Metropolitan Water Reclamation District of Greater Chicago

Welcome to the August Edition of the 2025 M&R Seminar Series

NOTES FOR SEMINAR ATTENDEES

- Remote attendees' microphones are muted at entry to minimize background noise. For attendees in the auditorium, please silence your phones.
- A question and answer (Q/A) session will follow the presentation.
- For remote attendees, please use "**Chat**" only to type questions for the presenter. For other issues, please send emails to MnRseminars@mwrd.org. For attendees in the auditorium, please raise your hand and wait for the microphone to ask a verbal question during the Q/A session.
- The presentation slides will be posted on the MWRD website after the seminar.
- This seminar is pending approval by the Engineering Society of Illinois (ESI) for one PDH and pending approval by the IEPA for one TCH. Certificates will be issued only to participants who attend the entire presentation. For PDH certificate seekers, **completing a brief course evaluation and submitting it are required**.

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For PDH Certificate seekers,

The link to the new on-line course evaluation form will be available in the Chat at the end of the seminar. The form will only be available online until the start of next month's seminar. Please be sure to fill it out promptly.

Towards Sustainable WRRFs: exploring the potential of internally stored carbon for efficient BNR

August 22, 2025

Acknowledgements

WSSC WATER
DELIVERING THE ESSENTIAL

Caroline Nguyen
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Mark Miller
(Pusker Regmi – *Stantec*)

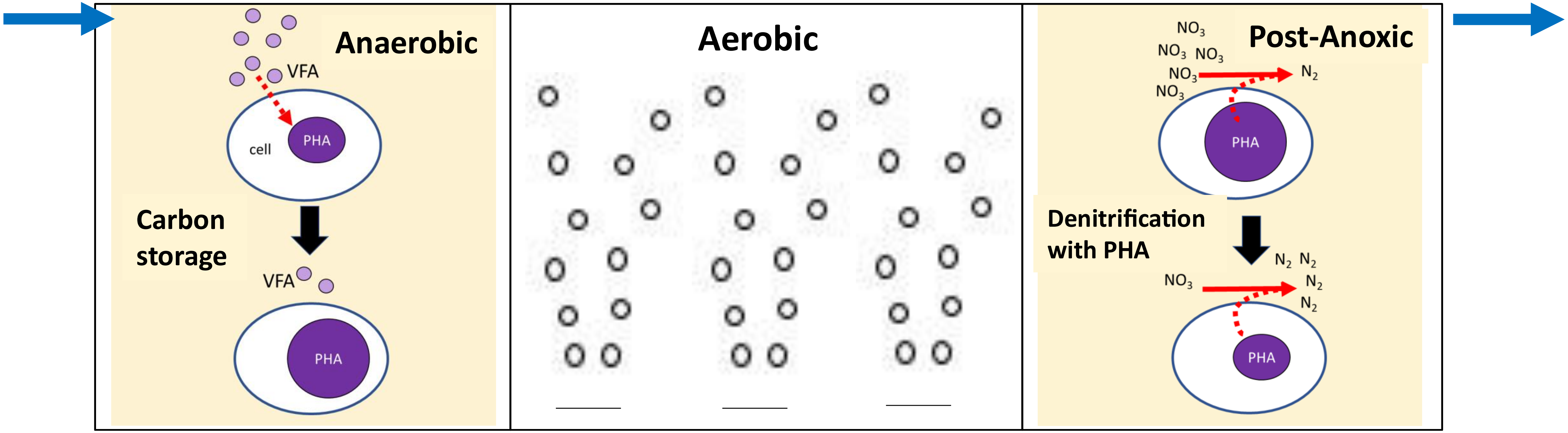
Agenda

1. Introduction to ISC
2. WSSC and HRSD Facilities Overview
3. Which conditions favor ISC for BNR?
4. Case Study: Seneca WRRF
5. Case Study: Damascus WRRF
6. Summary
7. Plans for future study – WRF 5245

