substrate utilization on EPS and granulation

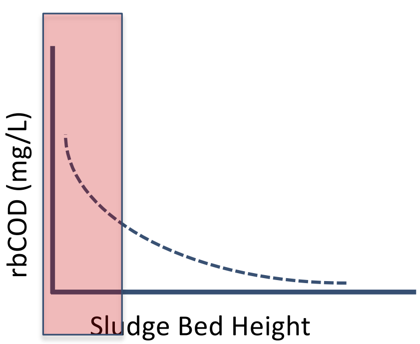


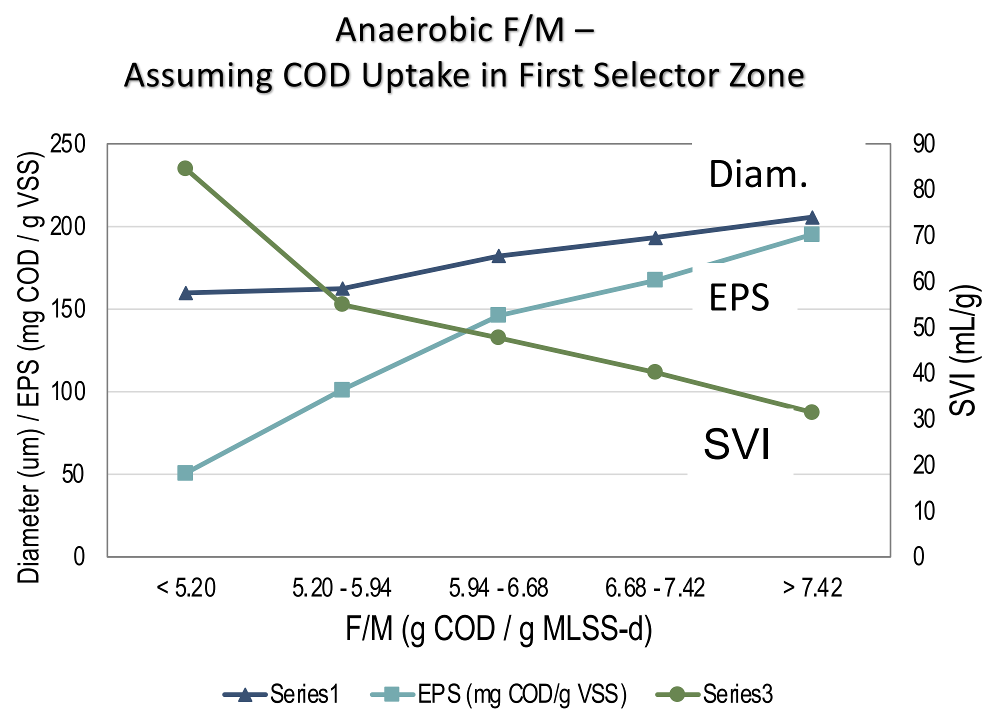
Anaerobic or Metabolic Selectors





Feeding





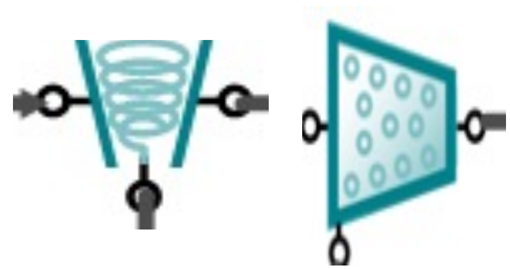
Experimental Plan

Aug. 15, 2015
to Mar. 25, 2016

Granule formation
