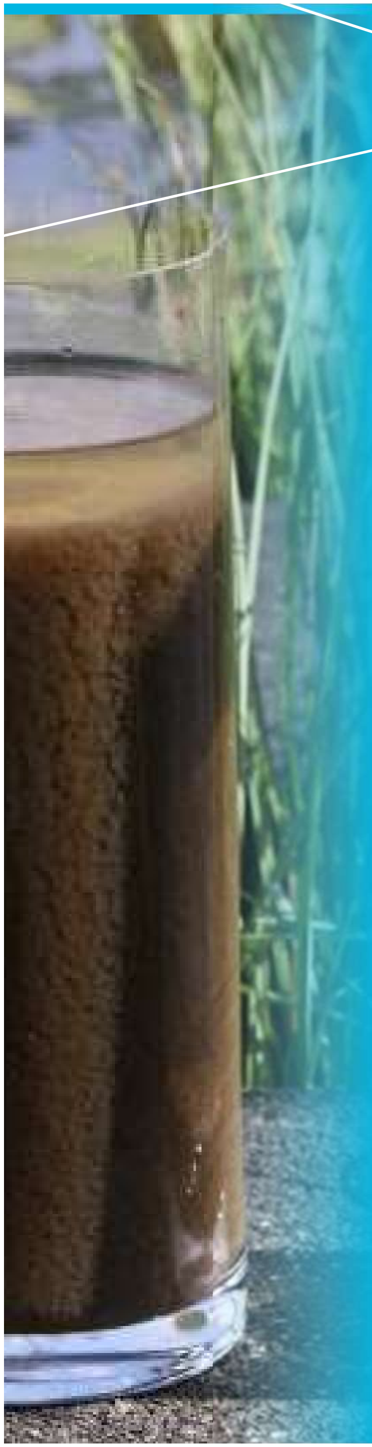

Innovative Process for Granulation of Continuous Flow Conventional Activated Sludge

Bev Stinson, Ph.D

AECOM, Global Wastewater Technology Leader

May 9th 2019

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Introduction

The objective of this presentation is to:

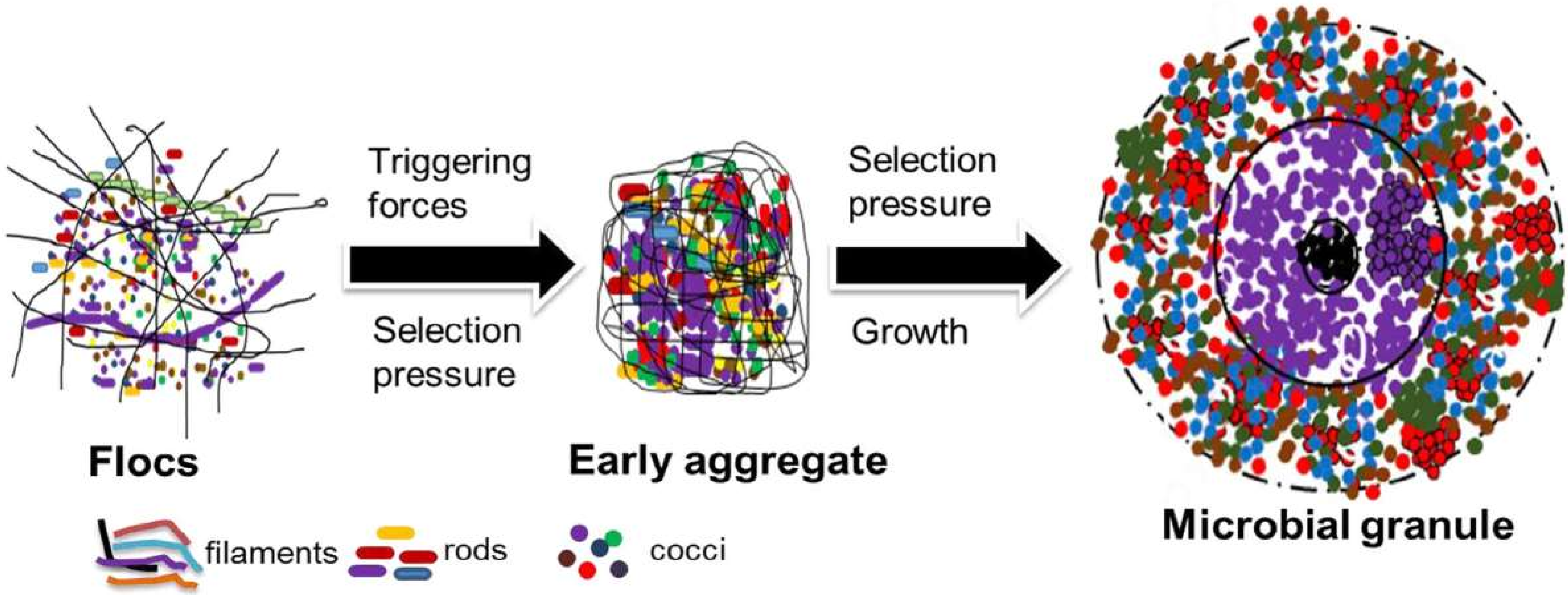
- Introduce Aerobic Granular Sludge (AGS), including mechanisms for formation and benefits
- Present performance data for a Nereda® SBR pilot
- AECOM’s continuous-flow granular sludge process for BNR infra-stretching or footprint reductions

What is Granular Sludge?

– Sludge granule is a tightly aggregated mass of microorganisms in a matrix of extra polymeric substances (EPS)

– A cross between floc and fixed film growth

– Their large size (>0.2mm) and density allow for excellent settling characteristics = more compact WWTPs



Reference: Sarma, S.J. et al., 2017. Finding knowledge gaps in aerobic granulation technology

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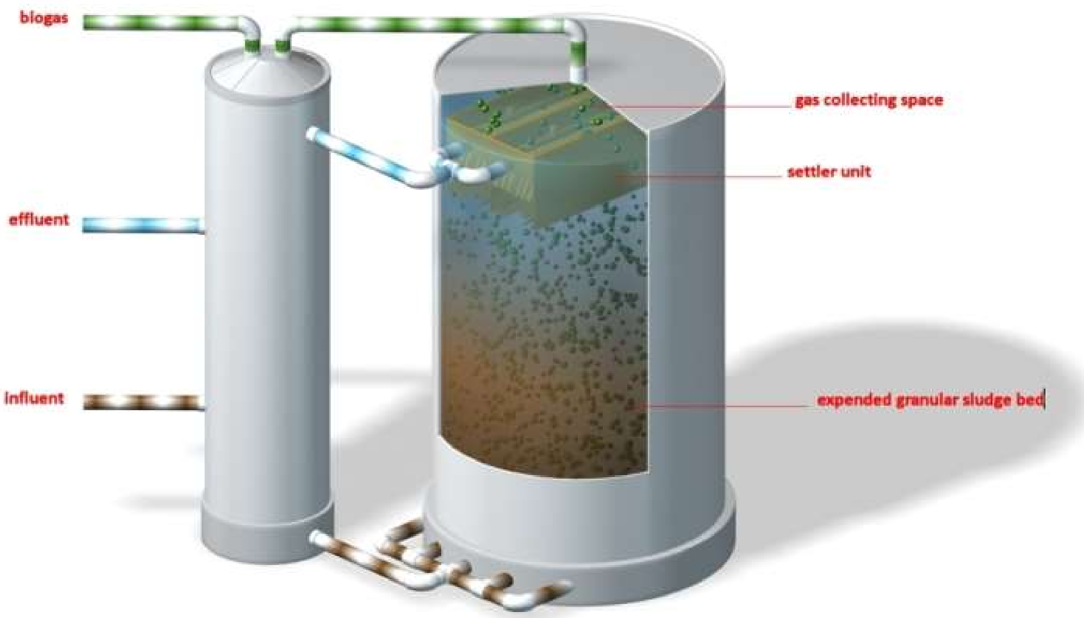
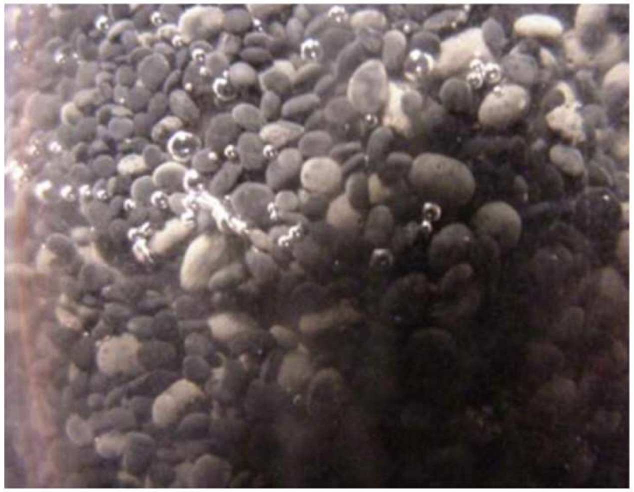
Granular Sludge Relies on Dominance Slow Growing Microorganisms

– Treatment processes that rely on slow-growing bacteria are better at granulation

– Anaerobic systems were the first granular sludge processes developed (Biothane™, Biobed™) to treat high strength soluble COD waste



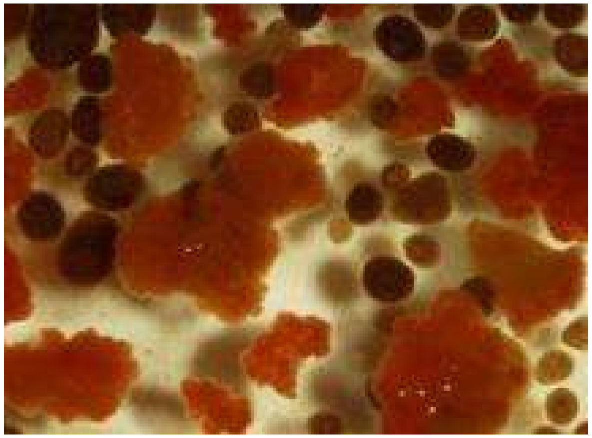


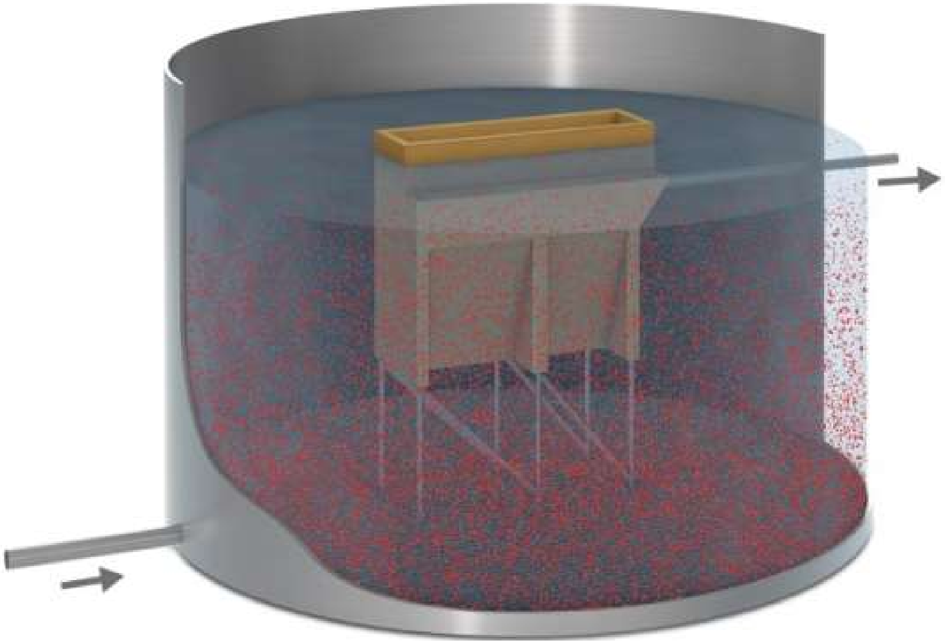
Anaerobic granules supporting acid formers & methanogen growth

Reference: van Lier, J.B. et al., 2015. Celebrating 40 years anaerobic sludge bed reactors for industrial wastewater treatment

Granular ANAMMOX

– The first Anaerobic Oxidizing Ammonia (ANAMMOX™) process was based on a granular sludge approach





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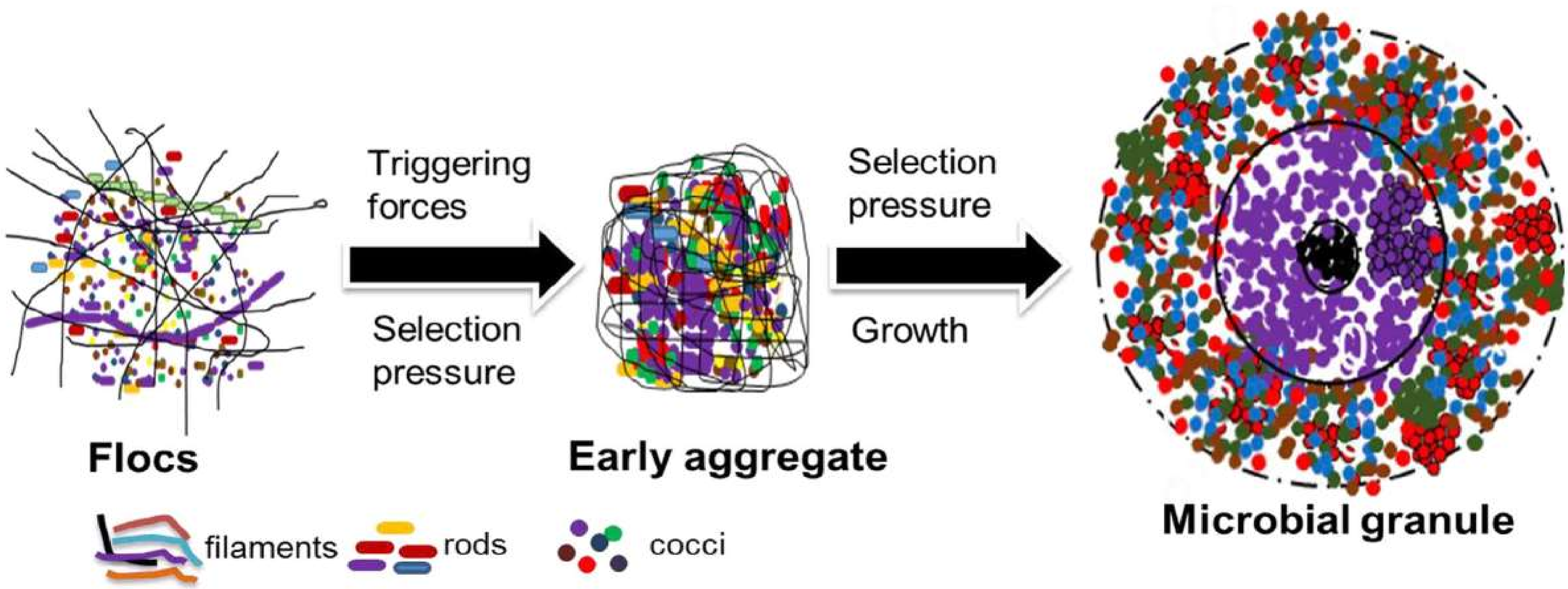
Aerobic Granular Sludge

– Developing aerobic granular sludge (AGS) for treating domestic wastewater has been more challenging

– Growth from floc to granule in an aerobic environment more complex

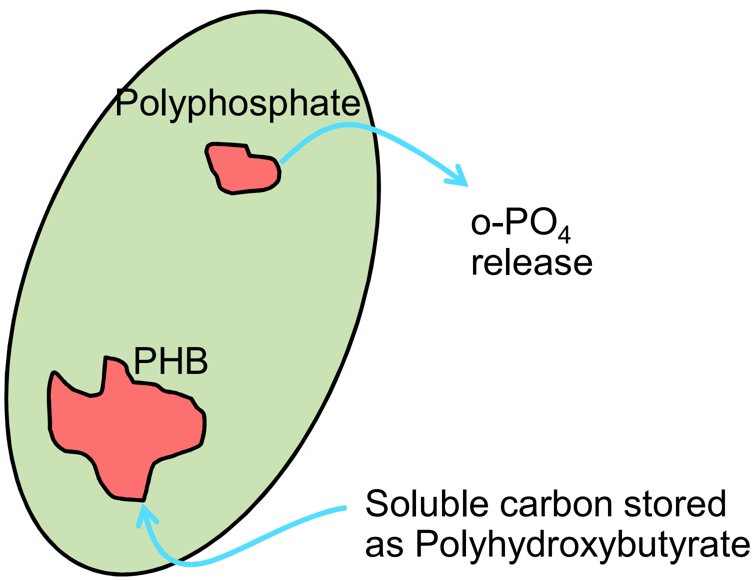


Reference: Sarma, S.J. et al., 2017. Finding knowledge gaps in aerobic granulation technology

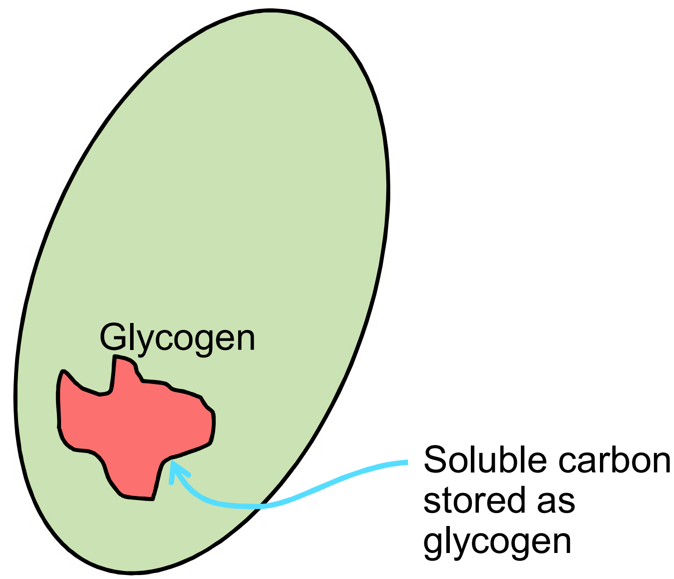
Core of Granule Relies on Growth of Dense PAOs & GAOs

- Feeding PE under anaerobic conditions selects for polyphosphate accumulating and glycogen accumulating organisms (PAO's & GAO's)
- PAOs & GAOs uptake and store soluble carbon (rbCOD) under anaerobic conditions for later use in the aerobic phase
- rbCOD is mostly gone before the aeration phase starts ('Famine' stage)