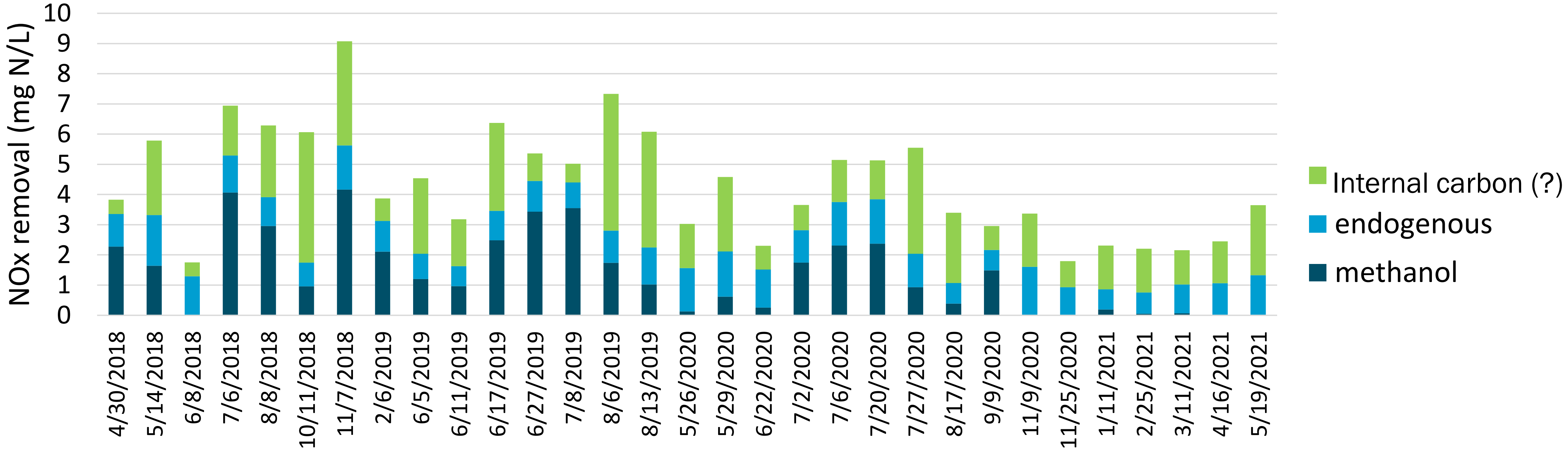
Introduction to ISC

Brown AND Caldwell

What is internally stored carbon (ISC)?
How is it used for denitrification?



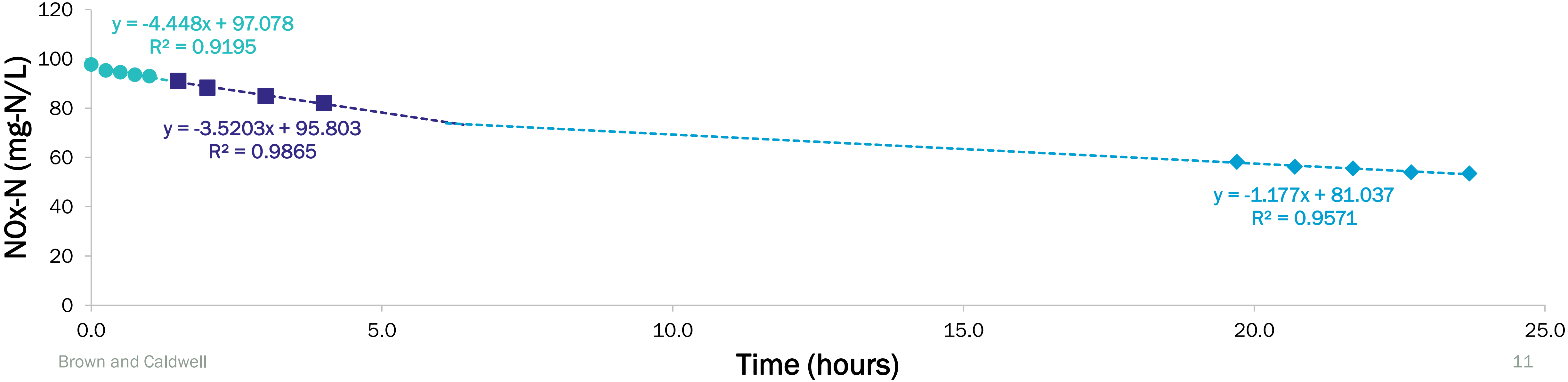
What are the signs? – VIP (HRSD)