and development

Mar. 25, 2016
to Oct. 1, 2016

External selector
implementation



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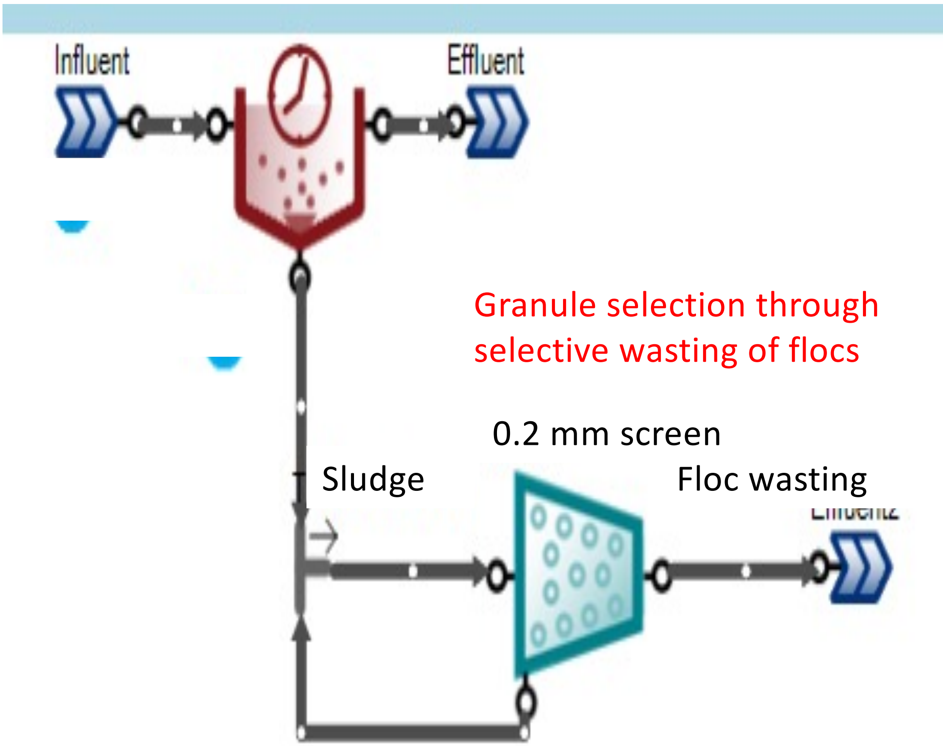
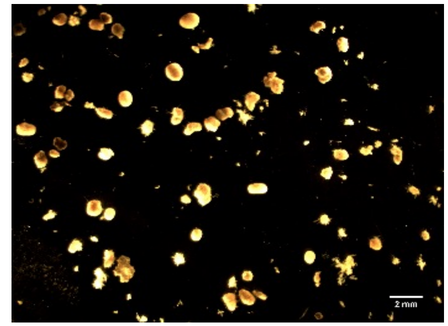
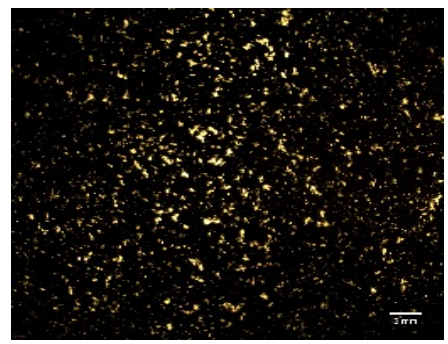
Selective Wasting