PAO's Under Anaerobic Conditions



GAO's Under Anaerobic Conditions



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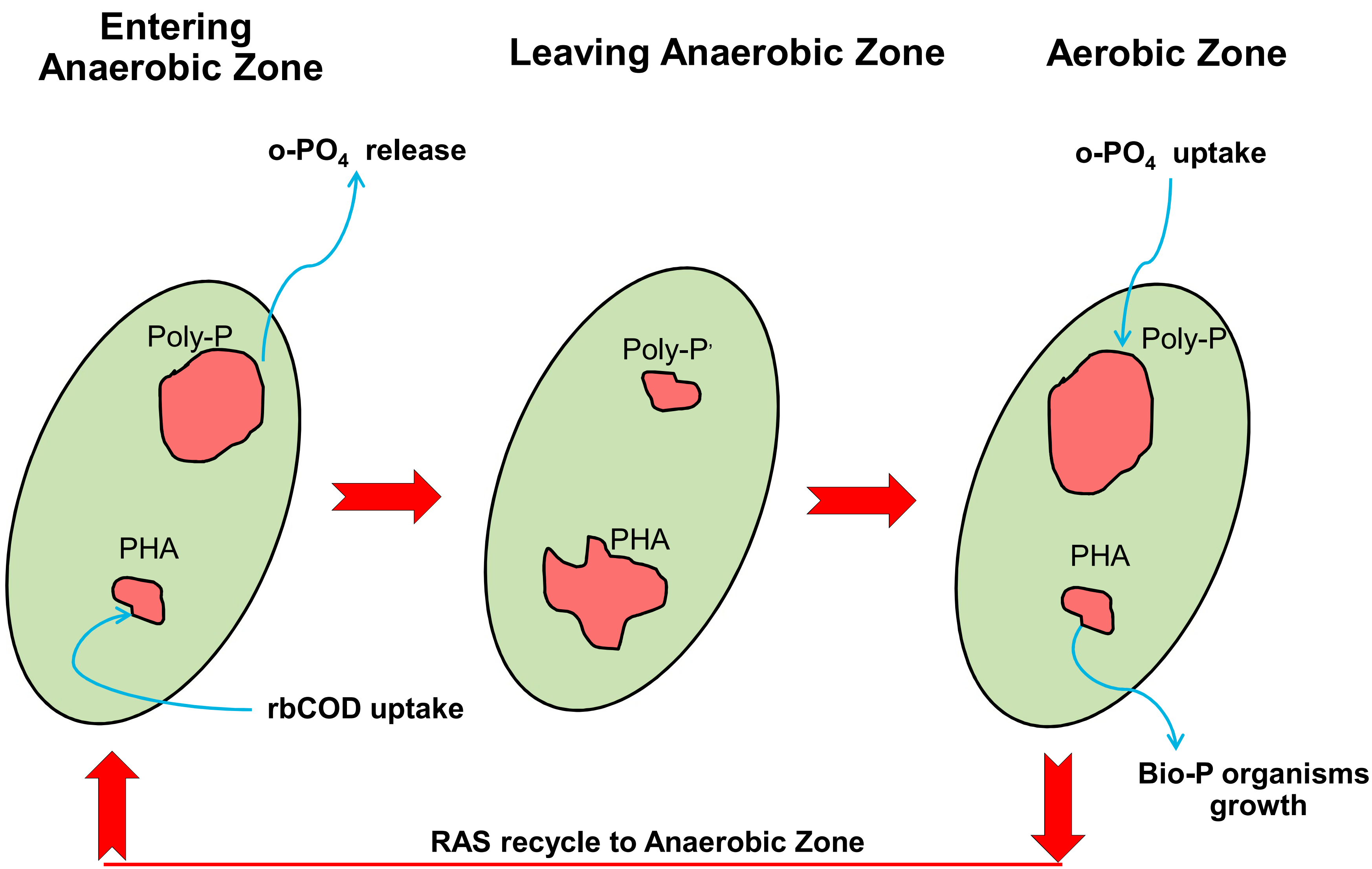
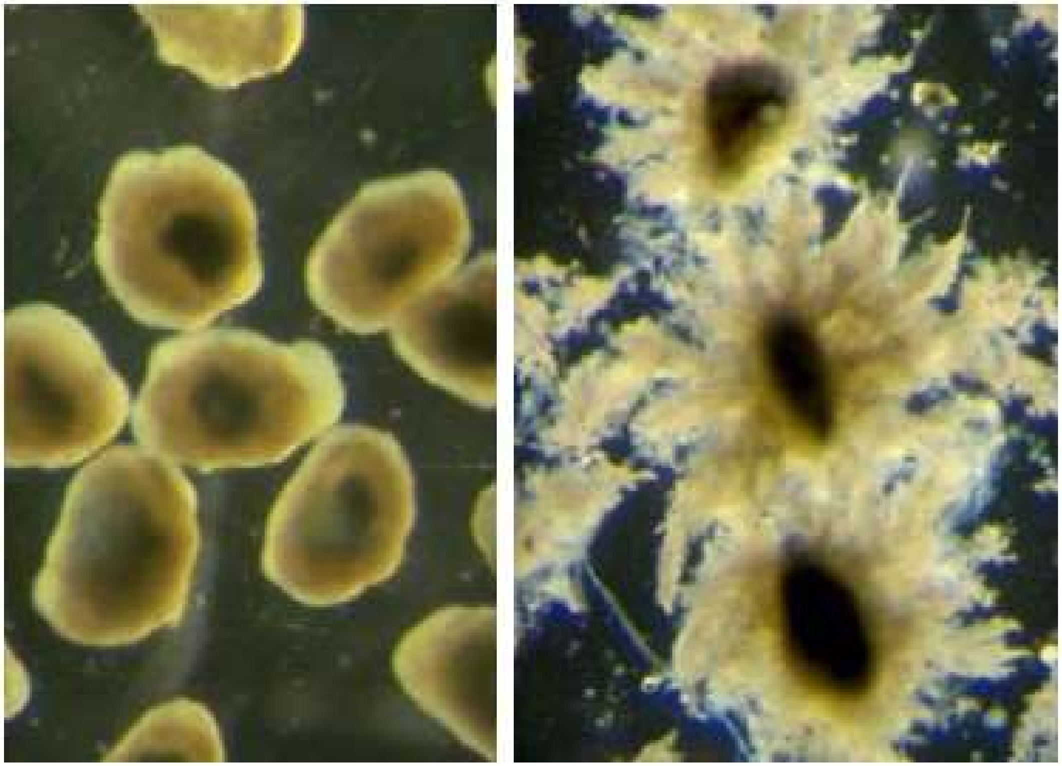
Feast / Famine cycles promotes EPS Production



Slow Growing Organisms Enhance Granule Morphology

– Feeding PE under anaerobic conditions selects for organisms that outcompete filamentous aerobic heterotrophs

– PAO's & GAO's do not have a filamentous morphology and allows for a reliably stable granule



Reference: adapted from van Loosdrecht, M., 2013. Advances in Aerated Granular Sludge Technologies (WEF presentation).

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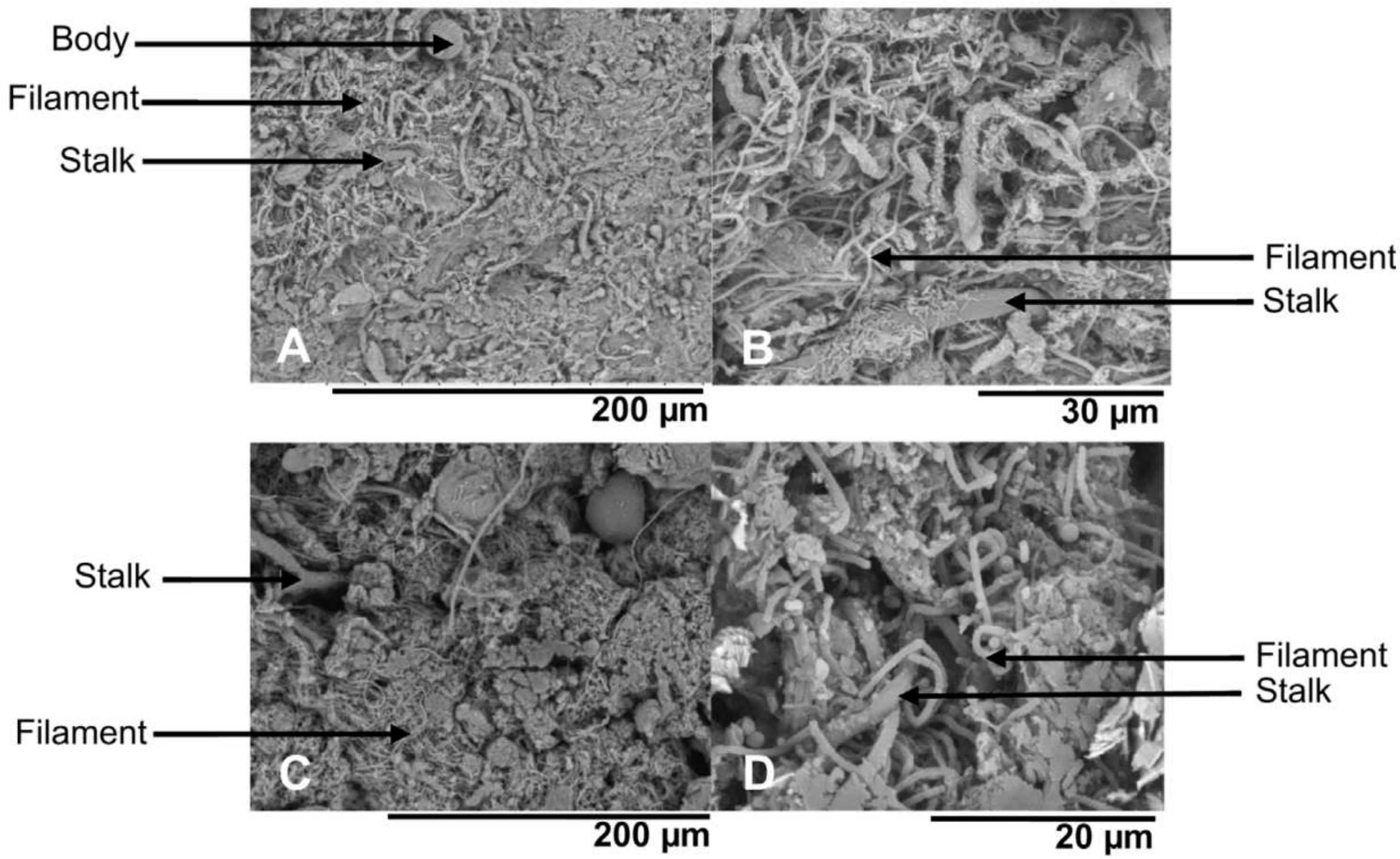
Aerobic Granular Sludge

– Granules are highly porous and allow for mass transfer through the microorganism EPS complex.



Reference: Liu, J. et al, 2018. Roles of bacterial and epistylis populations in aerobic granular SBRs treating domestic and synthetic wastewaters

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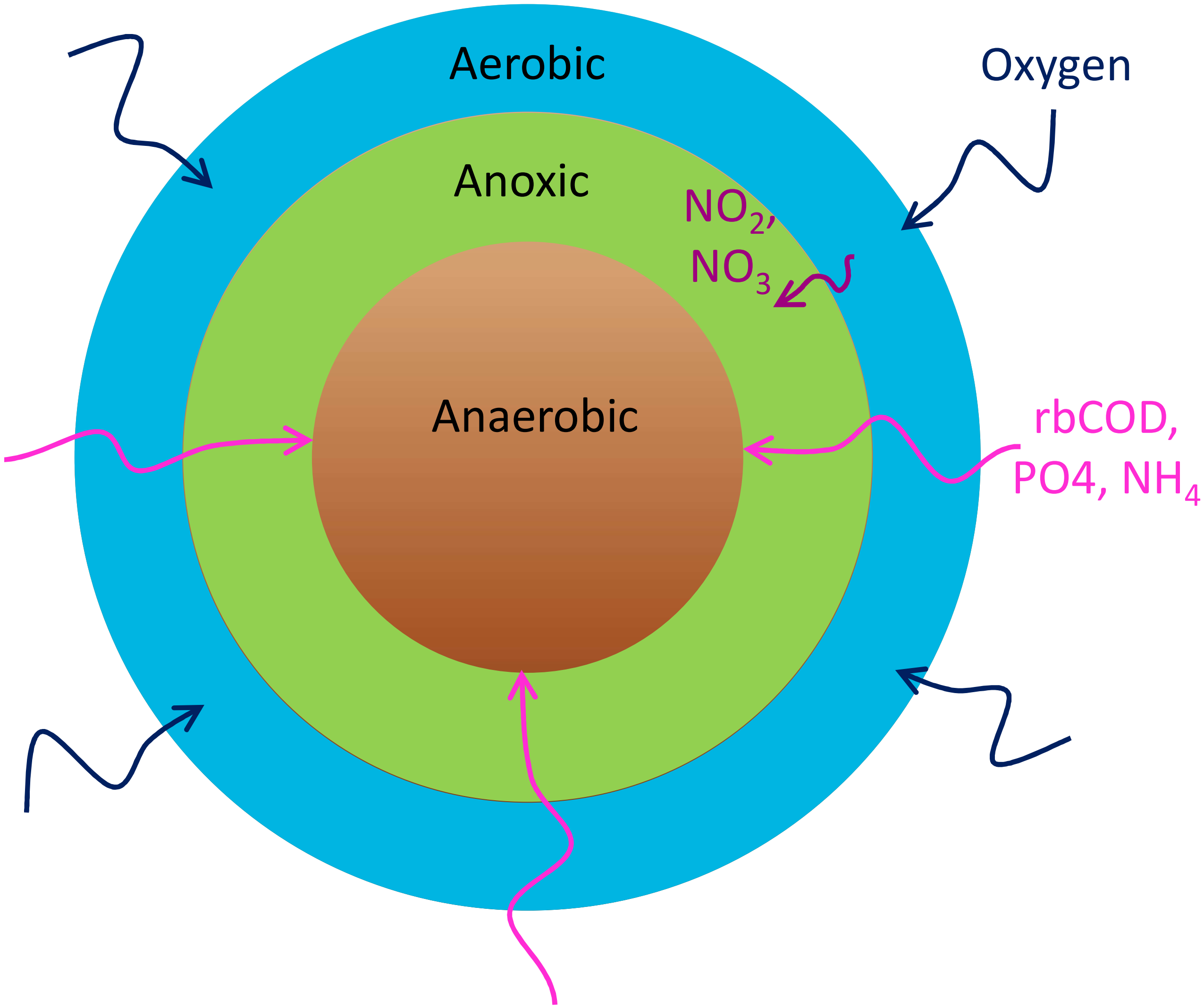
Granule Porosity Both a Strength and a Vulnerability



- Porosity allows for diverse ecological niches and biological conversions
- Porosity a strength & vulnerability

Reference: adapted from Nancharaiah, Y.V. et al, 2018. Aerobic granular sludge technology: Mechanisms of granulation and biotechnological applications

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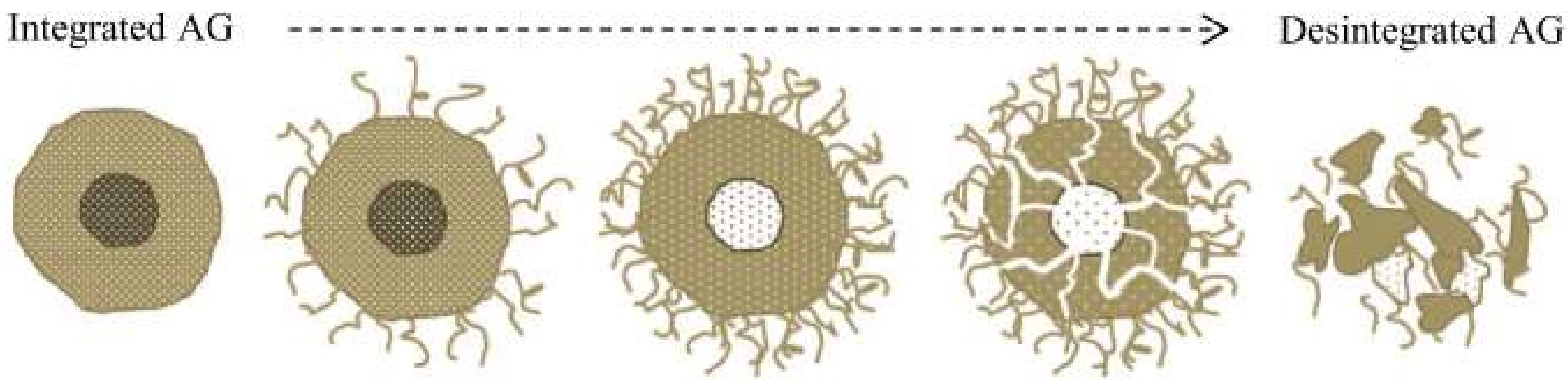
Granules Vulnerable with excessive attachment of fast growing organisms



- Pores can be clogged by overgrowth of filamentous bacteria on the outer layer when rbCOD is present under aerobic conditions.

- Reduction of porosity reduces mass transfer, internal core is consumed & granule disintegrates

- Need to control fast growing bacteria typically found in activated sludge systems

Reference: Franca, R.D.G. et al. 2018. Stability of aerobic granules during long-term bioreactor operation.

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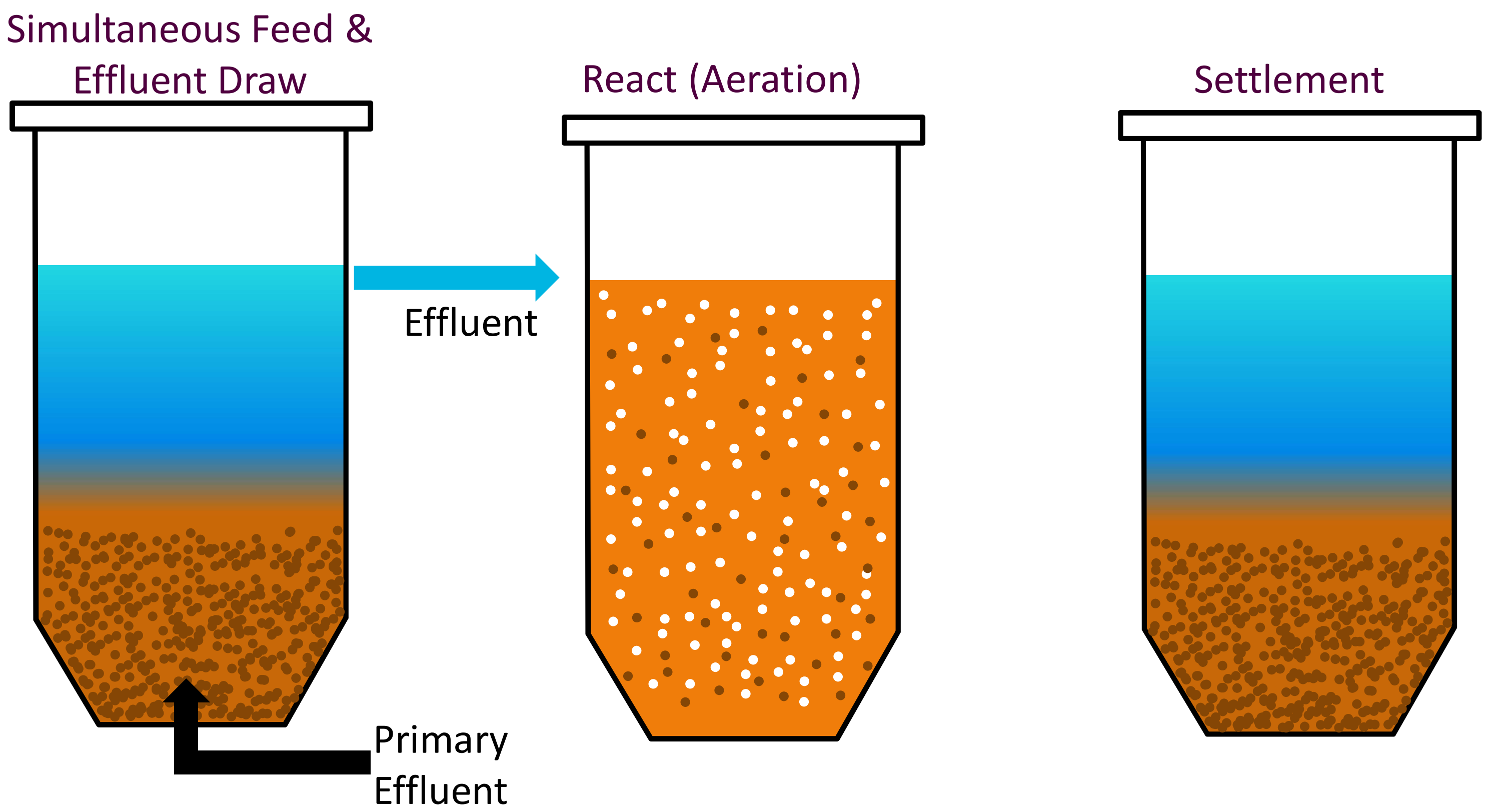
Nereda® - Batch "SBR" Granular Sludge

– An important milestone in the development of AGS was adding an anaerobic selector – the 'Feast' stage

– Nereda®, the first commercialized AGS, uses a batch process

– After the aeration phase and sludge settles, PE is fed to the reactor



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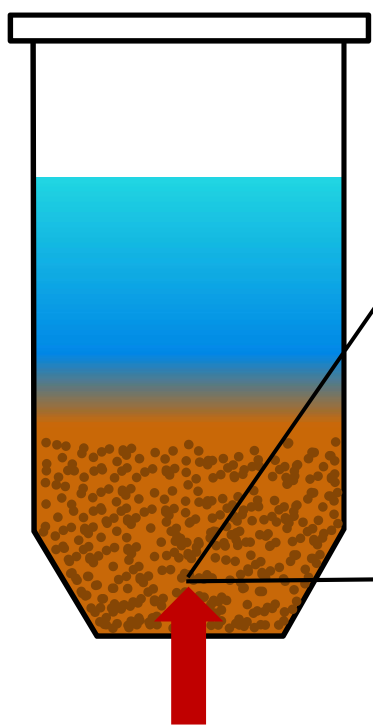
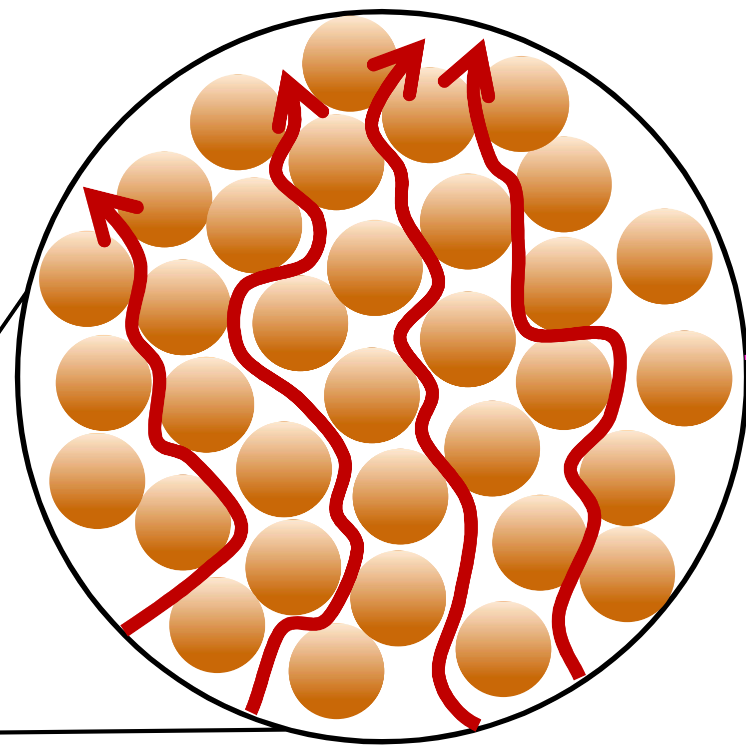
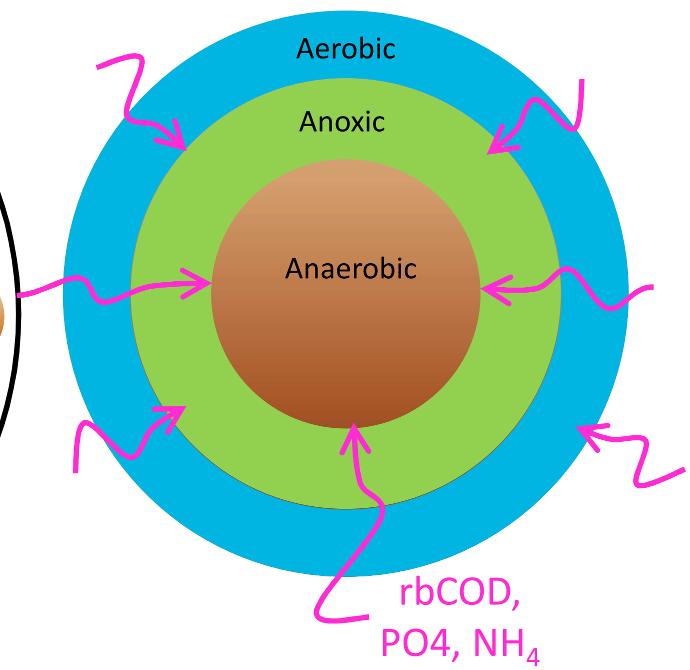
Promotes High rbCOD Concentration Contact with Granules to Overcome Diffusion Gradient & Feast Condition