Plant	Methanol dose	Cost of N removal	Avg. daily methanol demand		Total methanol demand 2020	
	lb COD/lb N	$/lb N	lb COD/day	$/day	lb COD/yr	$/yr
VIP	0.23	$0.03	1,003	$130	364,348	$47,000
NP	1.76	$0.23	10,100	$1,300	3,686,241	$476,000
AB	2.59	$0.33	4,087	$530	1,491,576	$193,000

Activity Testing - Multi-phase Denitrification (*Extended Post-Anoxic Phase)*

- Gradual change in denite rate rather than distinct phases…but rate decreases by ~0.9 mg N/L/hr within first 4 hours
- Ex: could approximate 3 phases of denite by C source
  - ISC?
  - sbCOD?
  - endogenous decay?



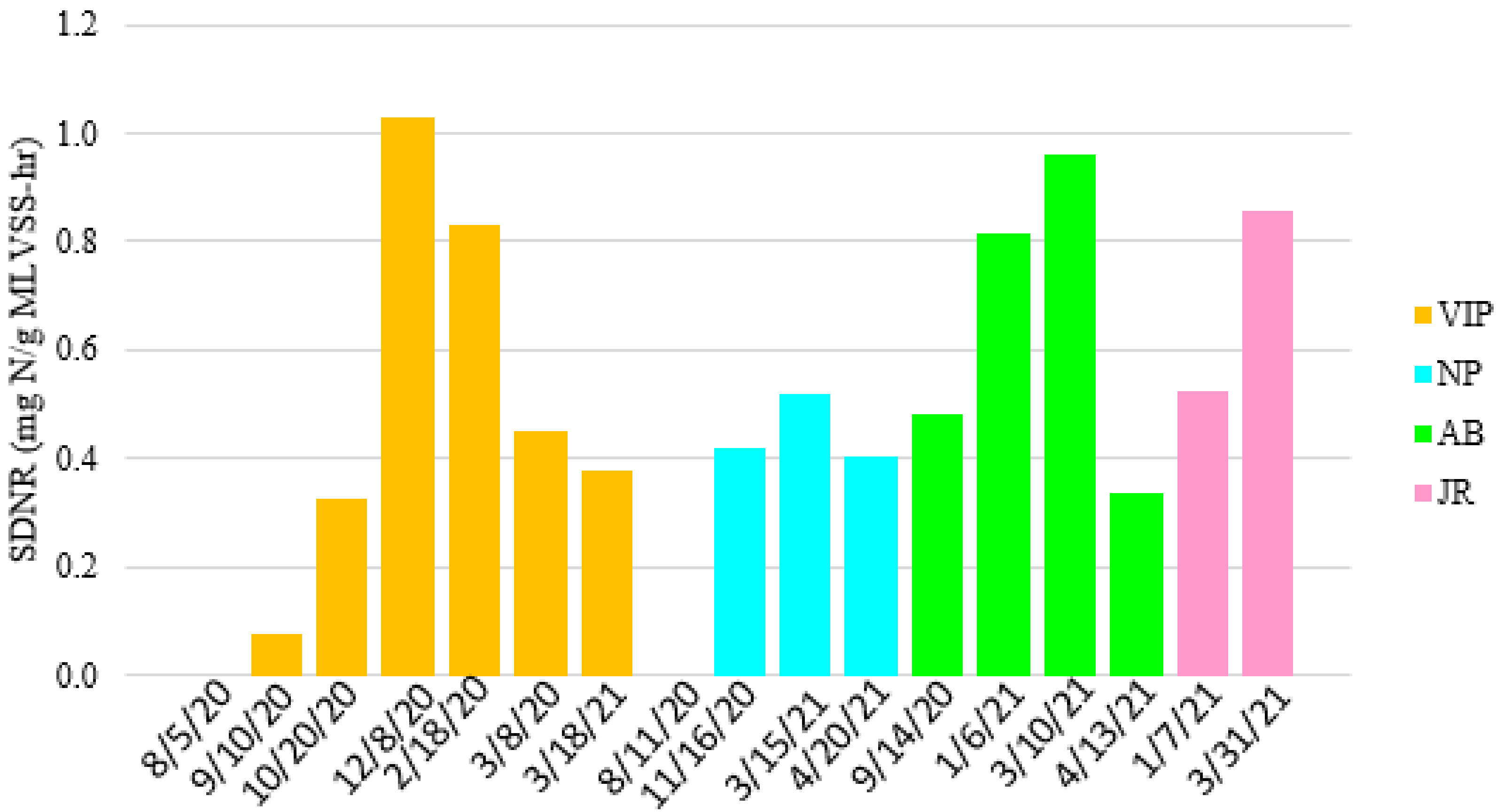
Endogenous decay denitrification rates

Source	Process type	Endogenous SDNR (mg N/g MLVSS/hr)