Granule selection through selective wasting of flocs



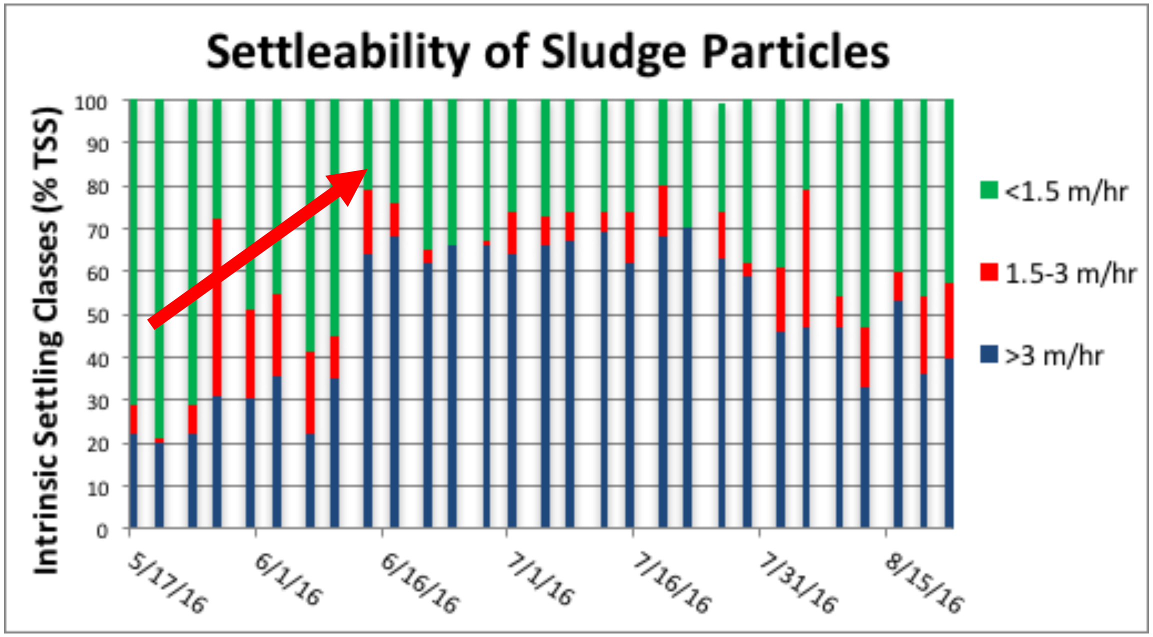
Retained fraction



Wasted fraction

Pilot Studies Manipulating F/M with Wasting

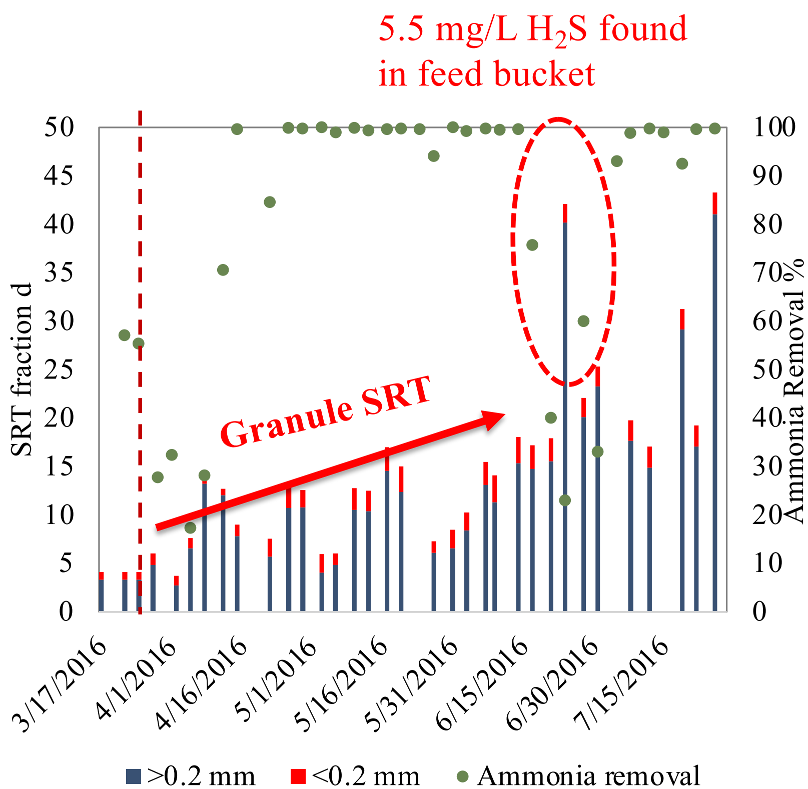
This graph shows the transition to mainly granule particles as the F/M > 0.21