Raw Influent or Primary Effluent

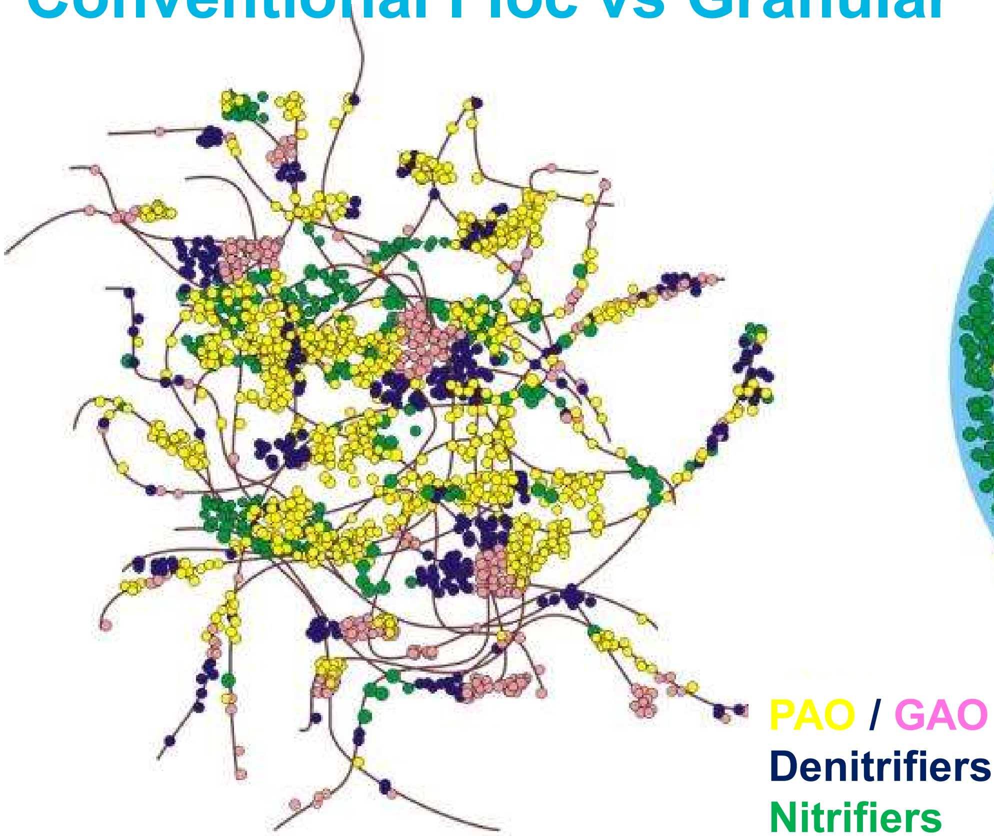


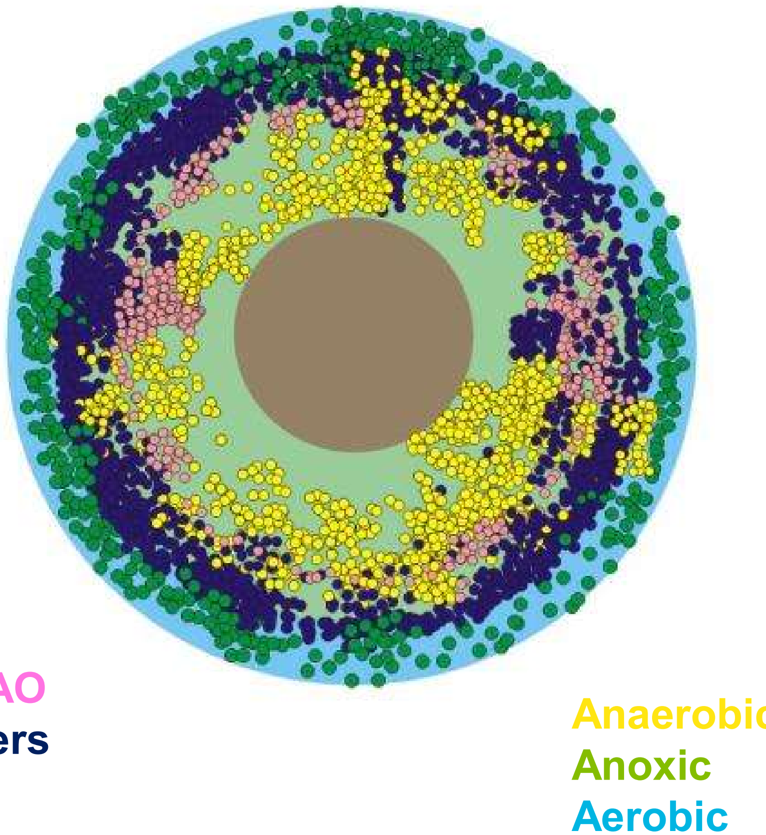


- Plug flow promotes PE contact with granule
- PE contact overcomes any diffusion gradient

Reference: adapted from van Loosdrecht, M., 2013. Advances in Aerated Granular Sludge Technologies (WEF presentation).

Conventional Floc vs Granular





Characteristic	Floc	Granule
Settling	Compression	Discrete
Settling Velocity (m/h)	±1.0	5 – 50
Size	na	> 0.2 mm
SVI, 30 minutes	100 -150	< 60

Picture Courtesy Delft Technical University

Nereda® Aerobic Granular Sludge

- The settled volume of sludge after 5 minutes is similar to that after 30 minutes
- SVI 5 / SVI 30 ≈ 1.0

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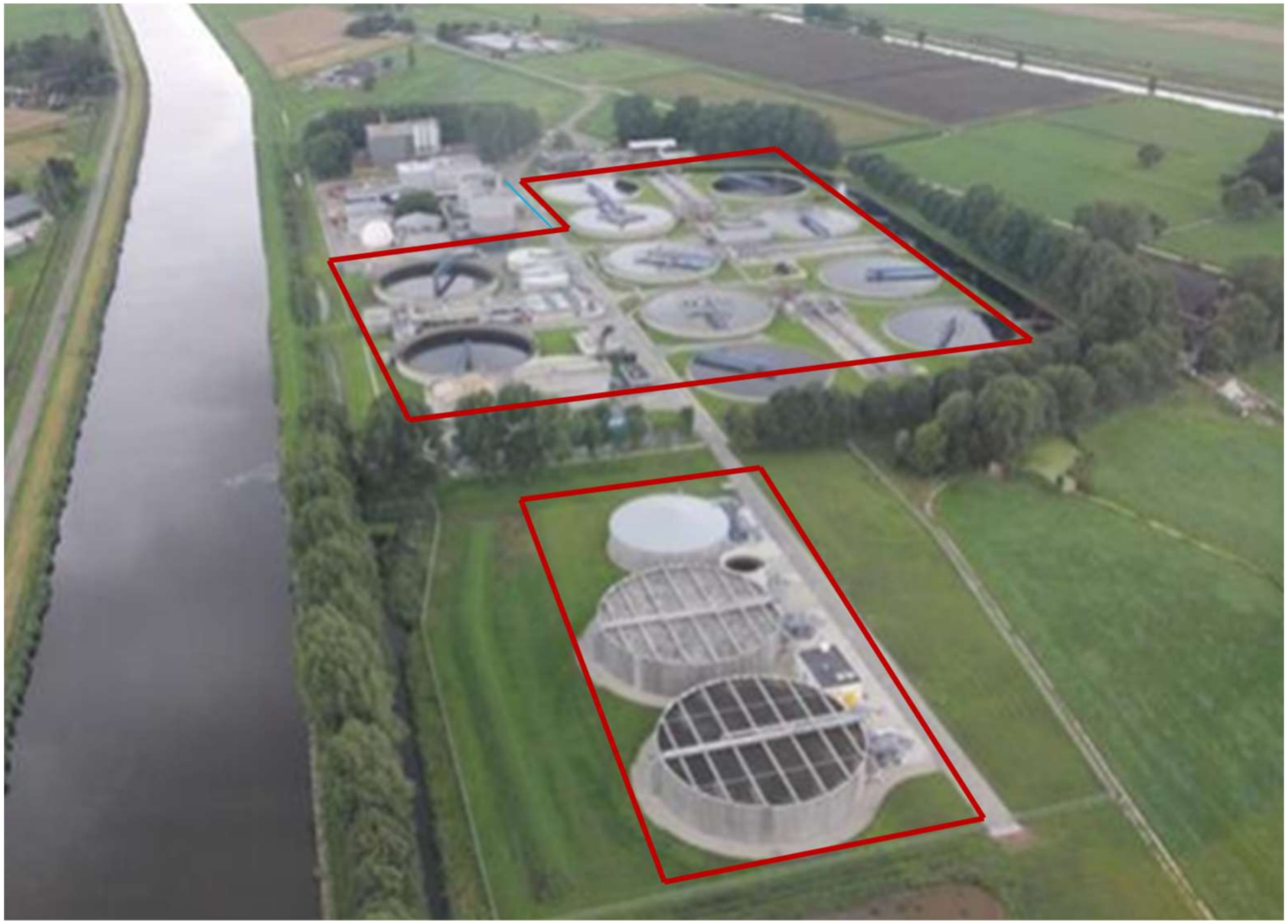
Benefits of Aerobic Granular Sludge



Garmerwolde, NL WWTP Nereda
Footprint Advantage – 75% Footprint Reduction

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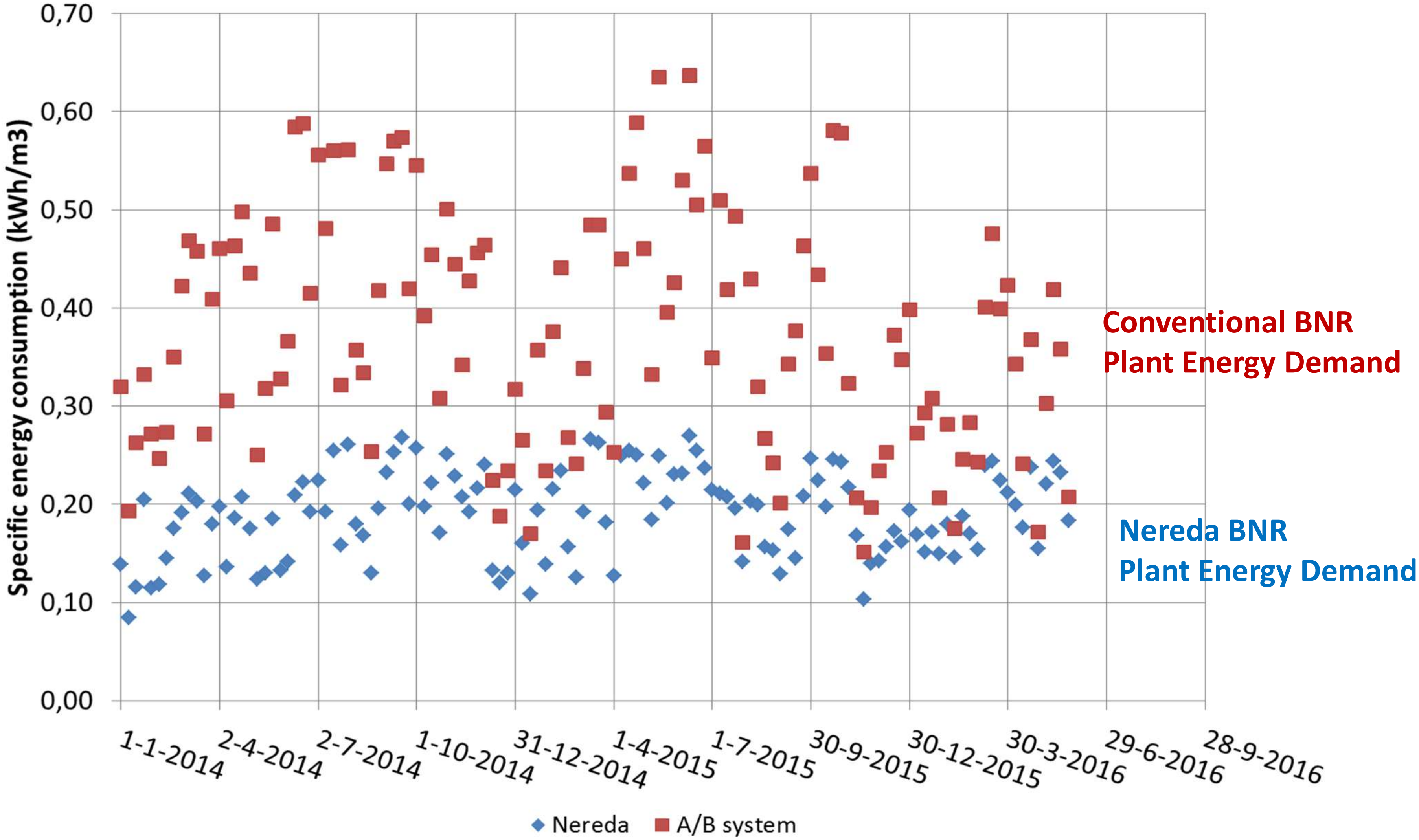
Garmerwolde, NL WWTP Nereda
Energy Advantage – >40% Energy Reduction



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30 Full Scale Nereda® Plants Around the World

	Daily average flow (MGD)	Peak flow (MGD)	Startup
Vika, Ede (NL)	0.07	0.07	2005
Cargill, Rotterdam (NL)	0.18	0.18	2006
Fano Fine Foods, Oldenzaal (NL)	0.10	0.10	2006
Smilde, Oosterwolde (NL)	0.13	0.13	2009
STP Gansbaai (RSA)	1.32	2.54	2009
STP Epe (NL)	2.11	9.51	2011
STP Garmerwolde (NL)	7.93	26.63	2013
STP Vroomshoop (NL)	0.40	2.54	2013
STP Dinxperlo (NL)	0.82	3.61	2013
STP Wemmershoek (RSA)	1.32	3.96	2013
STP Frielas, Lisbon (PT)	3.17	3.17	2014
STP Ryki (PL)	1.40	2.73	2015
Westfort Meatproducts, Ijsselstein	0.37	0.37	2015
STP Clonakilty (IRL)	1.29	3.97	2015
STP Carrigtwohill (IRL)	1.78	5.35	2015
STP Deodoro, Rio de Janeiro (BR)	22.82	38.80	2016
STP Jardim Novo, Rio Claro (BR)	0.47	11.18	2016
STP Hartebeestfontein (RSA)	1.32	7.93	2016
STP Kingaroy (AUS)	0.71	2.85	2016
STP Ringsend SBR Retrofit 1 Cell, Dublin (IRL)	21.66	42.80	2016
STP Highworth (UK)	0.37	1.27	2016
STP Cork Lower Harbour (IRL)	4.83	11.60	2016
STP Simpelveld (NL)	0.97	5.99	2016
STP Ringsend Capacity Upgrade, Dublin (IRL)	30.91	58.58	2019
STP Alphach (CH)	3.70	11.70	2017
STP Österröd, Strömstad (S)	0.99	2.28	2017
STP Tatu, Limeira (BR)	15.06	22.14	2016
STP São Lourenço, Recife (BR) 1st phase	5.04	10.61	2016
STP São Lourenço, Recife (BR) 2nd pahse	6.64	10.61	2024
STP Jaboatão, Recife BR) 1st phase	28.97	73.47	2017
STP Jaboatão, Recife BR) 2nd phase	40.81	73.47	2025
STP Jardim São Paulo, Recife (BR)	5.16	37.15	2017
STP Jardim São Paulo, Recife (BR)	20.64	37.15	2025
STP Utrecht (NL)	14.53	83.69	2018
STP Faro-Olhão (PT)	7.44	24.99	2018

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> 30 Full Scale Nereda Facilities Worldwide

Ringsend, Dublin Ireland, 2019 - Expansion and Upgrade

Flows	
Average Flow (MGD)	Peak Flow (MGD)
115	159

- Retrofit SBR – in stages
- High salinity

Original Activated Sludge:
- TN < 20 mg/l
- Poor settling

Nereda Conversion:
- TN < 10 mg/l
- TP reduction

- No increase in tankage
- Increased MLSS to 8-15 g/l

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AECOM Nereda Experience

Extensive experience in Demonstrating and Designing Nereda Aerobic Granular Sludge

Hong Kong 1 mgd Demonstration 2 year

Sand Island 100 mgd WWTP, Hawaii

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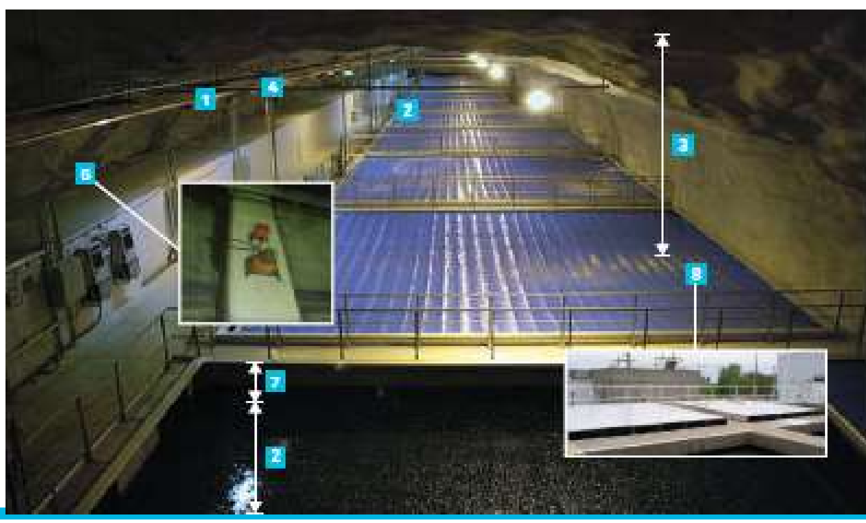
Intensification in Hong Kong – Sha Tin Cavern Relocation

- Recover prime water front property for commercial use

Treatment Intensification in Hong Kong

- State of the art compact technologies
- Compatible with saline water
- Water Reuse



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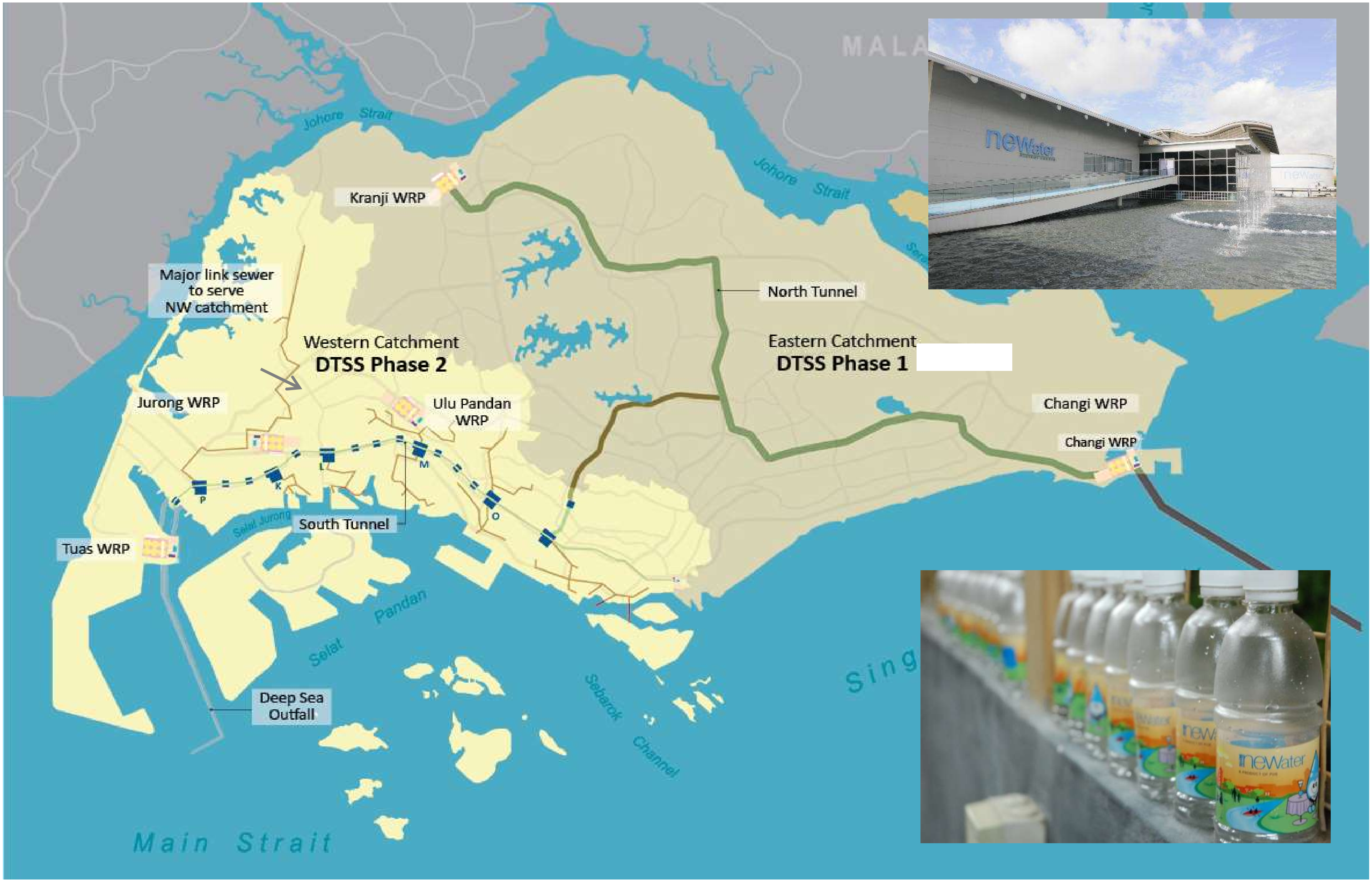
Singapore – New Tuas DTSS 2