Henze, 1991	Full-scale WRRFs	0.2-0.5
Kujawa & Klapwijk, 1999	Anoxic batch reactor	0.2-0.6
Vocks et al., 2005	Pilot-scale AOA with membrane	0-0.6
Tchobanoglous et al., 2014	[not specified]	0.42-1.25
Shi et al., 2019	AOA SBR	0.35

	Specific NO_3 Denit Rate ($mg\ NO_3$-N/ g MLVSS/hr)	Specific NO_x Denit Rate ($mg\ NO_x$-N /g MLVSS/hr)
VIP (n=5)	0.29 (± 0.10)	0.32 (± 0.09)
AB (n=3)	0.37 (± 0.11)	0.37 (± 0.11)
NP (n=3)	0.42 (± 0.09)	0.40 (± 0.07)
CE (n=1)	0.80*	0.80*
AT (n=1)	0.68*	0.68*
JR (n=1)	0.41*	0.41*

Batch-scale ISC SDNRs exceed endogenous

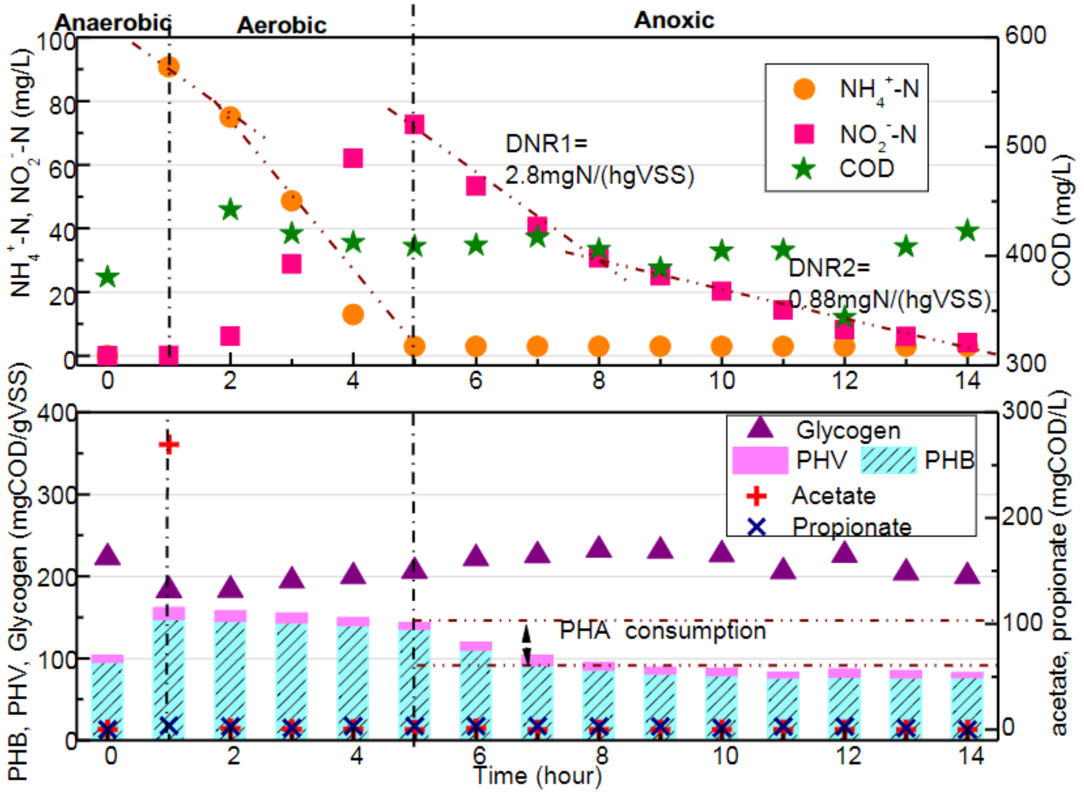
Rates shown are corrected for endogenous activity… shown are rates attributed to ISC only