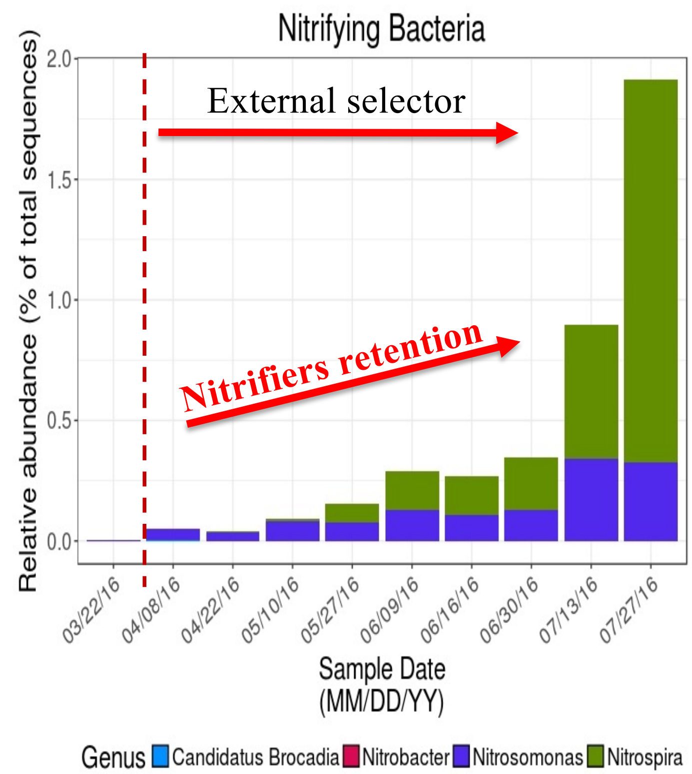


Increasing F/M

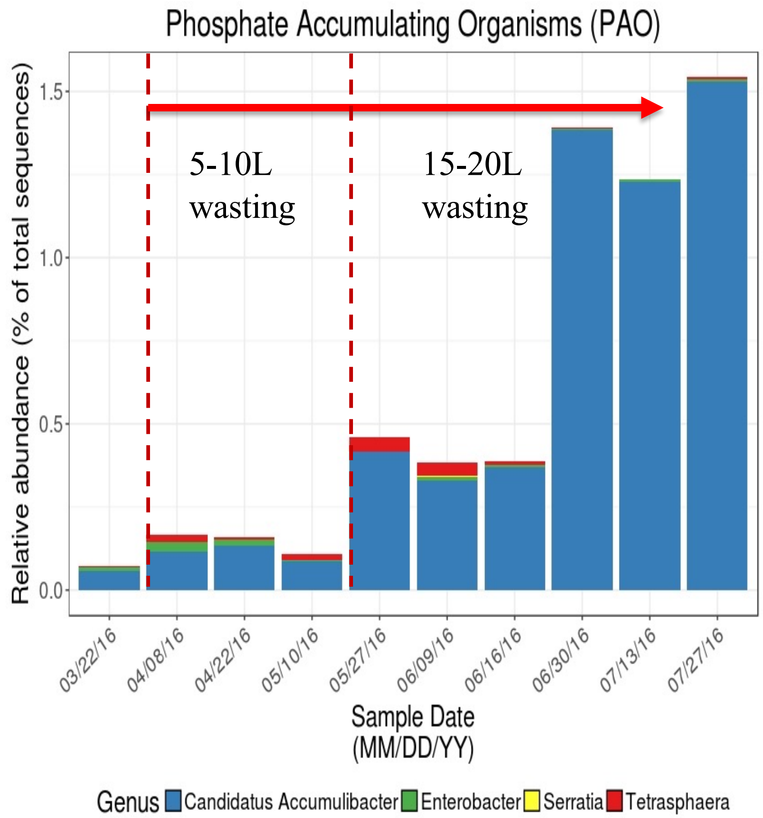
Floc → Granule transition

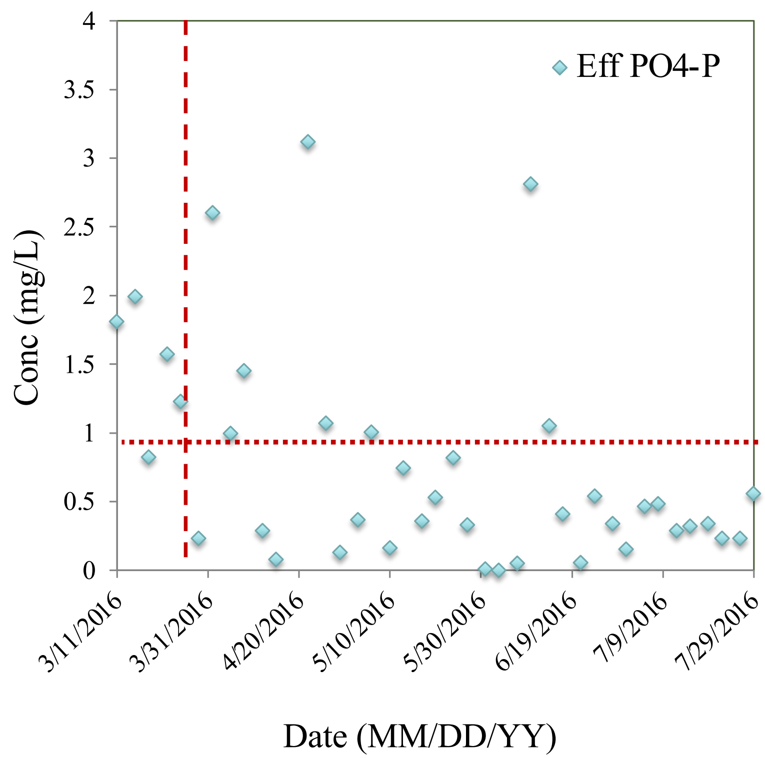
Impact of Selective Wasting on Sludge Structure