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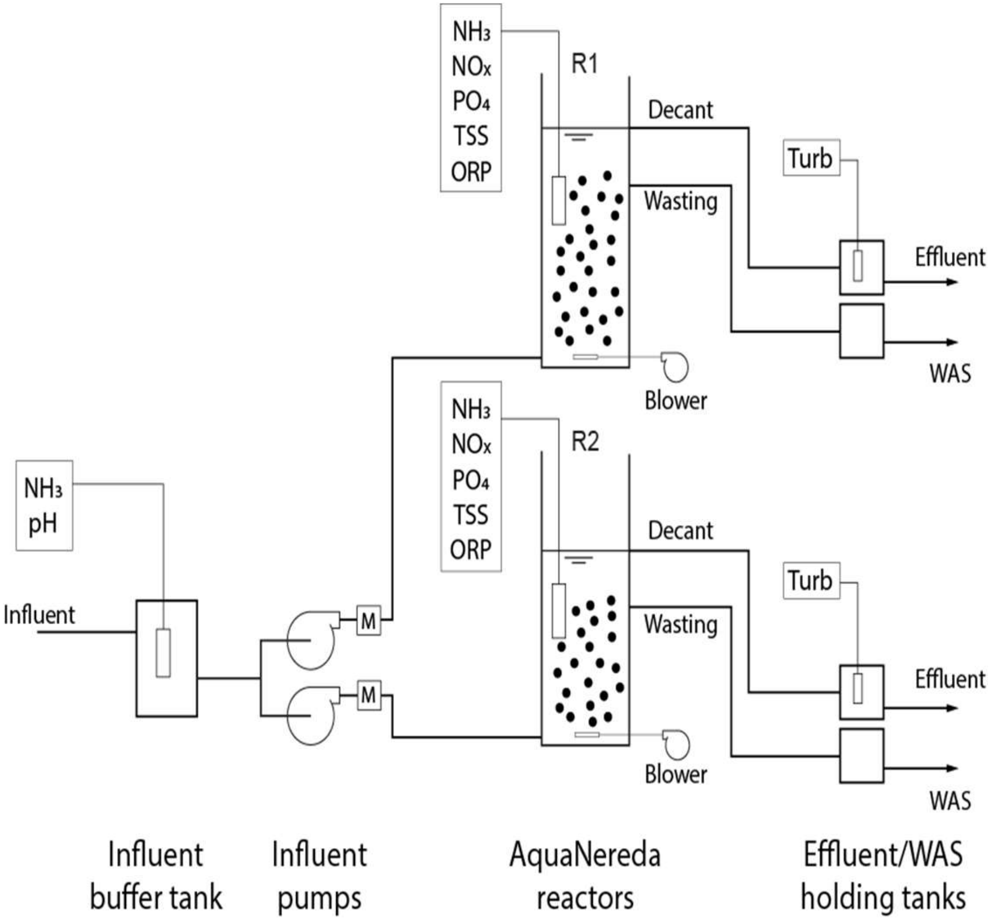
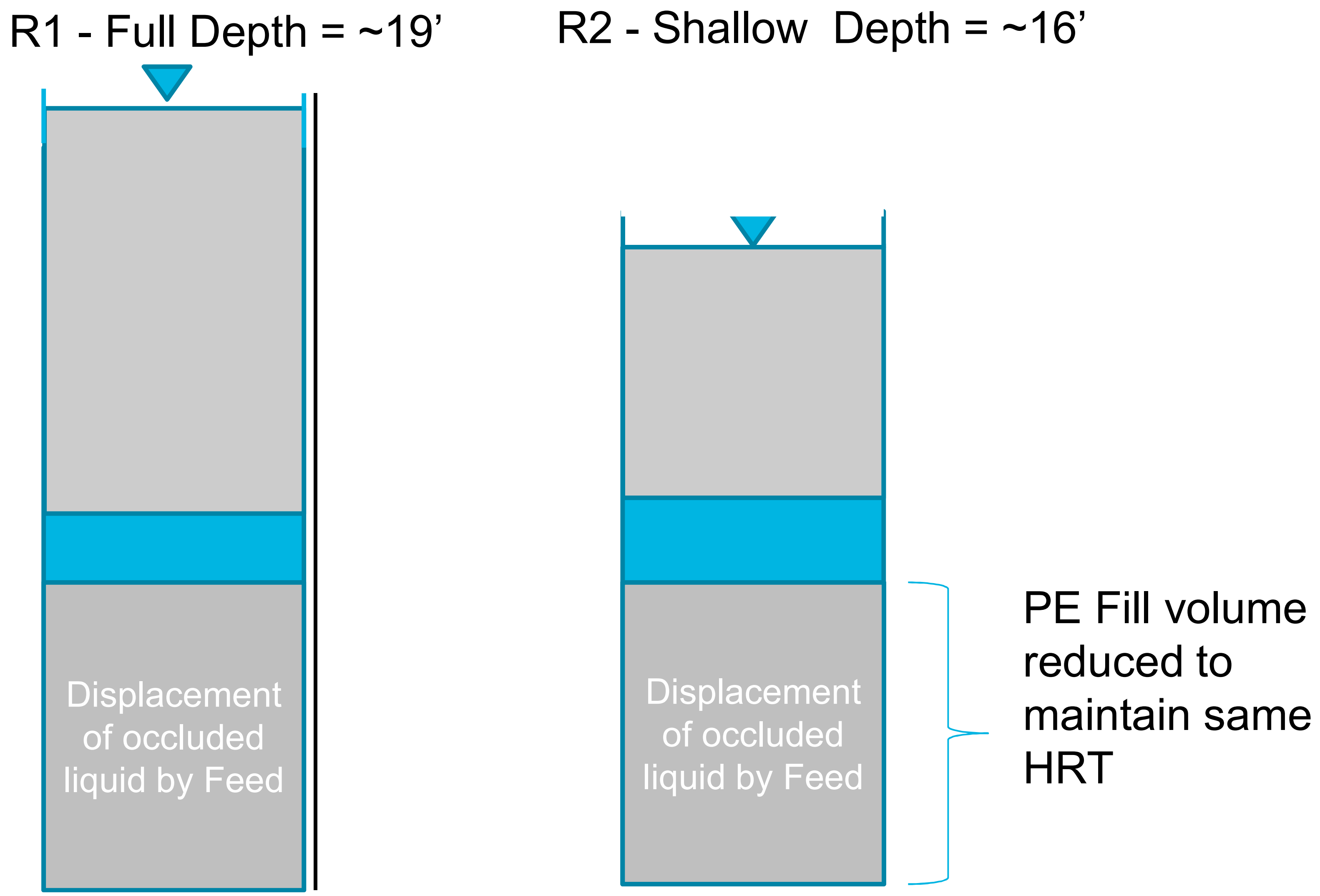
Is it feasible to convert an existing shallow activated sludge tank to Nereda cost effectively and meet stringent effluent Nutrient limits?

AECOM Fairfield Suisun, CA Pilot



Deep & Shallow Nereda® Reactors Tested Side-by-Side Same Flows & Loads



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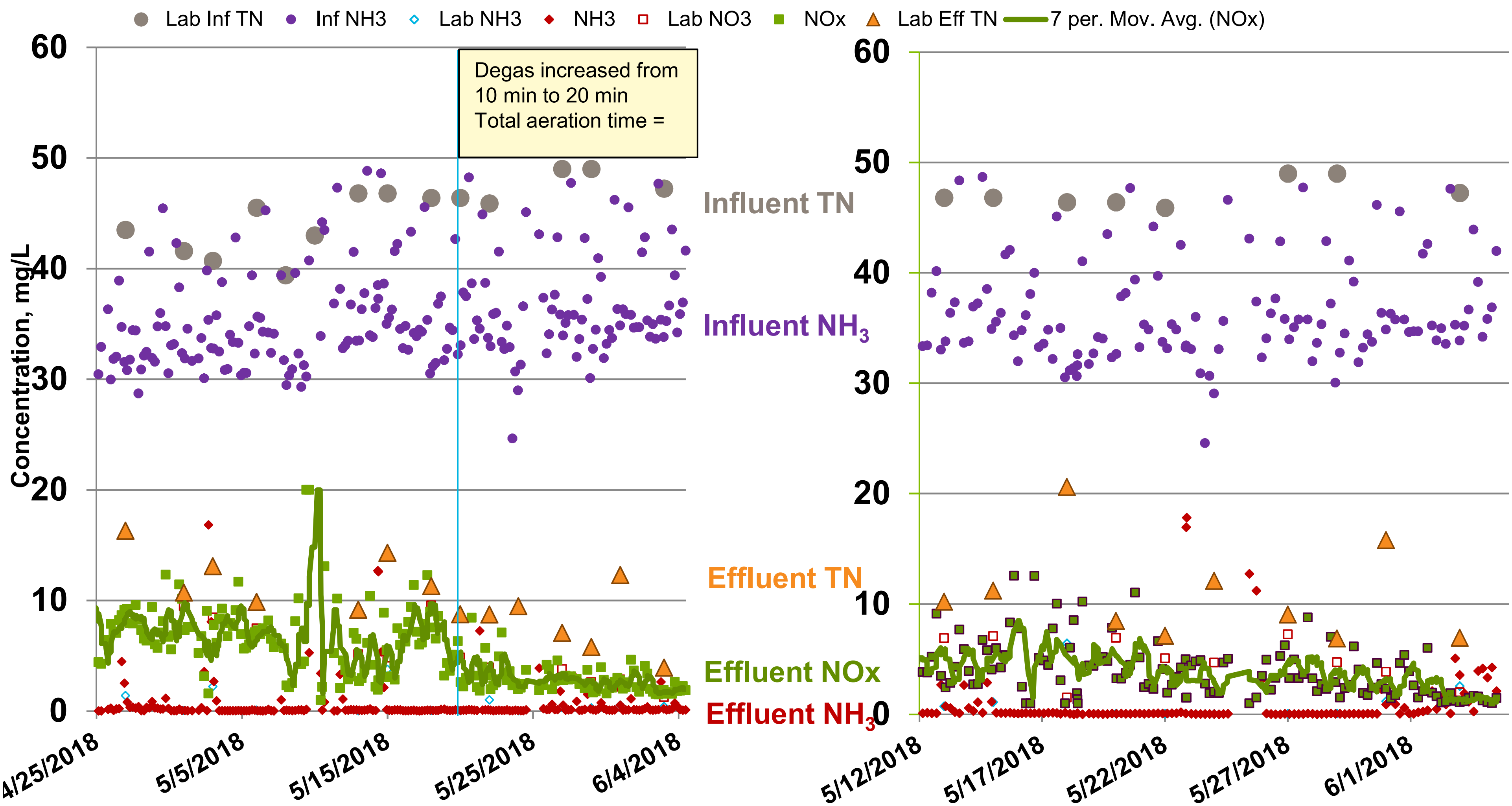
19’ SWD Nitrogen Removal

16’ SWD Nitrogen Removal



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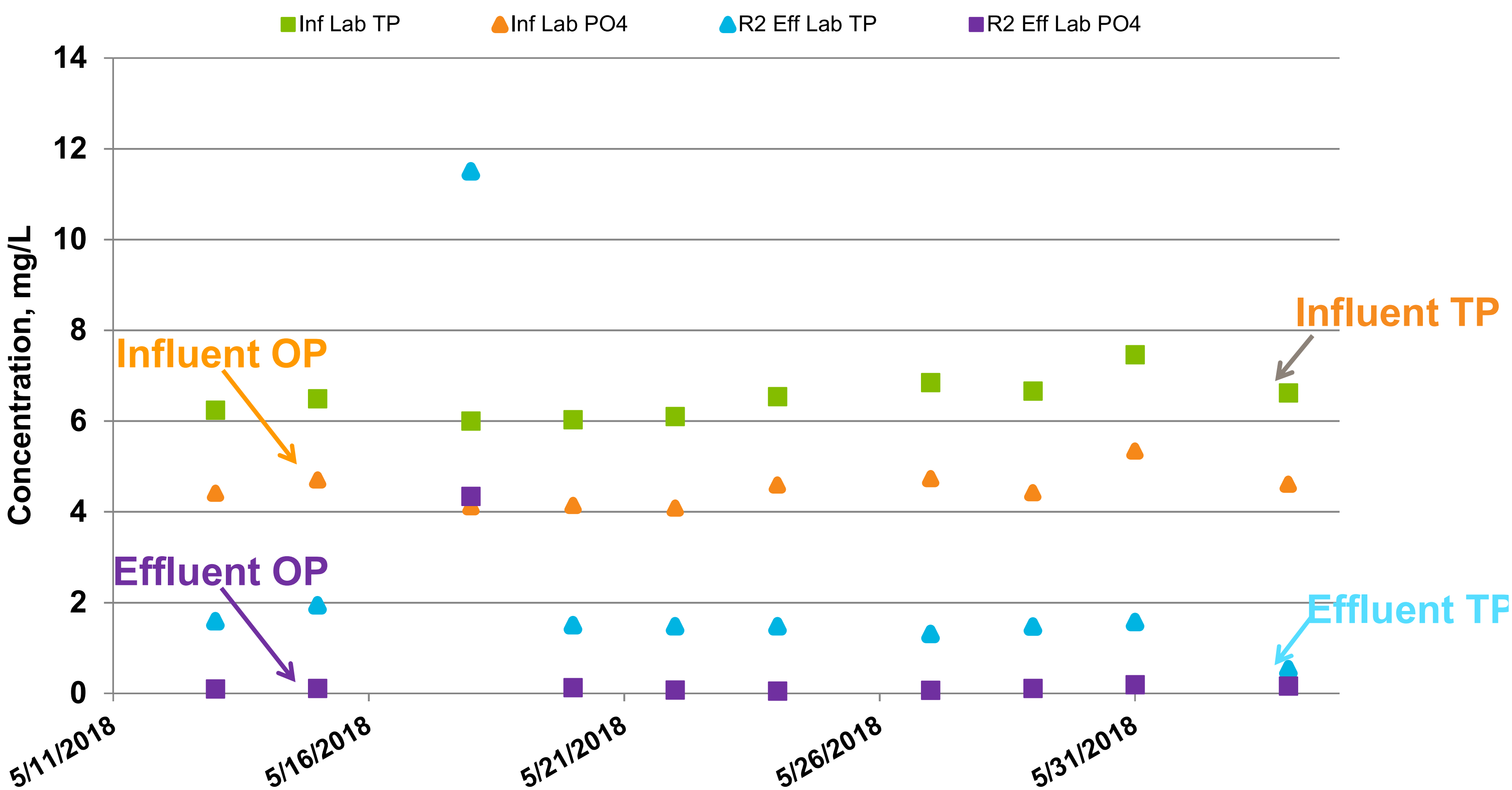
R2 (Shallow SWD) Phosphorus Removal - 100% of Loading



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Shallow (16') & Deep (19') Nereda® Performed Equally

19' SWD Nereda® Design Loading

Parameter	CBOD	COD	SCOD	TSS	TN	TKN	NH3	NO3	NO2	TP	SRP
Influent avg, mg/L	137.8	382.1	174.9	79.1	40.8	40.3	33.2	0.4	-	6.6	4.6
Average, mg/L	12.8	48.3	24.7	18.0	10.1	4.6	0.7	5.4	0.5	2.2	0.2
σ	4.1	11.0	4.0	12.7	3.3	2.5	1.1	2.9	0.3	1.7	0.5
5th percentile, mg/L	6.6	37.5	17.8	7.6	5.1	1.5	0.0	1.9	0.1	0.8	0.0
95th percentile, mg/L	17.6	68.5	31.0	40.3	15.0	8.4	2.7	9.5	0.9	1.8	0.8
% removed	91%	87%	86%	**77%**	75%	89%	98%	-	-	67%	96%

16' SWD Nereda® **Same Loading Rate**

Parameterr	CBOD	COD	SCOD	TSS	TN	TKN	NH3	NO3	NO2	TP	SRP
Influent avg, mg/L	141.1	391.1	172.2	92.7	49.7	49.1	34.0	0.4	-	6.5	4.5
Average, mg/L	11.8	37.9	25.1	8.5	9.8	4.3	0.7	5.0	0.5	0.5	0.1
σ	4.0	6.5	3.2	2.2	2.9	3.2	0.9	2.1	0.4	0.1	0.04
5th percentile, mg/L	7.0	31.3	21.3	6.1	6.9	1.6	0.0	1.7	0.1	0.4	0.06
95th percentile, mg/L	16.8	48.4	29.9	11.5	14.3	9.7	2.0	7.2	1.1	0.6	0.2
% removed	92%	90%	85%	**91%**	80%	91%	98%	-	-	92%	98%

Equivalent Performance – slightly better Including TSS

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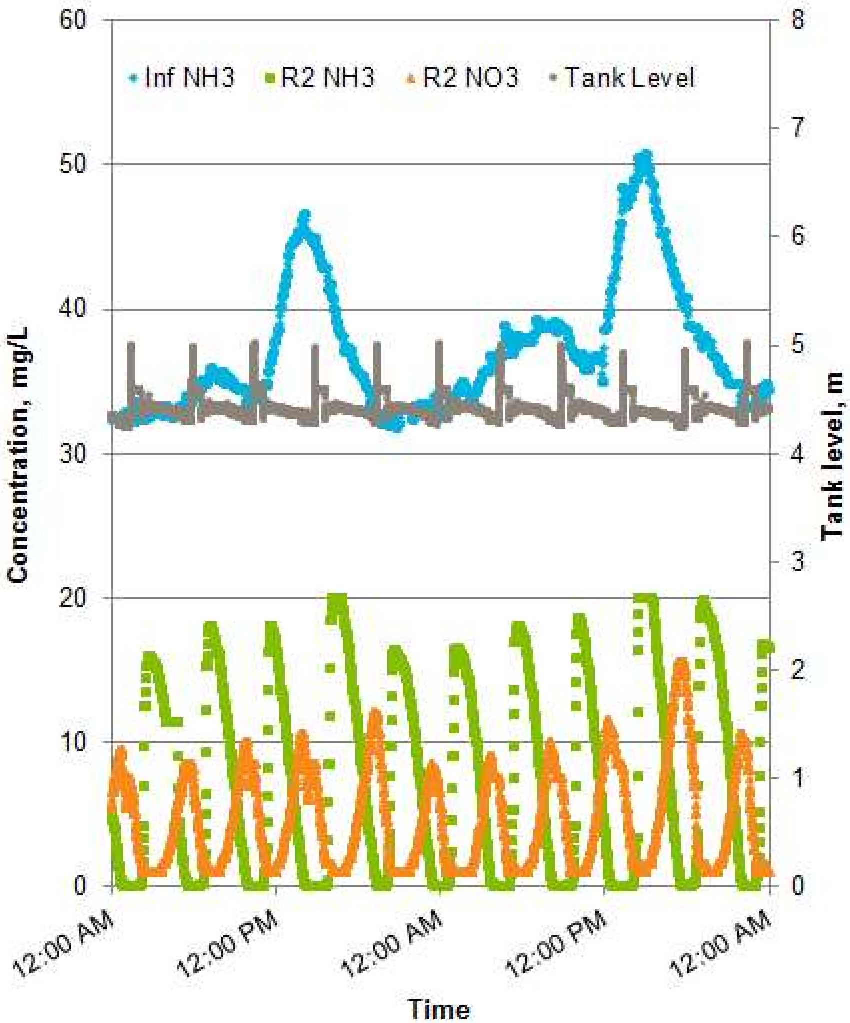
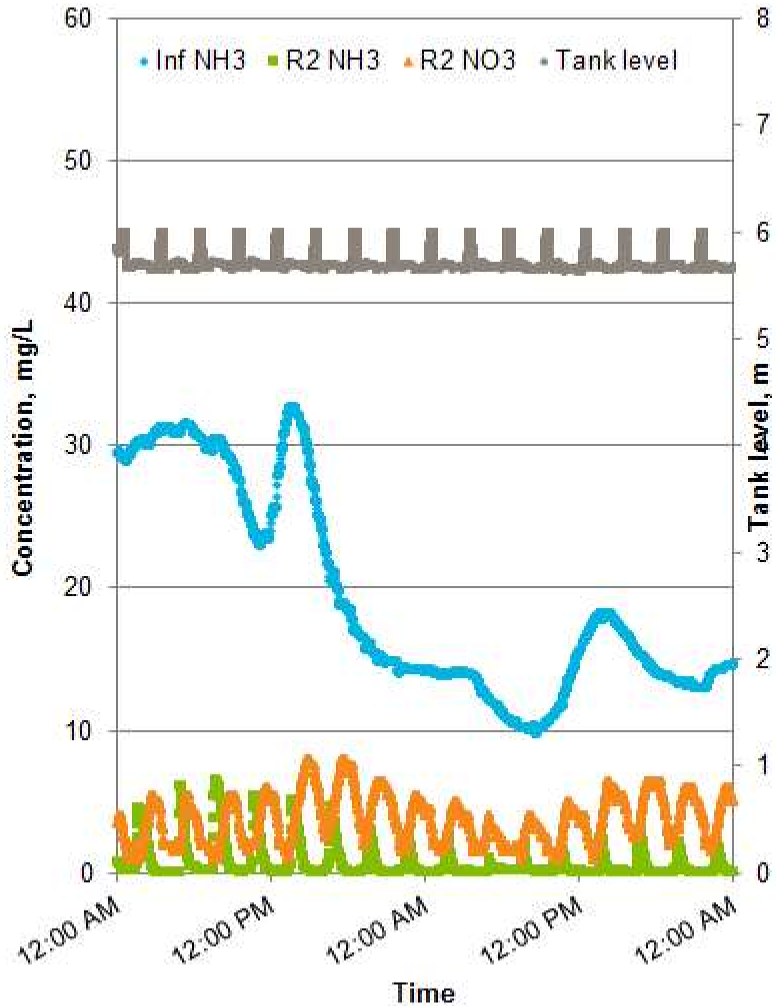
Rain Event Response versus Dry Weather Operation

R2 (steady operation)
Shallow SWD, 4.5 hr cycle



R2 (acclimation period)
Full SWD, 3 hr cycle

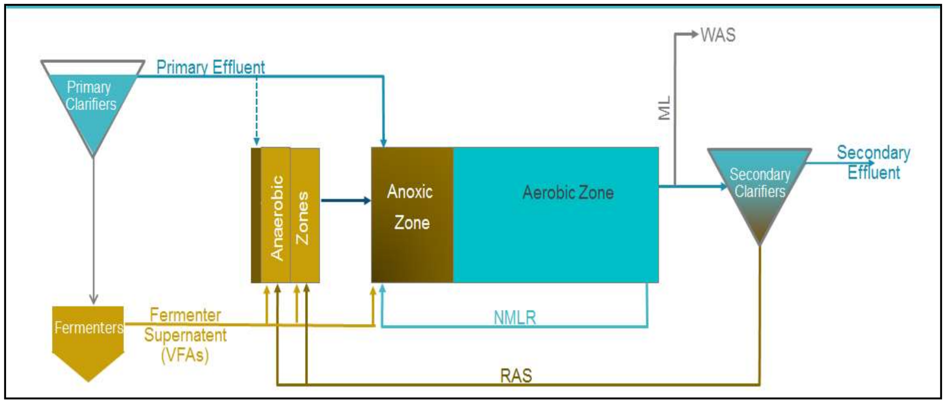


Two Types of Granular Sludge

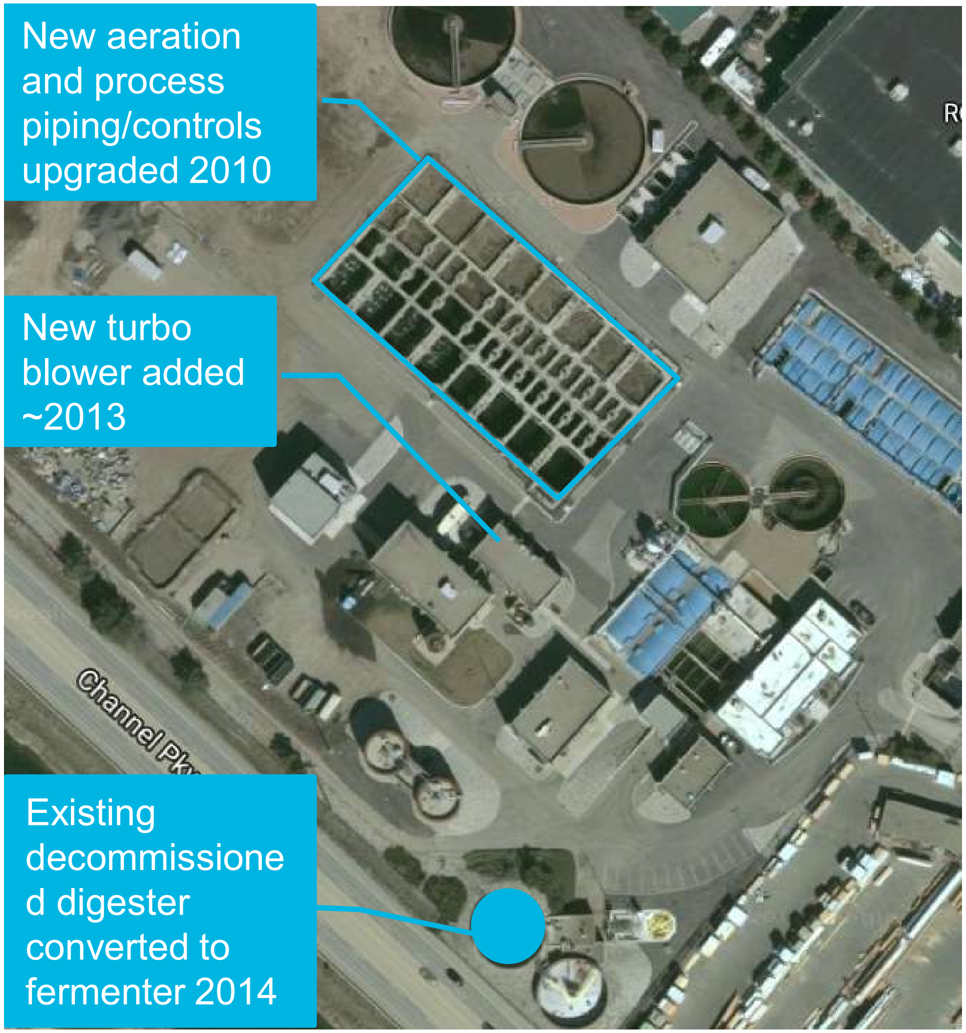
1. SBR Nereda® Aerobic Granular Sludge
   - Batch process, well established at >30 plants
   - Not easily amenable to upgrading existing conventional activated sludge process
   - Min. SWD = 18' (5.5m)

Nereda®

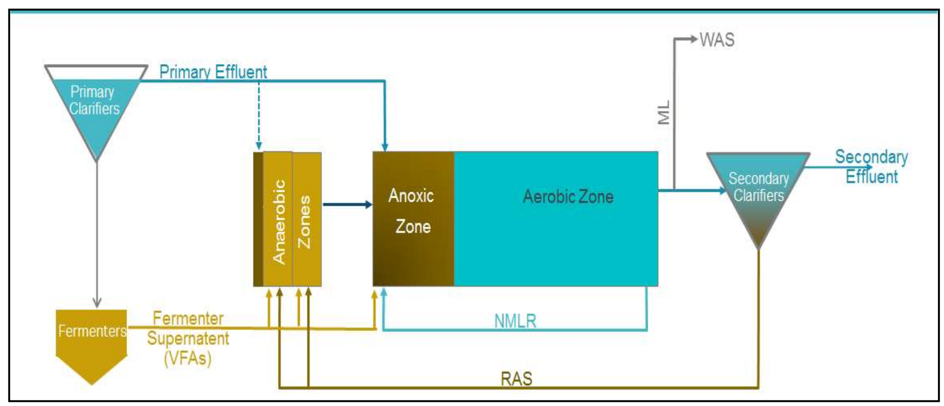
2. Continuous Flow Granular Activated Sludge – R&D
   - Adapting conventional activated sludge BNR to produce granular sludge



AECOM / City of Penticton AWWTP Granular Sludge Full Scale Demonstration



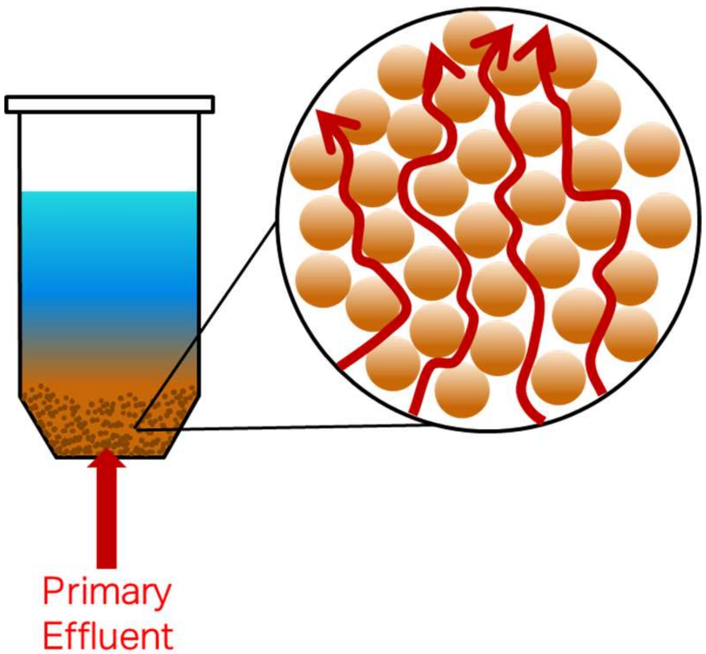
- Existing influent flow = 11 ML/d (~36,000 PE)
- Two independent trains with PE equally split just upstream of the bioreactor inlet
- Final effluent discharged to nearby river with TP < 0.20 mg P/L and TN < 6.0 mg/L (based on annual average)



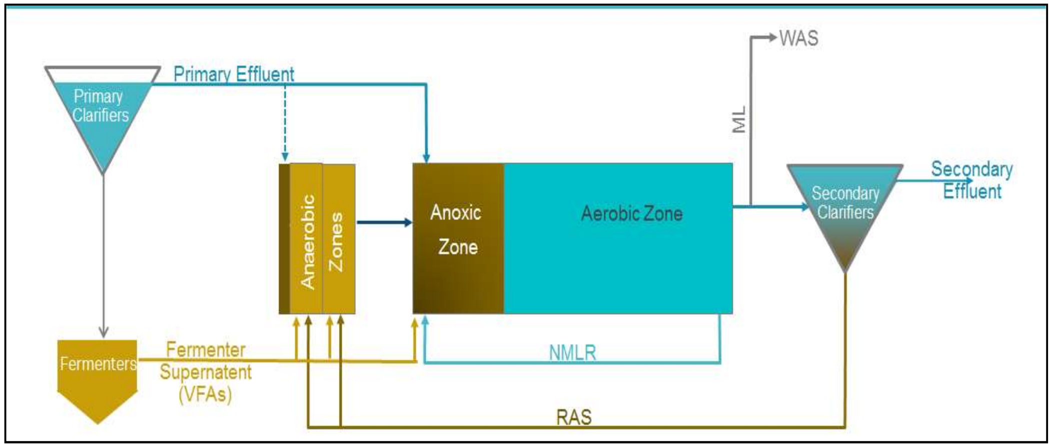
Adapting the Westbank BNR Process to AGS

- Granule formation relies on contact time with solubilized substrate to overcome the diffusion gradient in order to grow PAOs & GAOs ('Feast')
- AECOM's Westbank BNR process incorporates a similar phase but has been tuned to favor PAO's over GAOs

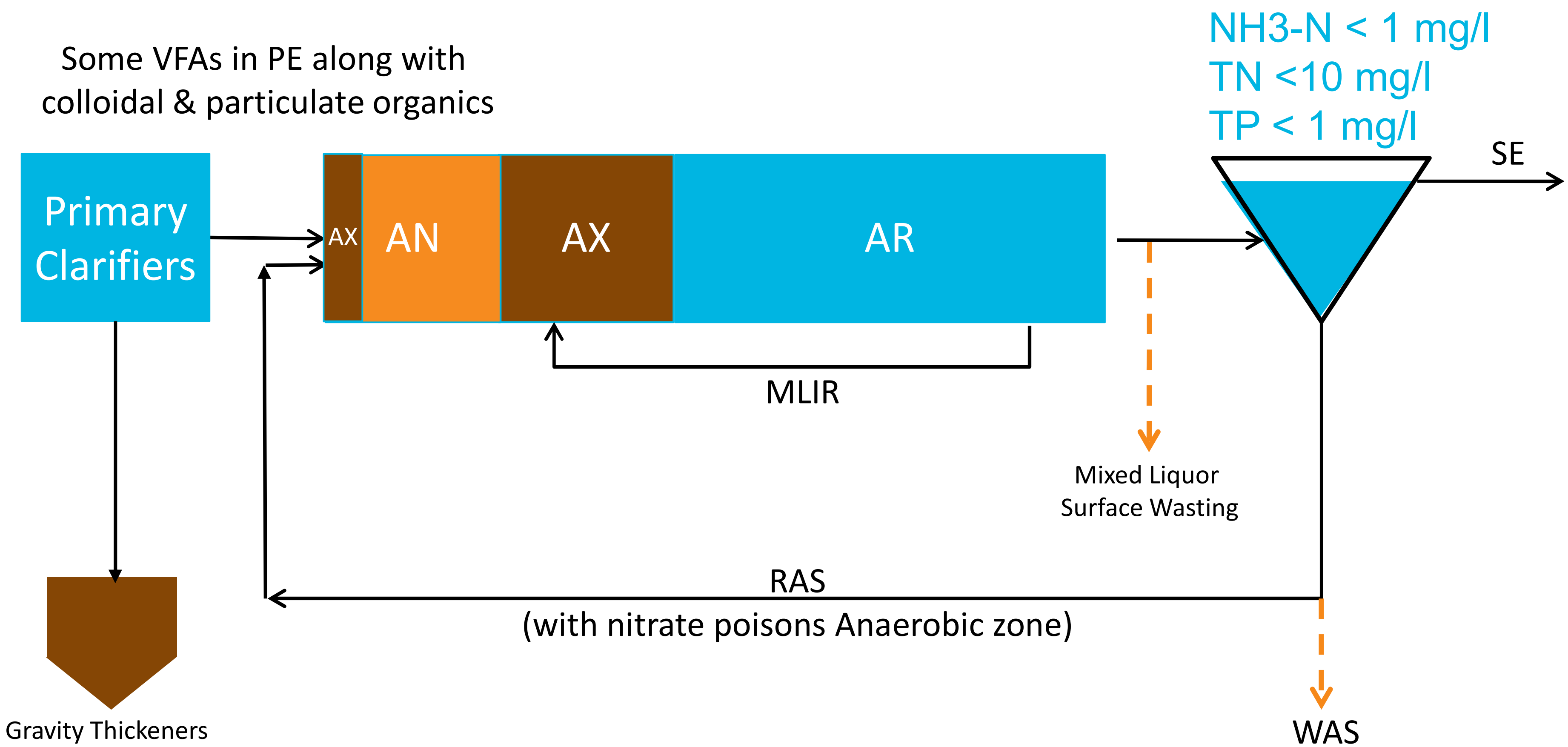
AGS Feast Stage



Westbank BNR Anaerobic Stage



Conventional Activated Sludge Enhanced Biological Phosphorus Removal (EBPR) Systems – A_2O



1. Anaerobic zone - VFA formation (Fermentation) & Uptake (Phosphorus Release)
2. Anoxic Zone - RAS and MLIR Nitrate Reduction
3. Aerobic zone – ammonia oxidation to NOx & Luxury Phosphorus Uptake
4. Remove Phosphorus in the WAS in EBPR microorganisms

Adapting Activated Sludge For Smaller, Simpler Phosphorus Removal System - Westbank Process

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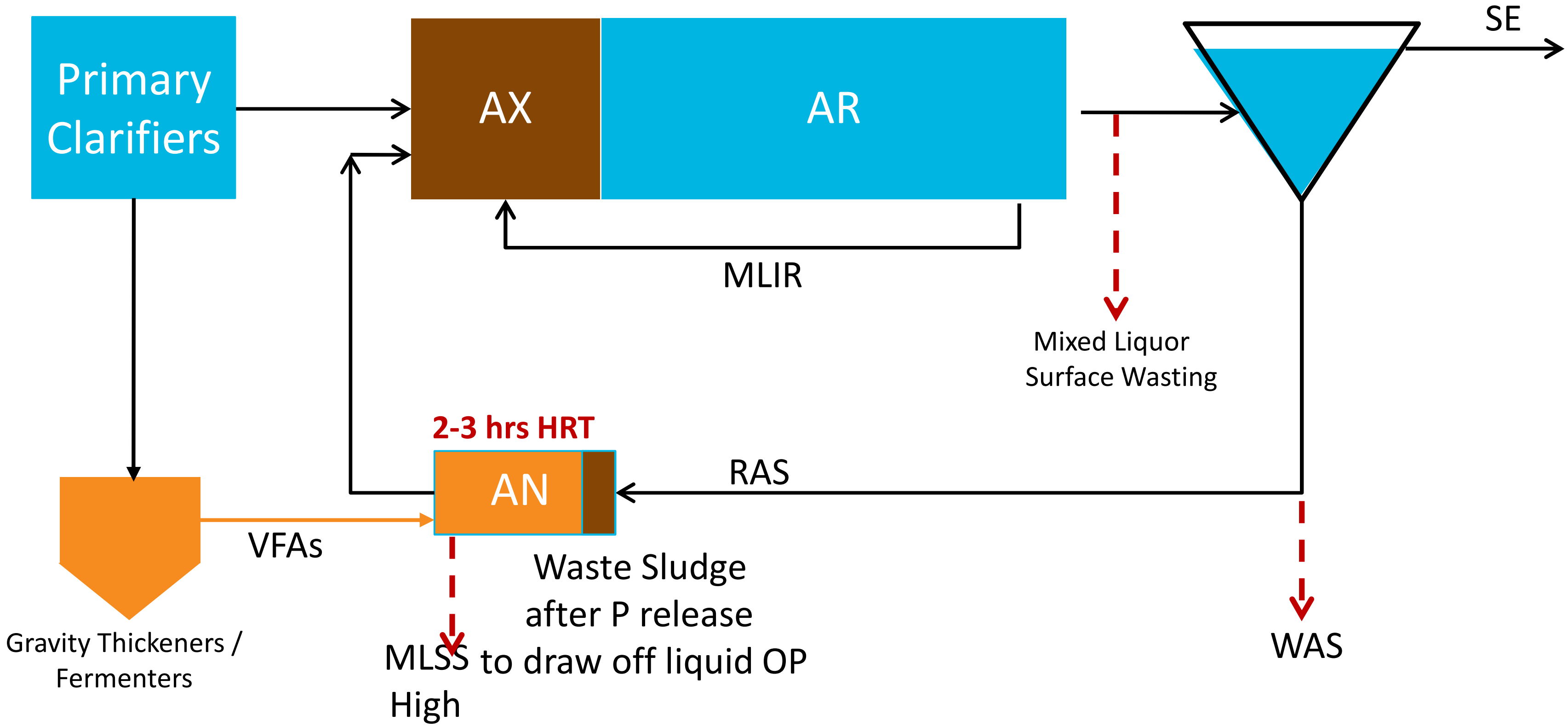

1. Smaller Concentrated Anaerobic zone – 33% less volume – less cost & space
2. Organics fermented to VFA in fermenter – less volume, cost, space
3. Stable Low ORP – Less / No NOx DO intrusion – More Reliable Performance
4. More diverse & stable population of Phosphorus Accumulating Organisms
5. Compatible with WASSTRIP – prevent struvite, enhanced sludge dewaterability & facilitate Phosphorus harvesting

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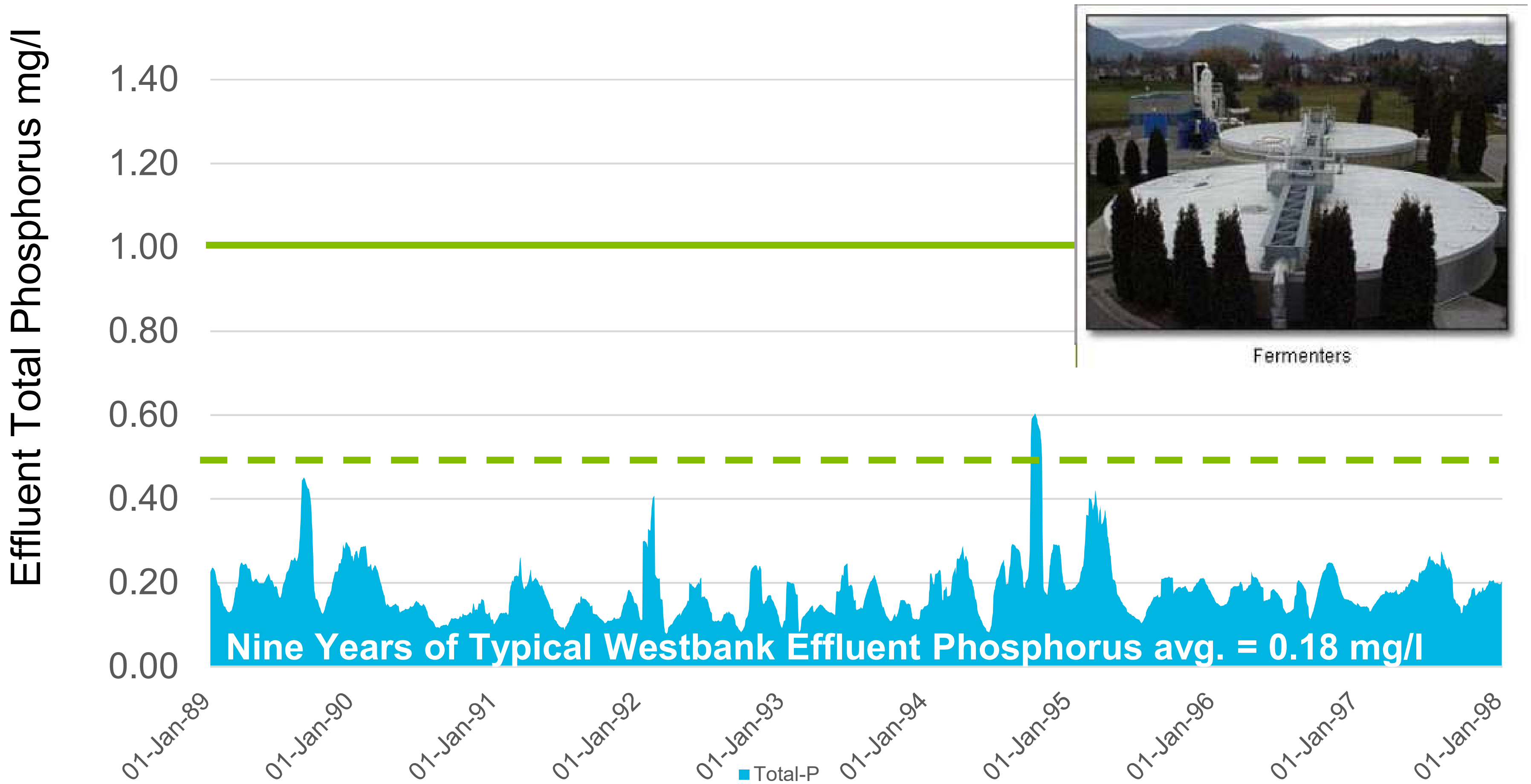
Kelowna Westbank Effluent Phosphorus 1989 to 1998