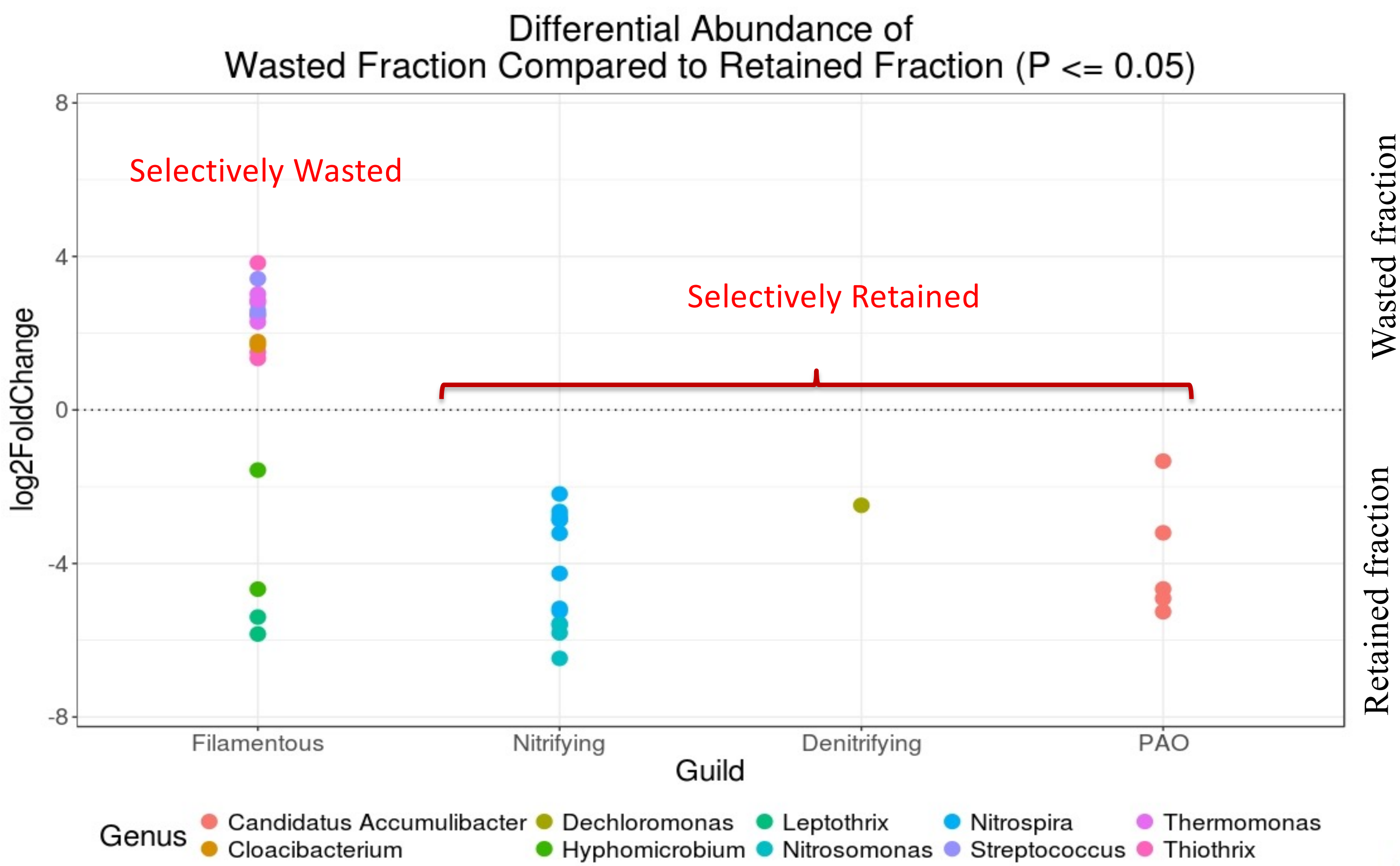
Impact of Selective Wasting on Sludge Structure