- Reliable Effluent TP Average = 0.18 mg/l, No Chemical, No Filtration
- TP < 0.06 mg/l with tertiary filtration polishing
- 33% reduction in tank volume when compared to conventional Bio-P
- Modified Westbank can reduce tank volume even further



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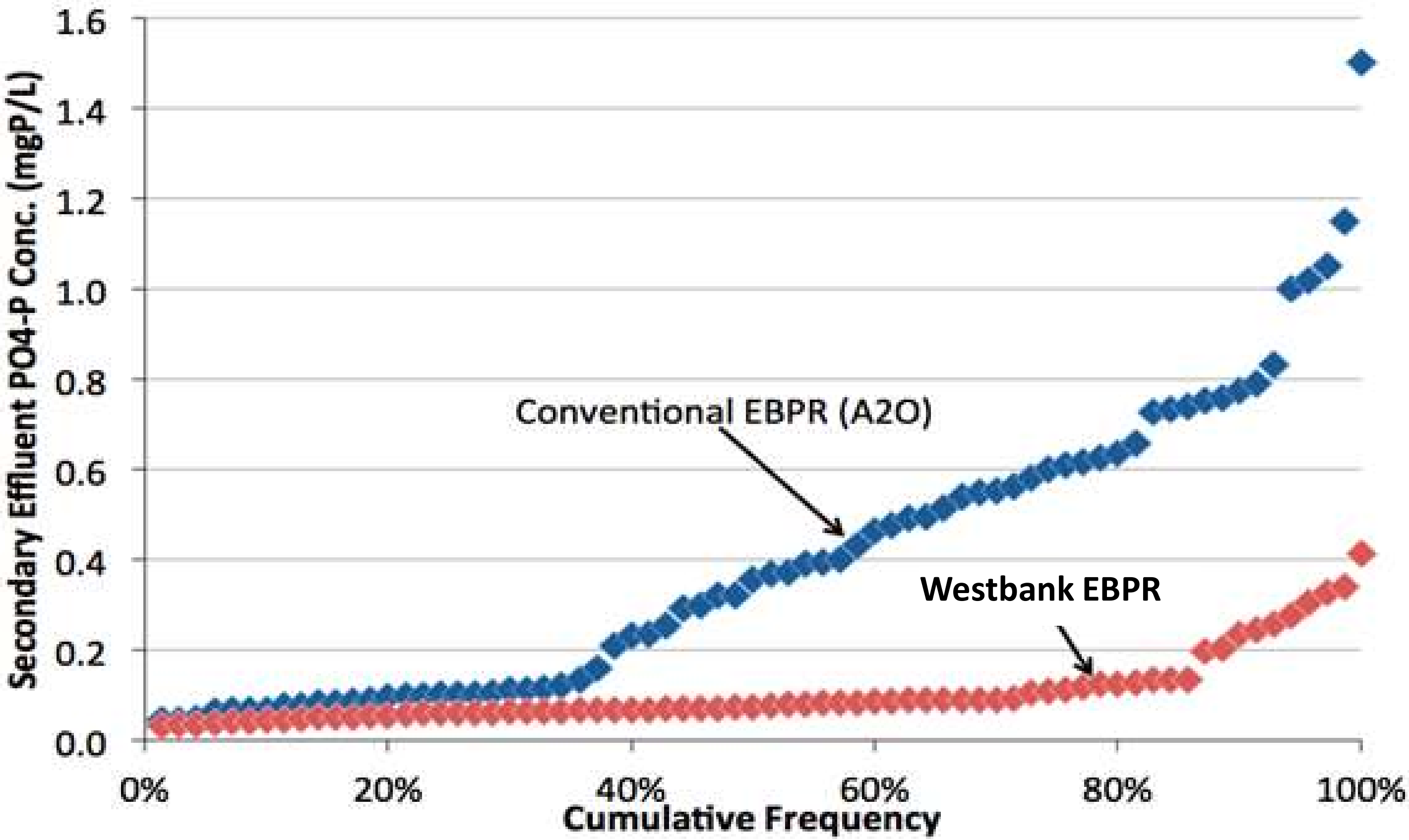
Comparison of A2O vs Sidestream EBPR – Rock Creek side-by-side data

- More stable performance
- Most likely due to the diversity in the PAO culture, right VFA in right location with right conditions, fermentation of the RAS, and suppression of GAOs



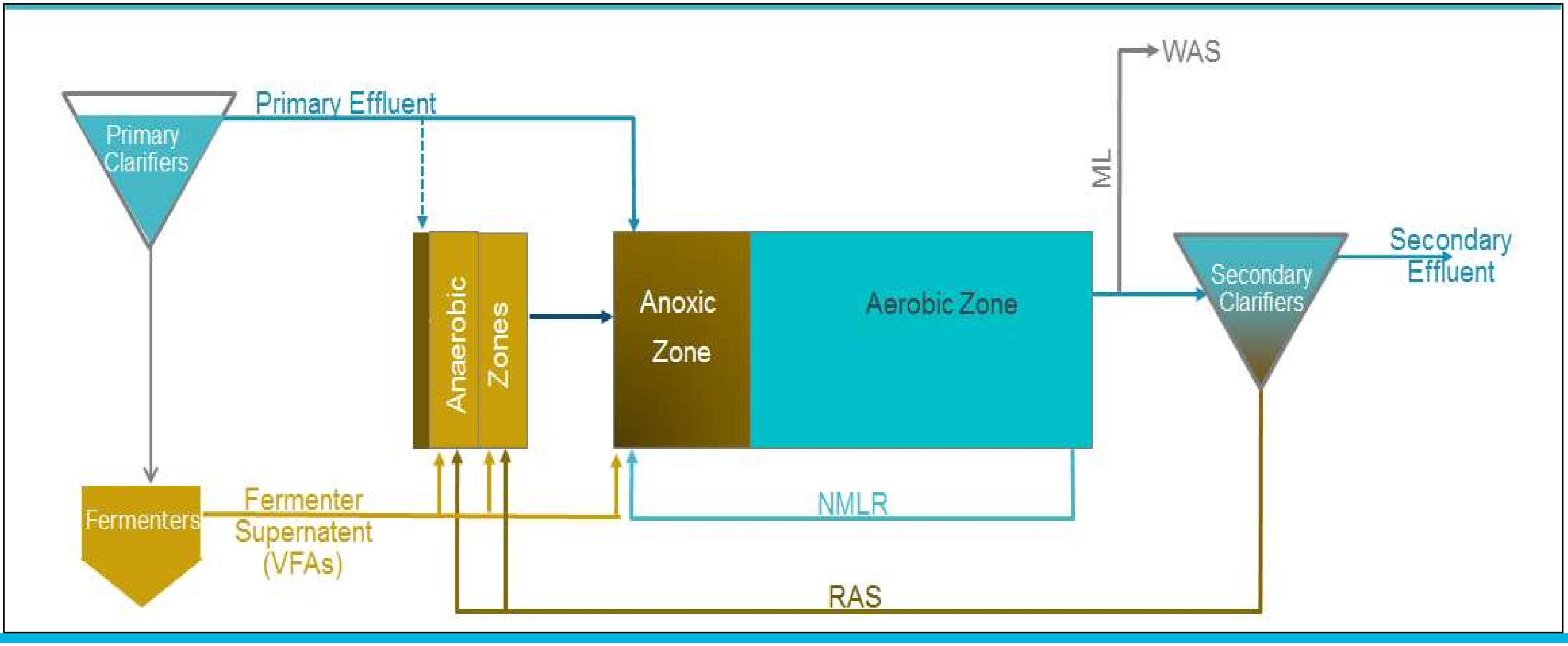
Adapting the Westbank BNR Process to AGS

- The Westbank process evolved from the first North American BNR installation in Kelowna in 1984
- The bioreactor is separated into 3 zones to provide BOD, phosphorus and nitrogen removal

Selector for PAOs

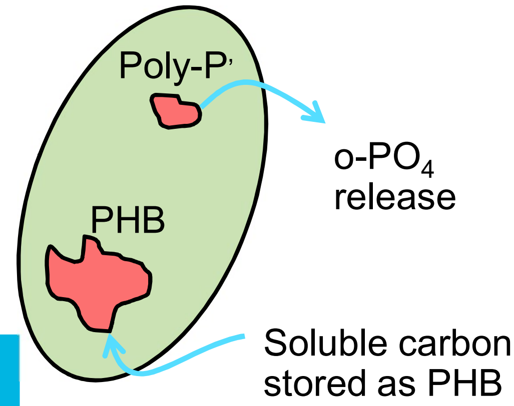
NO_3 converts to N_2

NH_4 oxidized & PAOs uptake phosphate



Adapting the Westbank BNR Process to AGS

- In BNR fermenter supernatant is high in VFAs (e.g. acetate) and is the ideal carbon source for PAOs



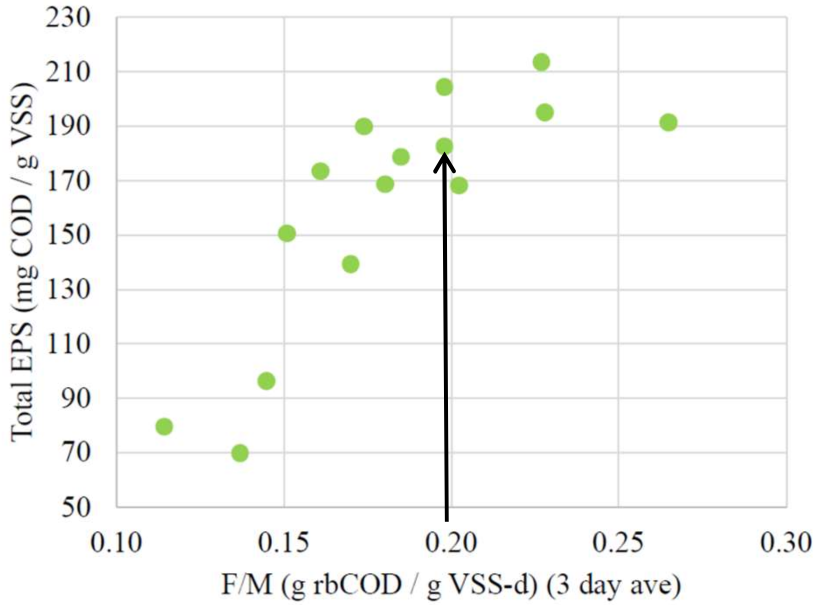
Parameter	Fermenter Supernatant (Kelowna WWTF)
VFA Total, mg/L	226
VFA, % acetate	56%
pH	6.4
Alkalinity, mg/L (as $CaCO_3$)	260
COD soluble, mg/L	644
TSS, mg/L	203
Ammonia, mg N/L	27
Phosphate, mg P/L	10

Why is Westbank a good baseline for mainstream granulation?

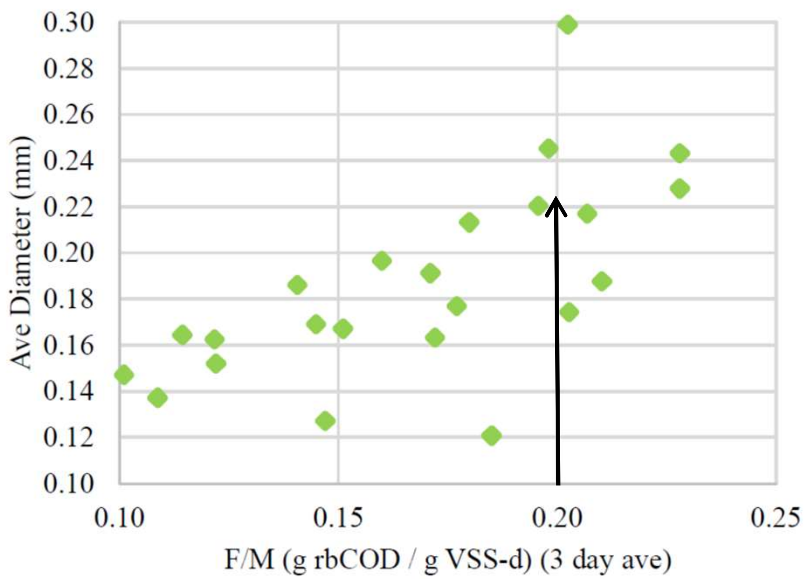
– High F:M using the Fermentate

– Ability to Step-feed the RAS in Westbank

EPS formation relative to F:M



Granule formation relative to F:M



The Impact of Applying an Internal Substrate Selection Strategy to Improve Aerobic Granular Sludge Formation

Rasha Faraj, Theresa Amante, Jennifer Warren, Mariela Mosquera, and Belinda Sturm. The University of Kansas.

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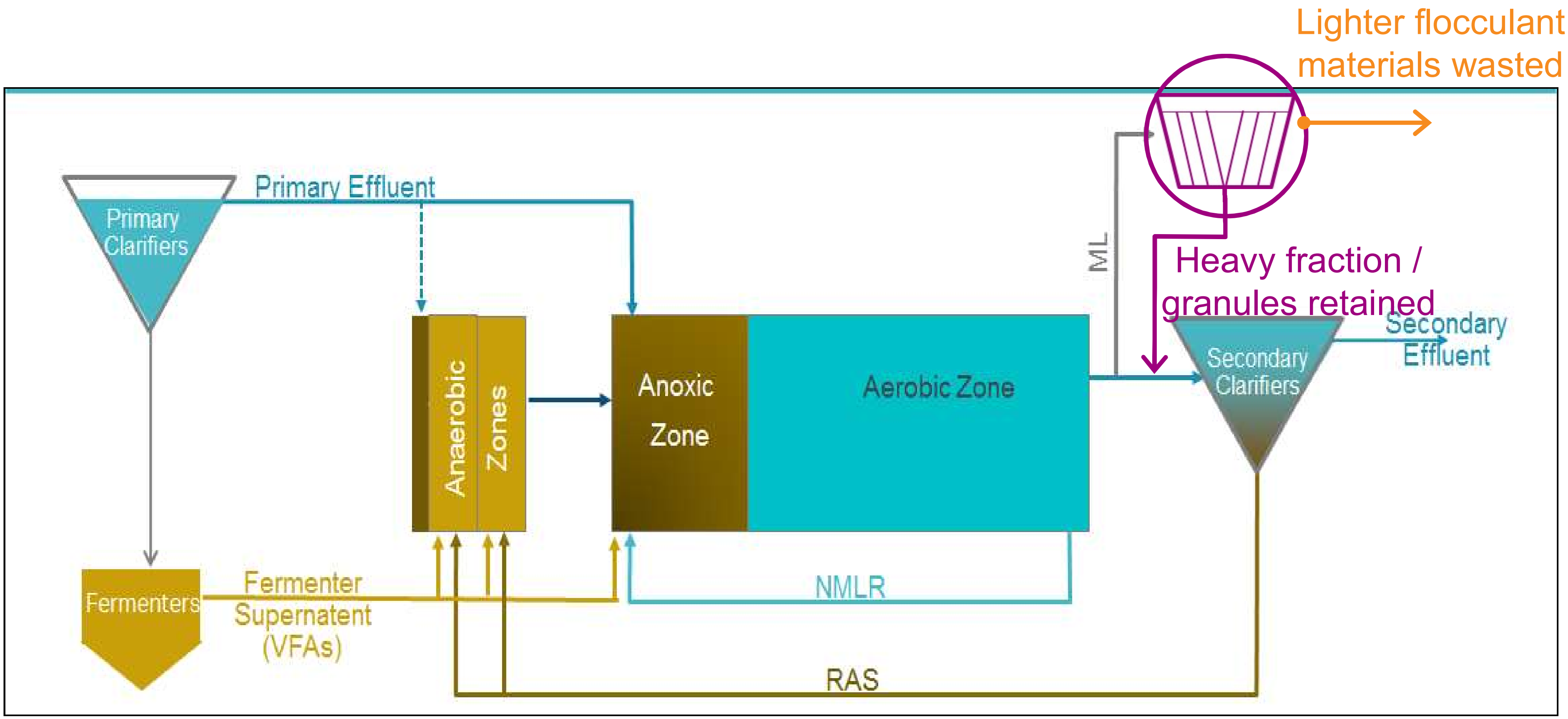
Adapting the Westbank BNR Process to AGS

- Westbank BNR process provides the right conditions for AGS
- Just need a way to select for the heavier particles and waste lighter floc
- How about a plate settler?



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Installation of Lamella Plate Settler for Surface Wasting

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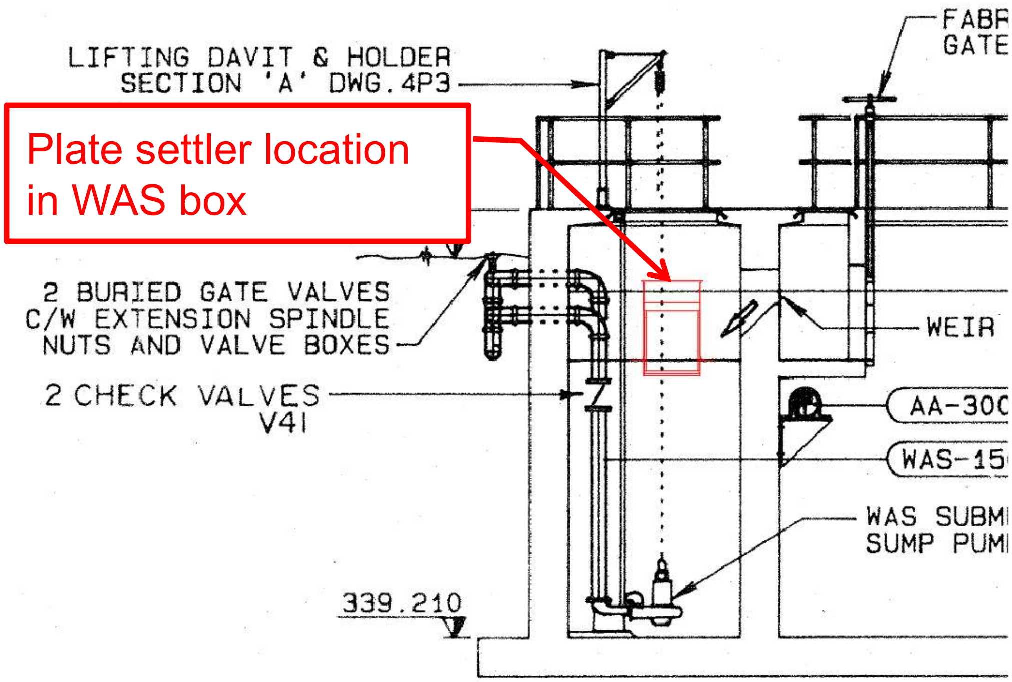
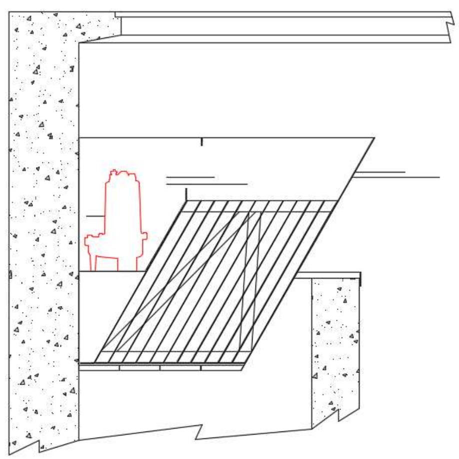
Installation of Lamella Plate Settler for Surface Wasting

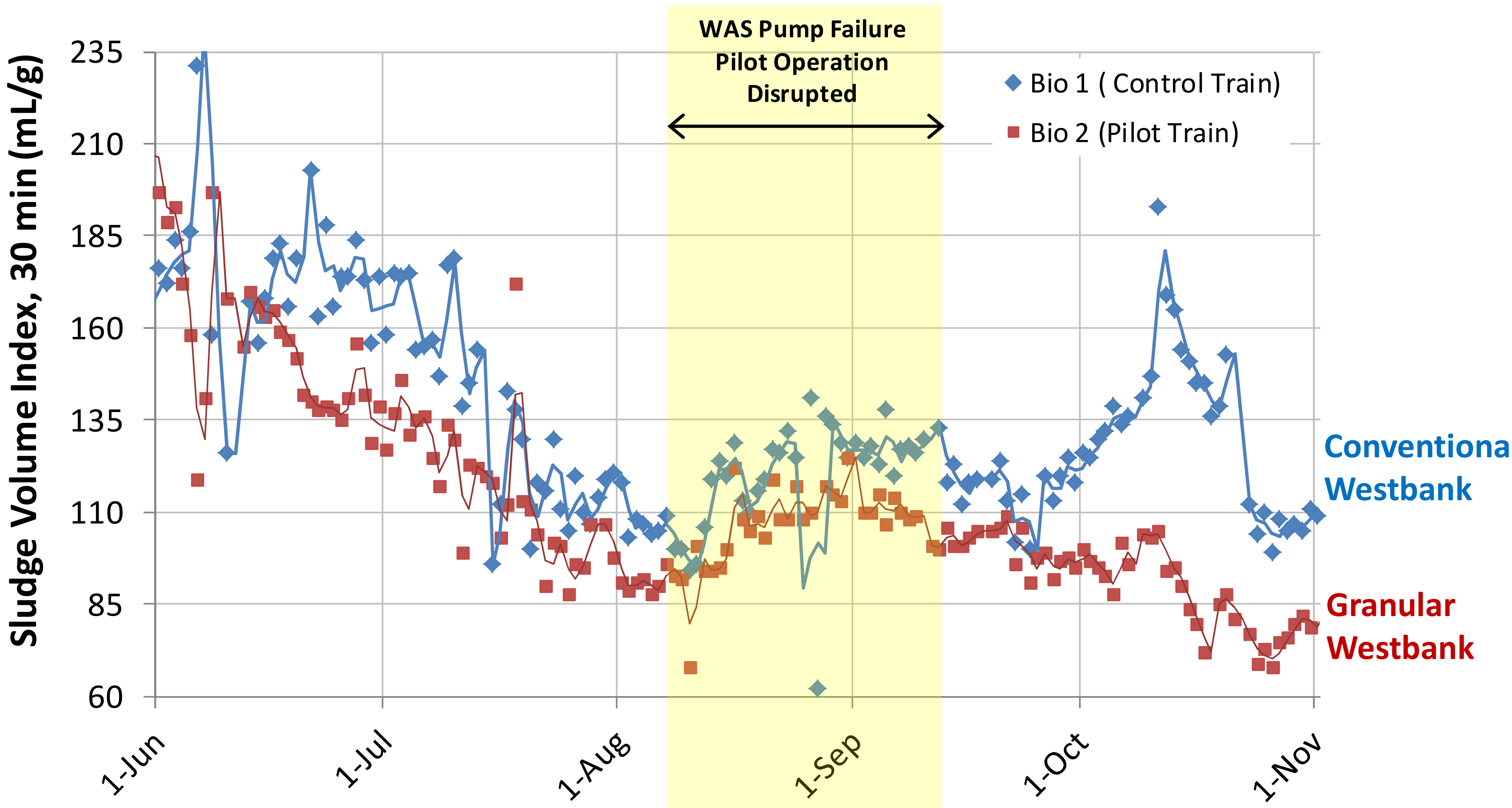




Section

Lamella plate settler installed (without pump)

AECOMs Continuous Flow Granular Sludge Process Proves to be Very Successful In Full Scale Demonstration

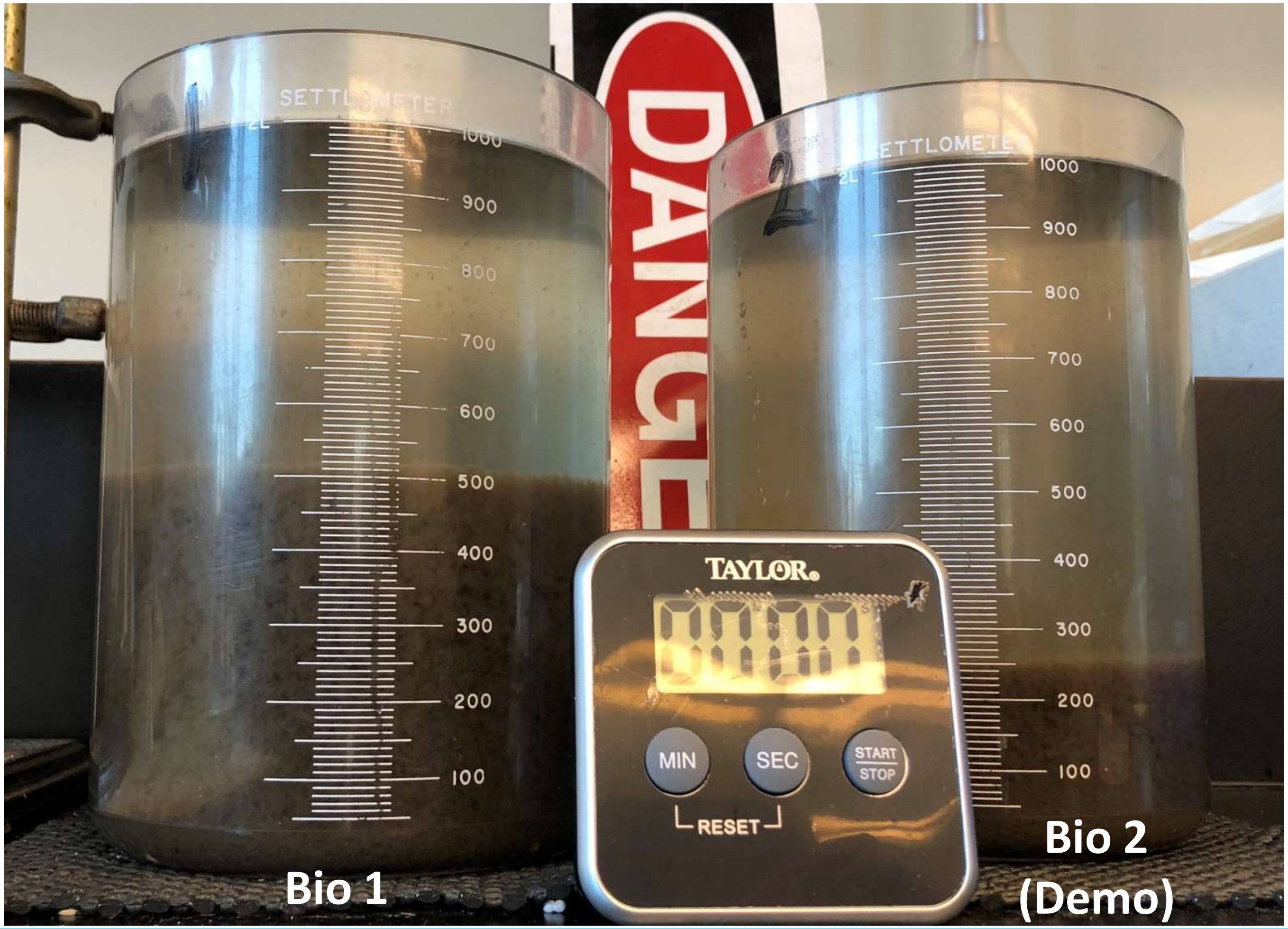


Settling Video

Penticton AGS Pilot – Settling Comparison

- Sludge in Bio 2 settles faster

Sludge settlement after 5 minutes (SVI 5) at same MLSS



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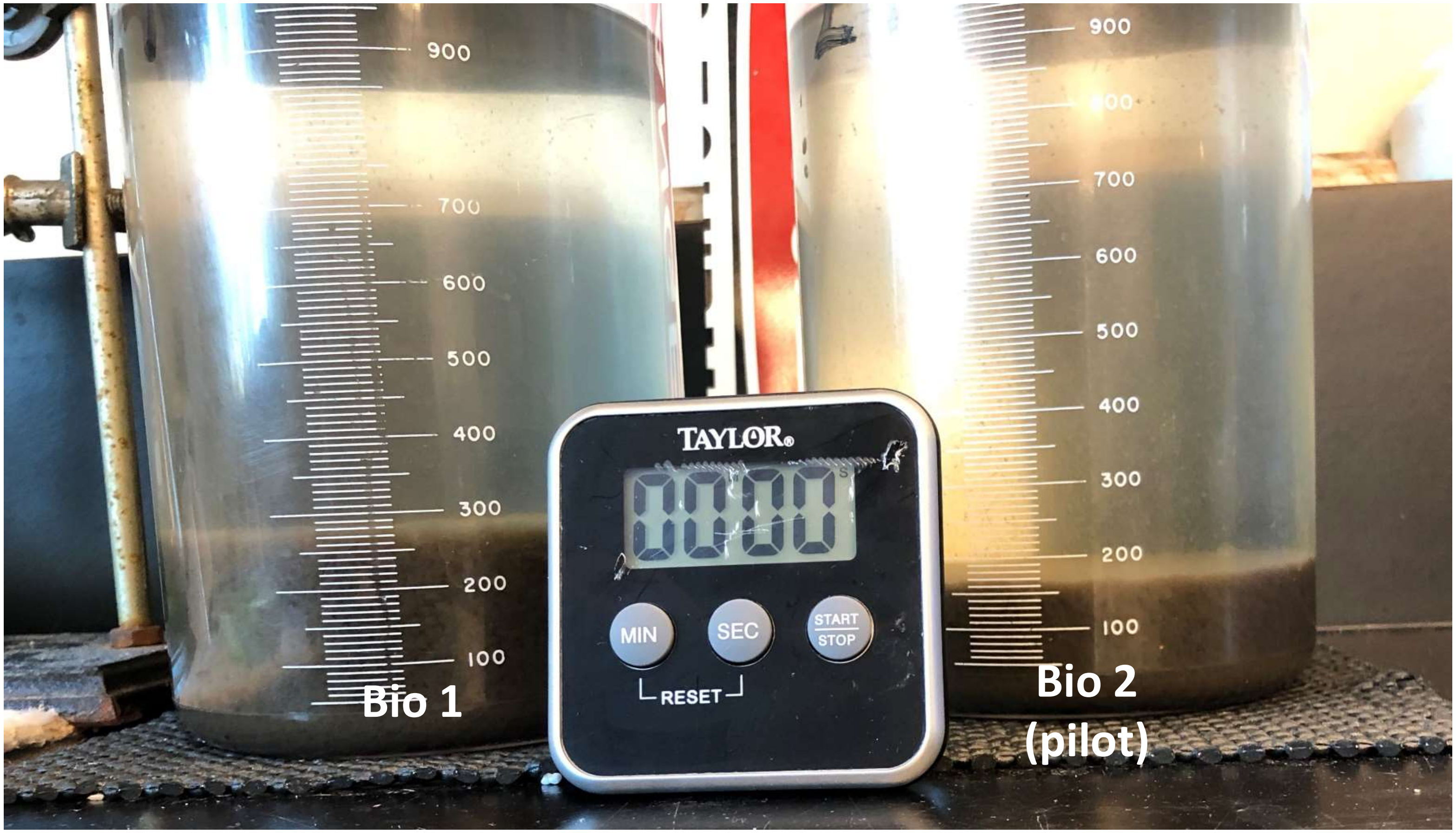
Penticton AGS Pilot – Settling Comparison

- SVI 30 is now significantly lower in the pilot train (Bio 2) compared to the control train (Bio 1)

Sludge settlement after 30 minutes (SVI 30) at same MLSS



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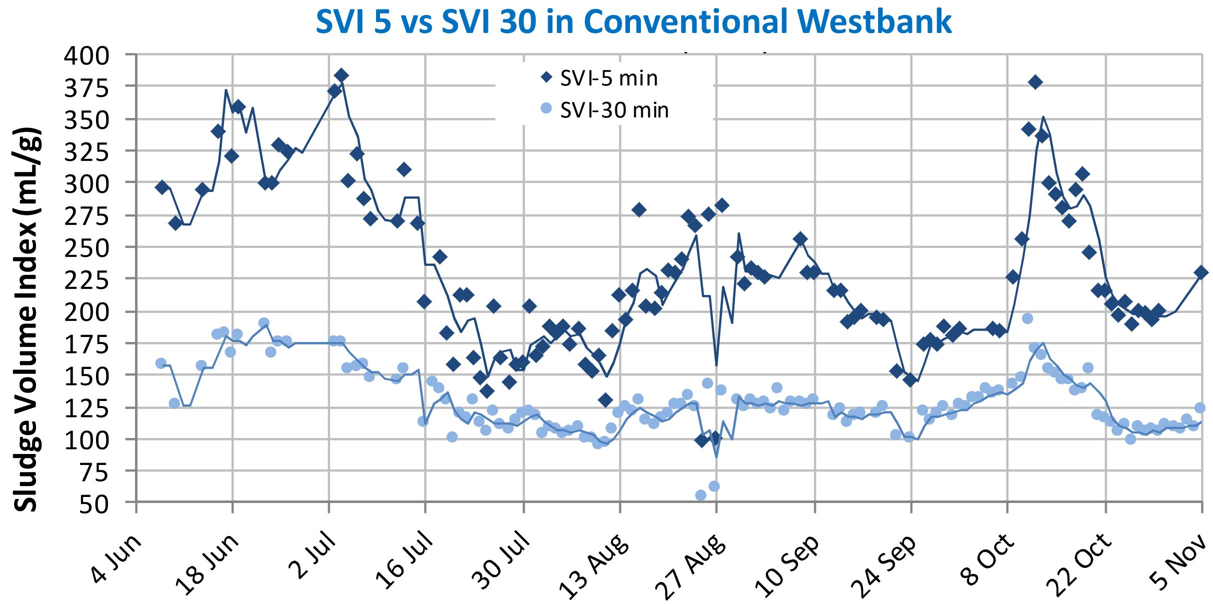
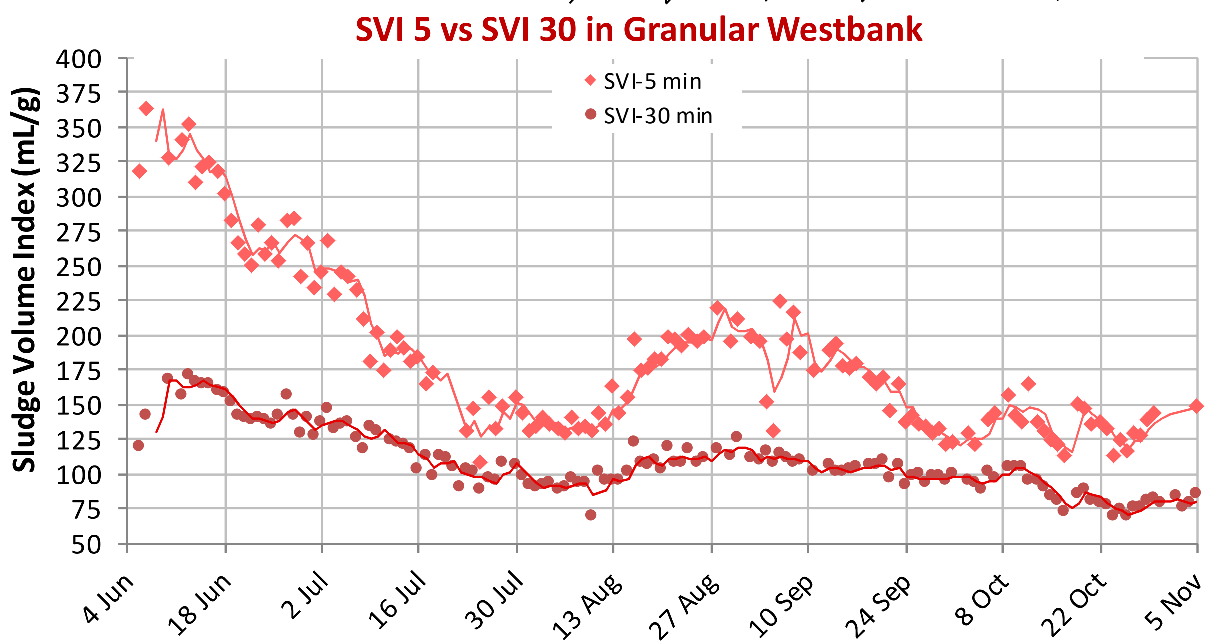
AECOM AGS Demo – Settling Comparison SVI 5 and SVI 30





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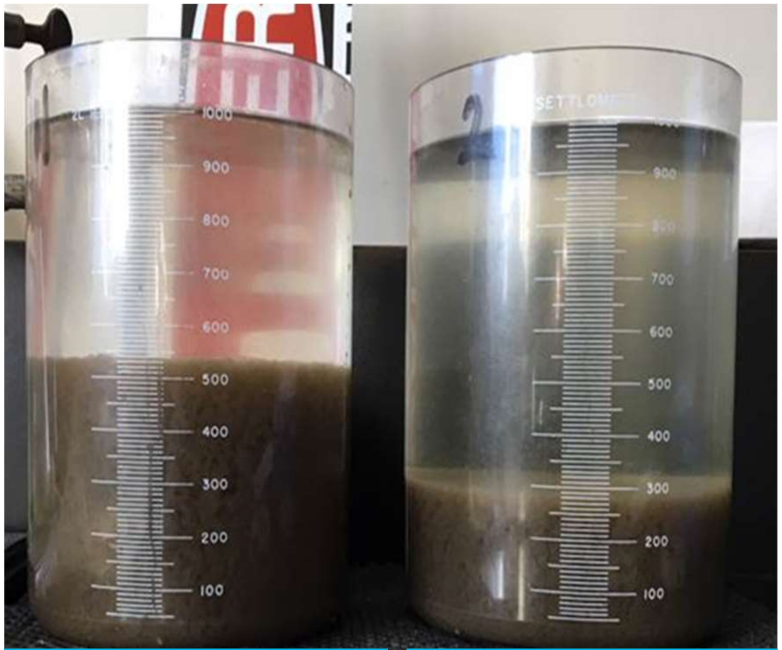
Improved settling - 5 min settling almost equal to 30 min settling in AECOM Mainstream Granulation Demonstration Test Train

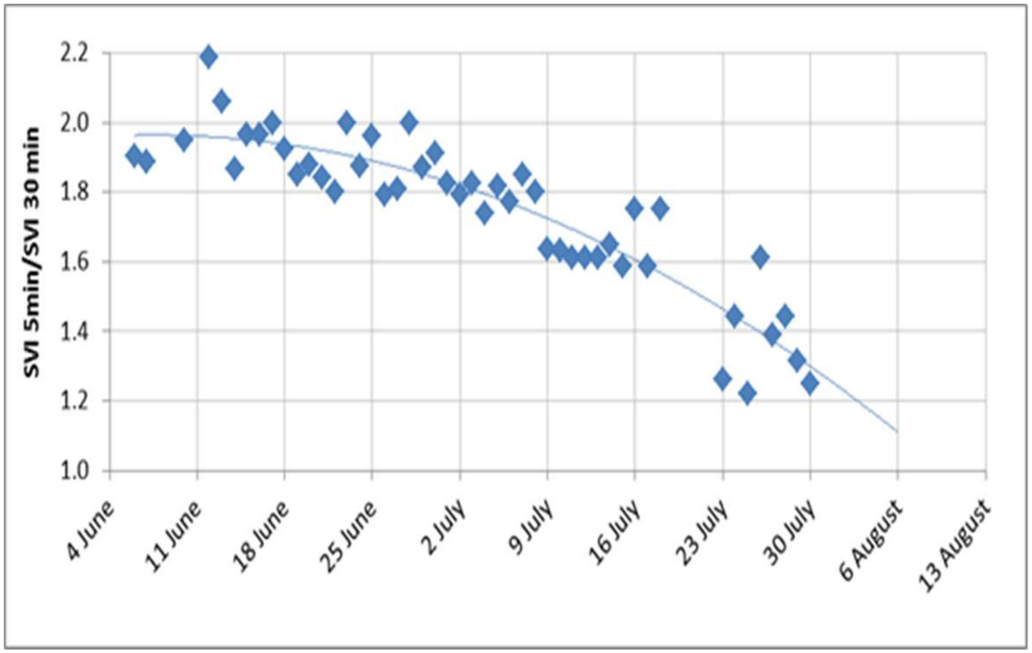
SVI 5 Results (13-Jul-18)