Granule retention → PAOs accumulation and phosphate removal improvement

Microbial Community Selection through Wasting



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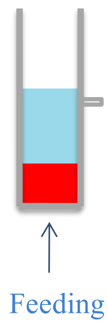
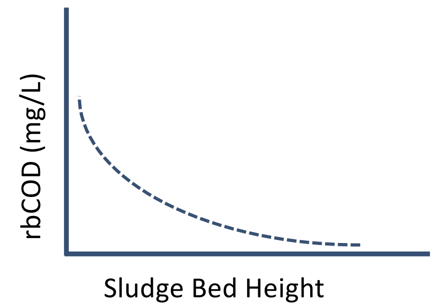
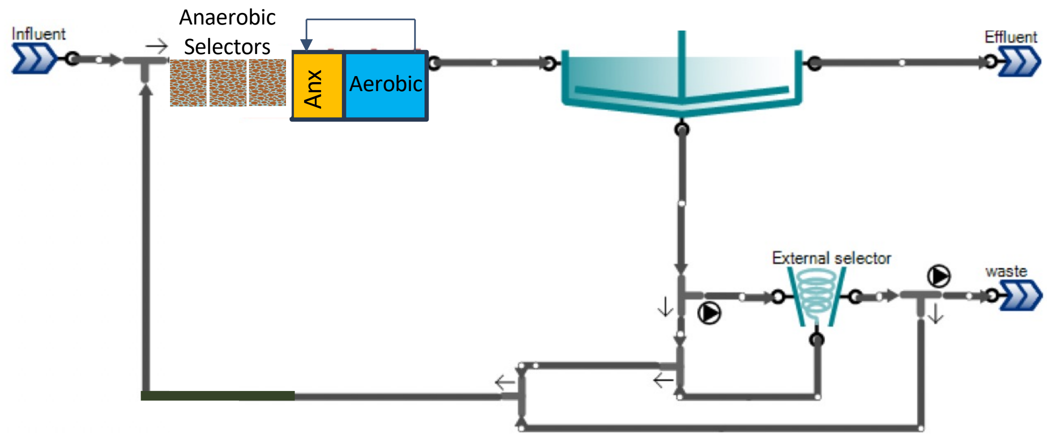
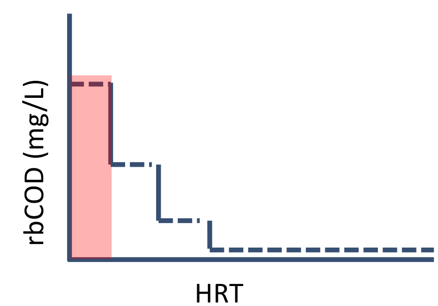
Substrate Utilization in SBR vs Plug Flow