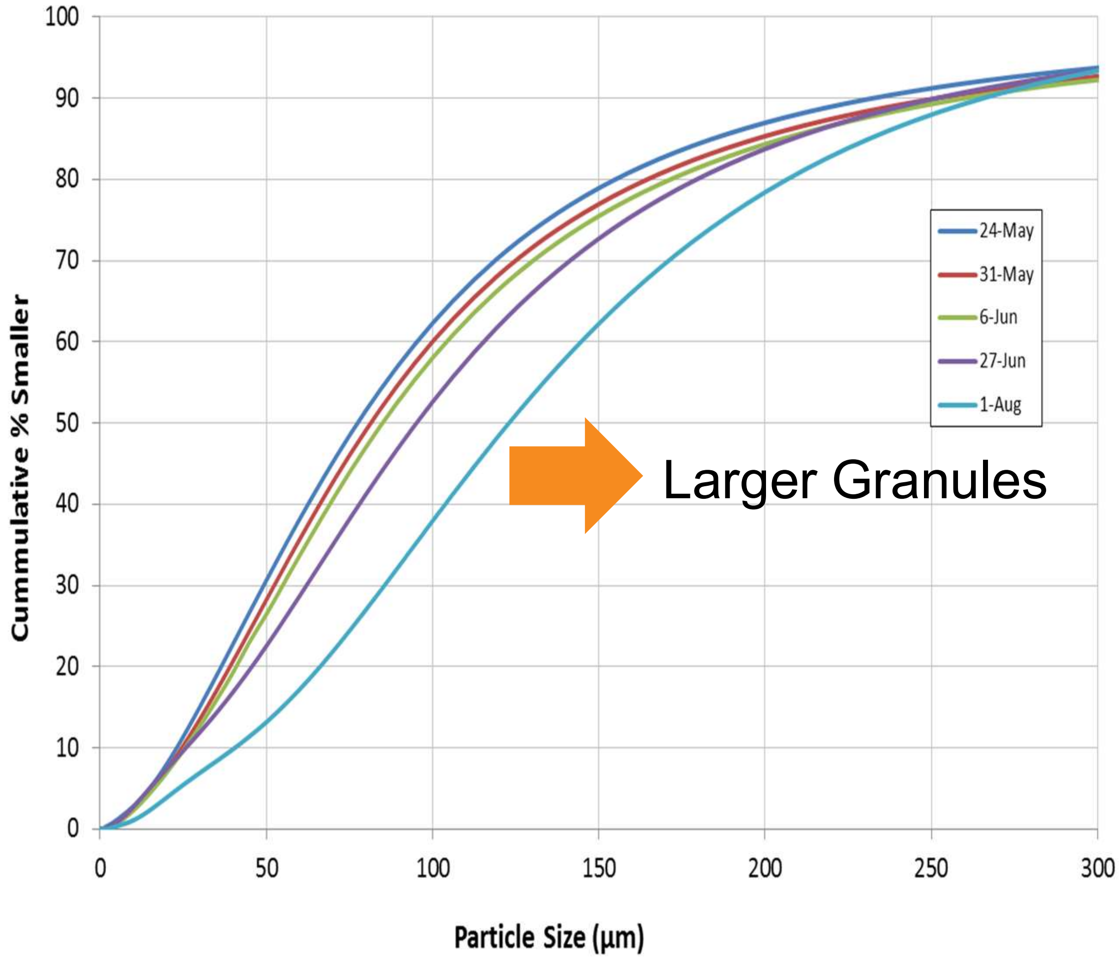
Conventional Westbank Process Train

Granulation Demonstration Train

SVI 5/ SVI 30 in Granulation Train

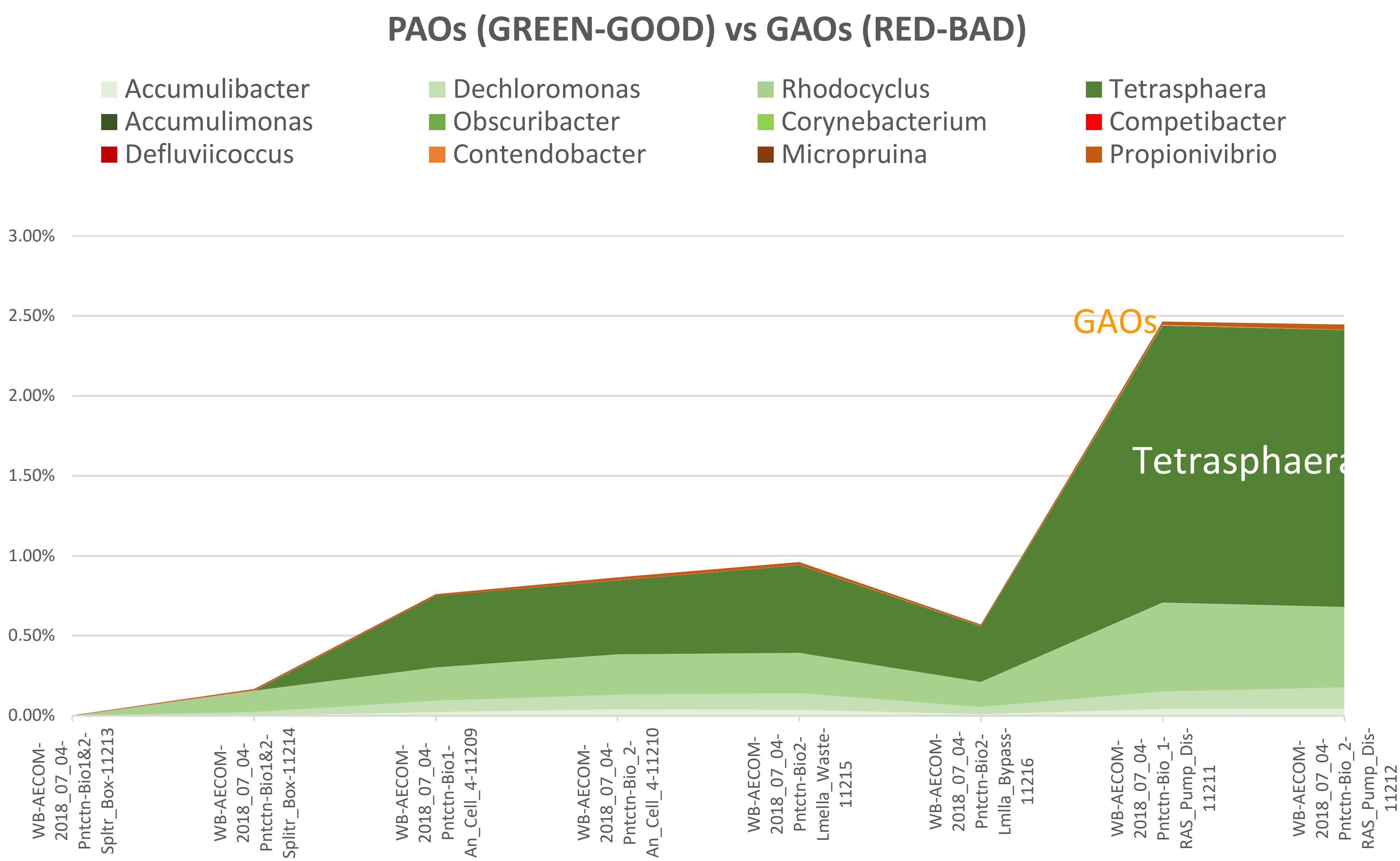


Sludge Size Characteristics



- Particle size in the pilot granulation train continues to increase
- Microscopy shows agglomerations that have granular features

Microbial Analysis



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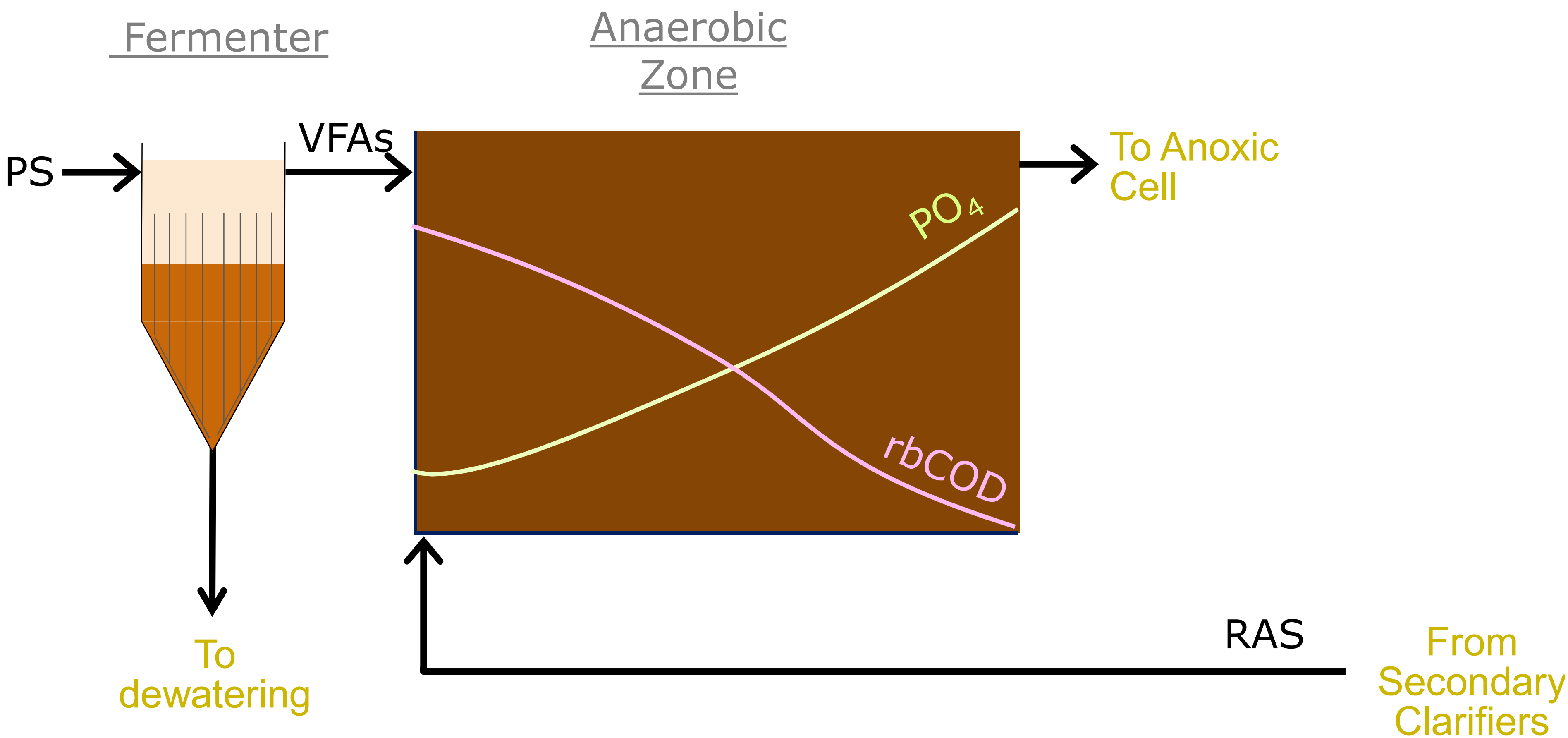
Microbial Manipulation in Westbank BNR Process

- With sufficient HRT, the RAS anaerobic zone seems to deselect for GAOs
- HRT typically only 1.3 -1.6 hrs in Westbank Process and is effective in eliminating the GAOs
- Seeding with fermenters along with VFA from fermenter



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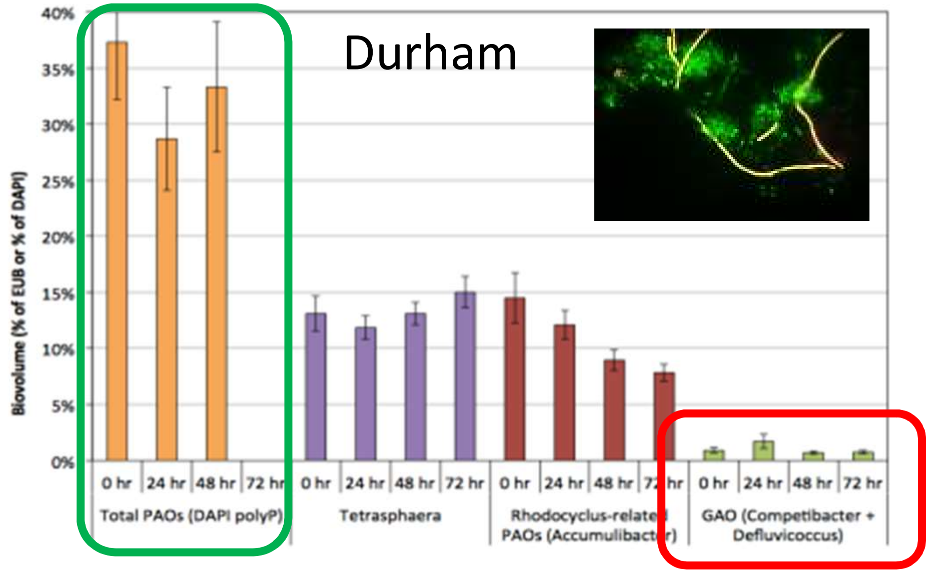
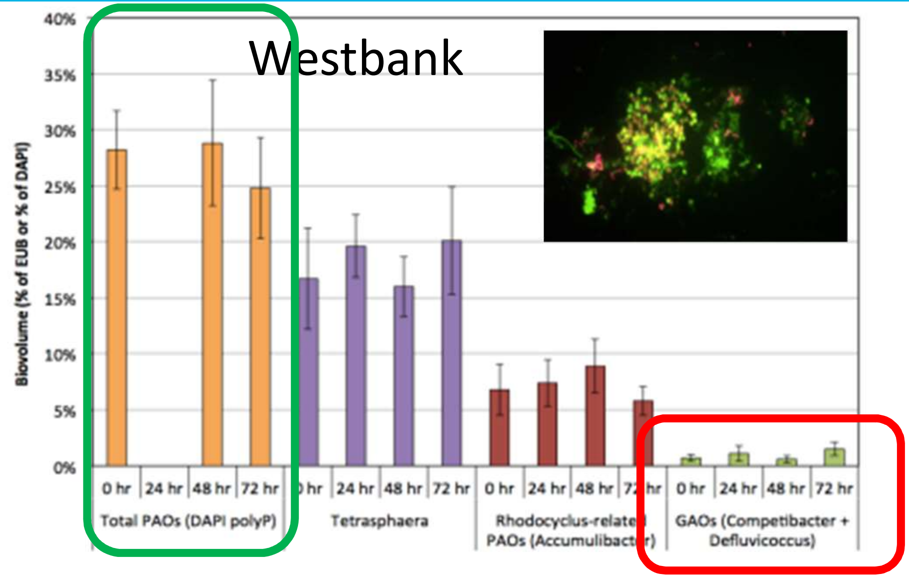
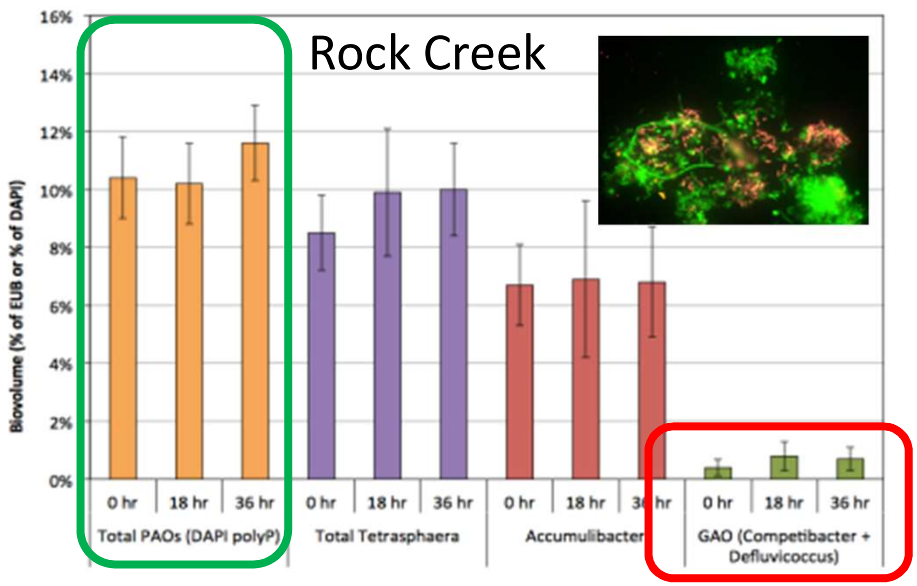
Westbank Promotes Enhanced PAO & Reduced GAO Growth







- In a recent study, all RAS sidestream fermentation processes had very low population of GAOs

Reference: Tooker, N. et al, 2018. Rethinking and reforming enhanced biological phosphorus removal strategy

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The New Kid on the Block- “Tetrasphaera” Denitrifying PAOs

– *Tetrasphaera* encompasses a broad class of bacteria but some unique traits

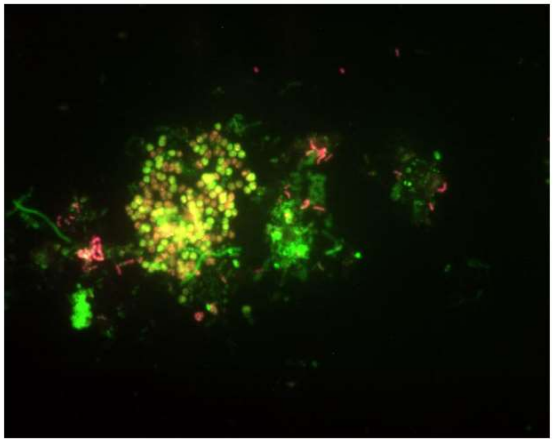
– Many / All can ferment complex organic molecules such as carbohydrates and amino acids (including glucose, glutamate, aspartate) and produce stored carbon in the process. **More Carbon available for P & N removal**.

– Some *Tetrasphaera* can produce VFA during fermentation under more severe anaerobic conditions which could subsequently be utilized as substrate by other PAOs.

– **All types of *Tetrasphaera* are able to denitrify** and possibly able to couple nitrite/nitrate reduction with phosphorus uptake. Because of these behaviors, the net impact on EBPR could be significant

– ***Tetrasphaera species* have the ability to take up phosphates under anoxic conditions** .The indications are that it is necessary to pass these organisms through a deeper anaerobic condition (-250 to -300mV)

– Occupy a slightly different ecological niche compared with ‘*Candidatus Accumulibacter’* contributing to stability of the EBPR process



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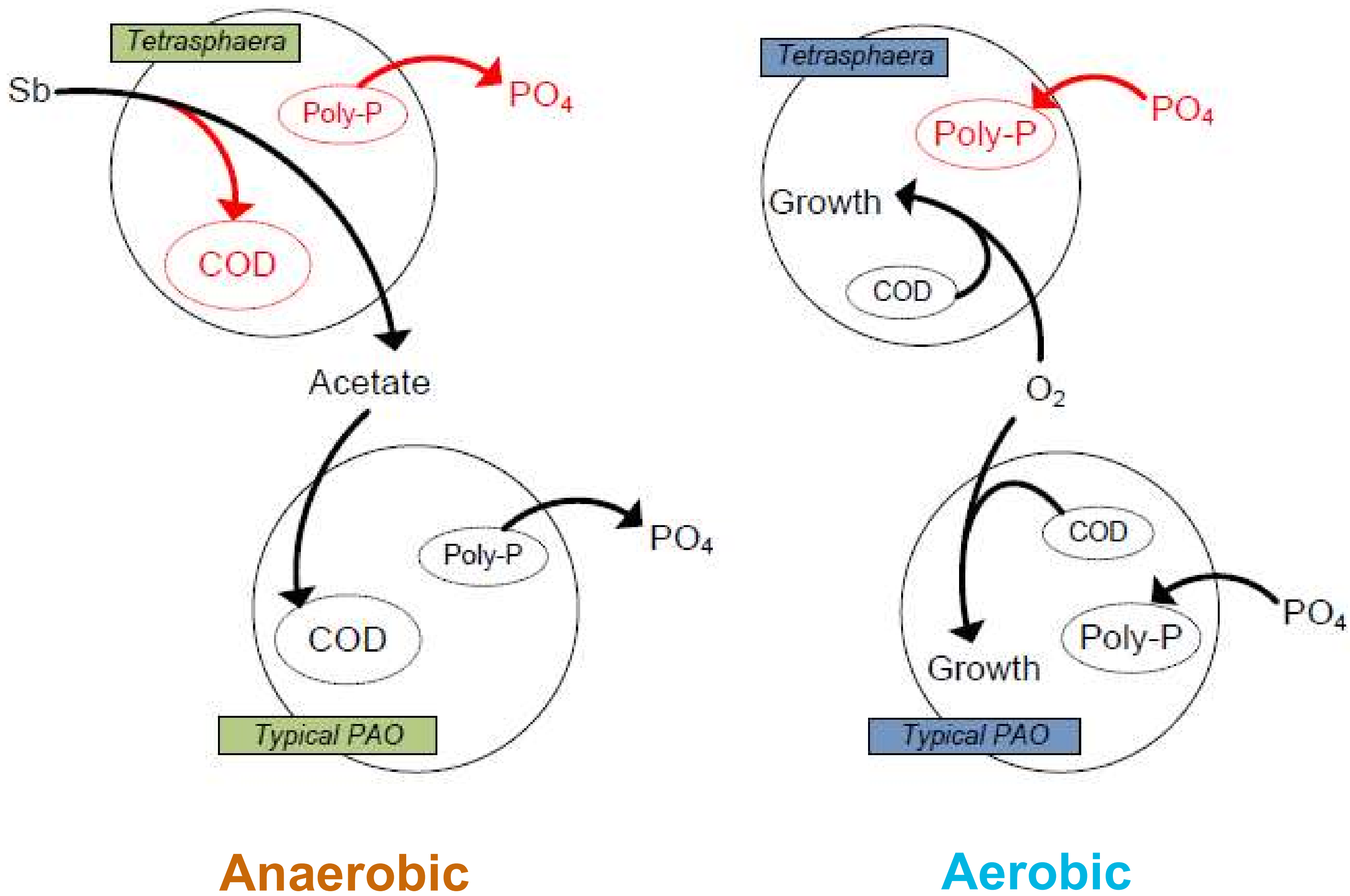
Tetrasphaera reactions under anaerobic & aerobic conditions



– Fermentation of complex organic molecules such as carbohydrates and amino acids. More Carbon available for P & N removal.

Penticton AGS Pilot - Next Steps

1. Additional treatment characterization and refinements
2. Apply results of Penticton pilot at other WWTPs to test:
   - Alternative size selection methods
   - Warm weather & wet weather operation
   - Operation without fermenter

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Summary

- AGS shows great promise as a compact treatment process for domestic wastewater
- Batch Nereda® process is well-proven
- Early research suggests that a continuous flow AGS process is feasible and full-scale application is on the near-future horizon

Thank you for listening

October, 2018

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