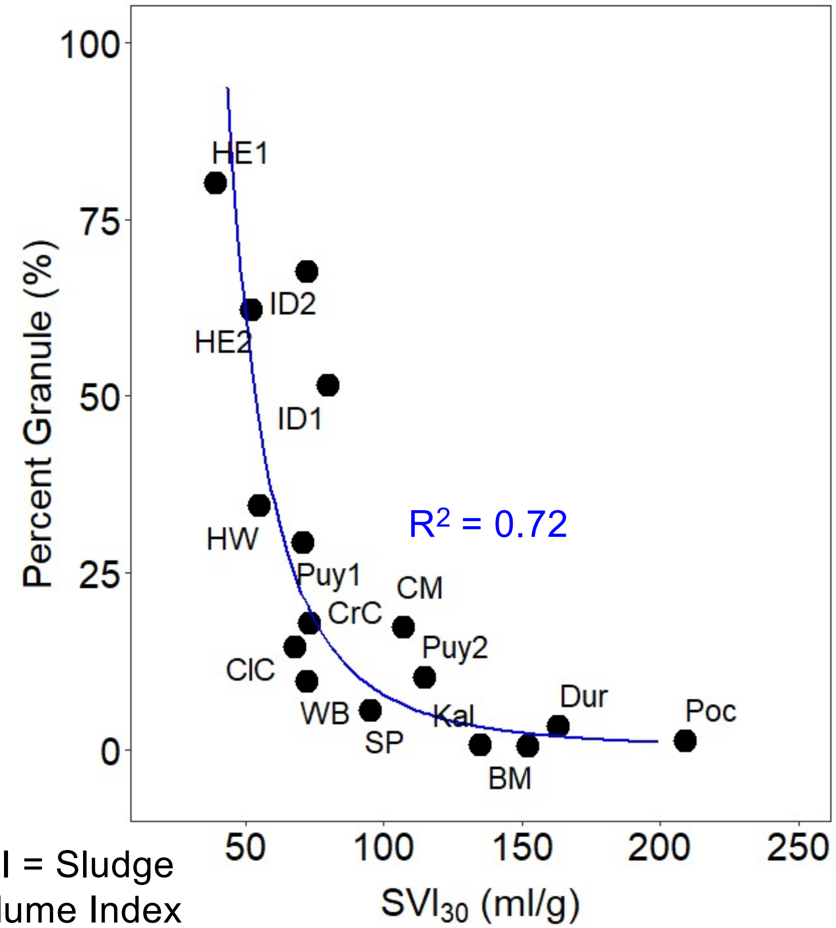


Continuous Flow configuration with high F/M selector

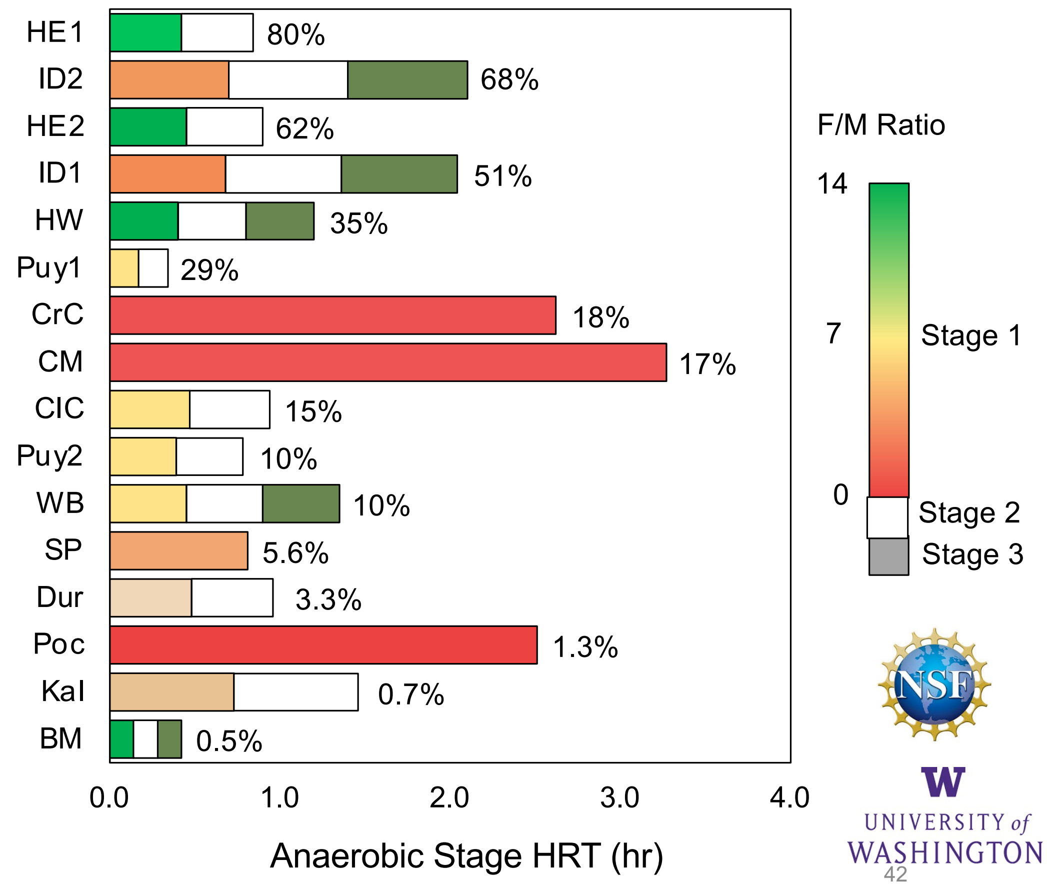




Selection Factors Leading to Granule Growth at CFAS



SVI = Sludge Volume Index



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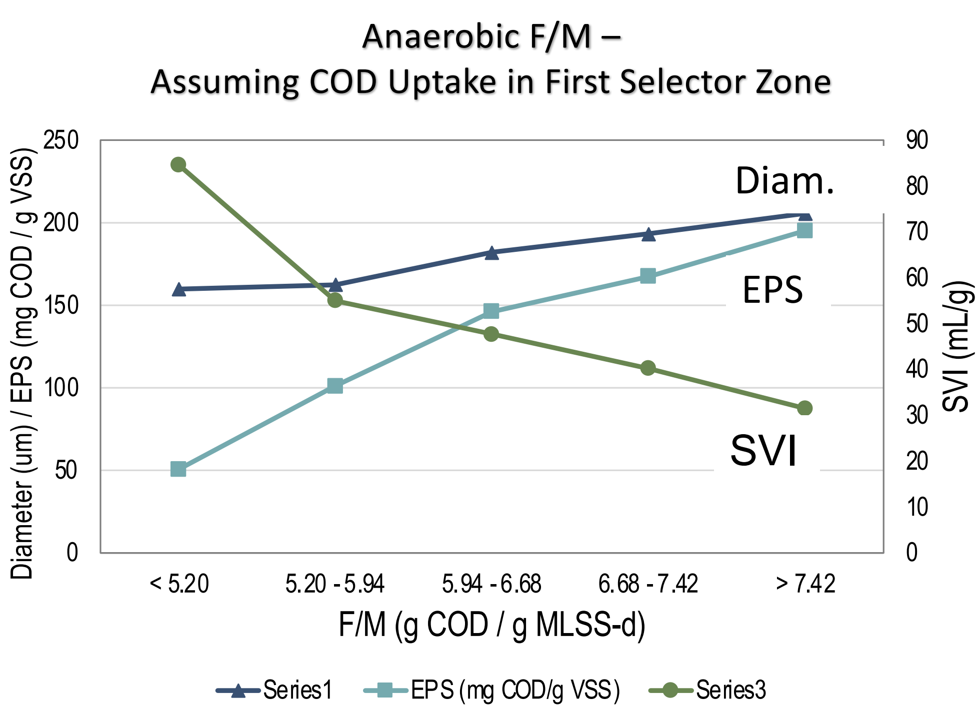
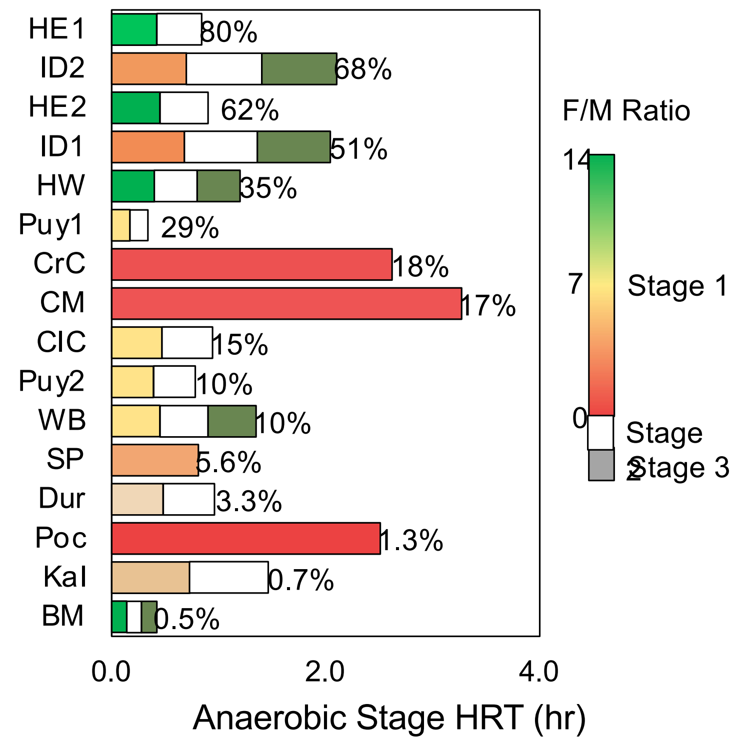
Anaerobic or Metabolic Selectors





Wei, S. P., Stensel, H. D., Nguyen Quoc, B., Stahl, D. A., Huang, X., Lee, P.-H., Winkler, M-K.H., 2020. Flocs in disguise? High granule abundance found in continuous-flow activated sludge treatment plants. Water Research

Summary

Metabolic selectors should be designed to achieve high rbCOD uptake rates, with virtually complete rbCOD removal

An anaerobic F/M ratio greater than 5.2 gCOD/gVSS corresponded to higher EPS production; Anaerobic F/M greater than 7 has been associated with granulation

Microorganisms subjected to high F/M may accumulate substrate as internal storage products

It is possible to form granular sludge in continuous flow systems

Future Work

As densification is achieved….

- How do existing clarifiers handle the additional solids loading rate?
- Full-scale experience with fines will provide confidence
- Implementation of hydrocyclones or screens to selectively waste flocs and retain granules has great potential
    - But operators need experience managing TWO sludge fractions separately

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