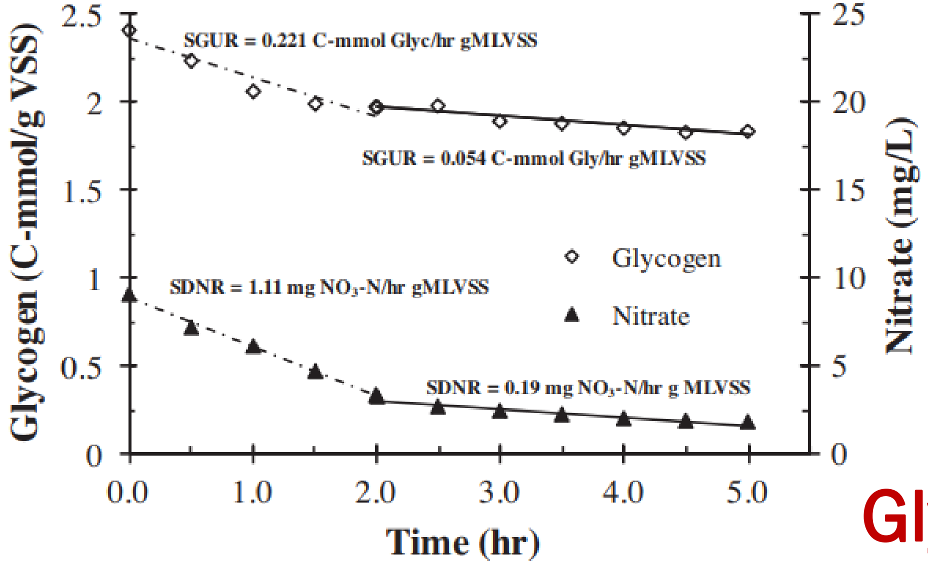


Evidence in Literature

- Internally stored carbon (ISC) denitrification has been documented in several studies
- (Beun et al., 2000, Ji et al., 2017, Vocks et al., 2005, ...)

PHA (Miao et al., 2016)





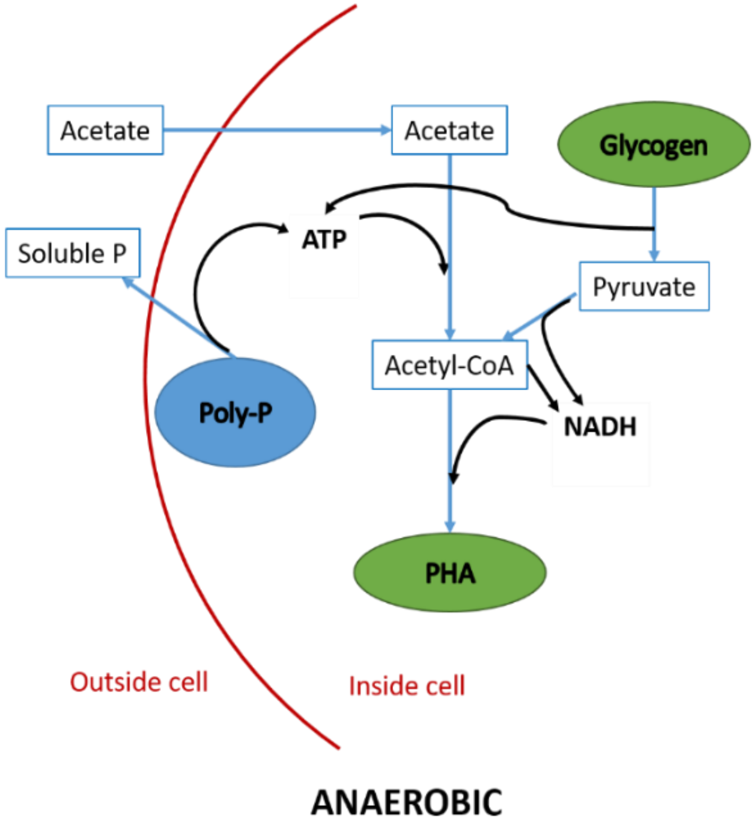
Glycogen (Coats et al., 2011)

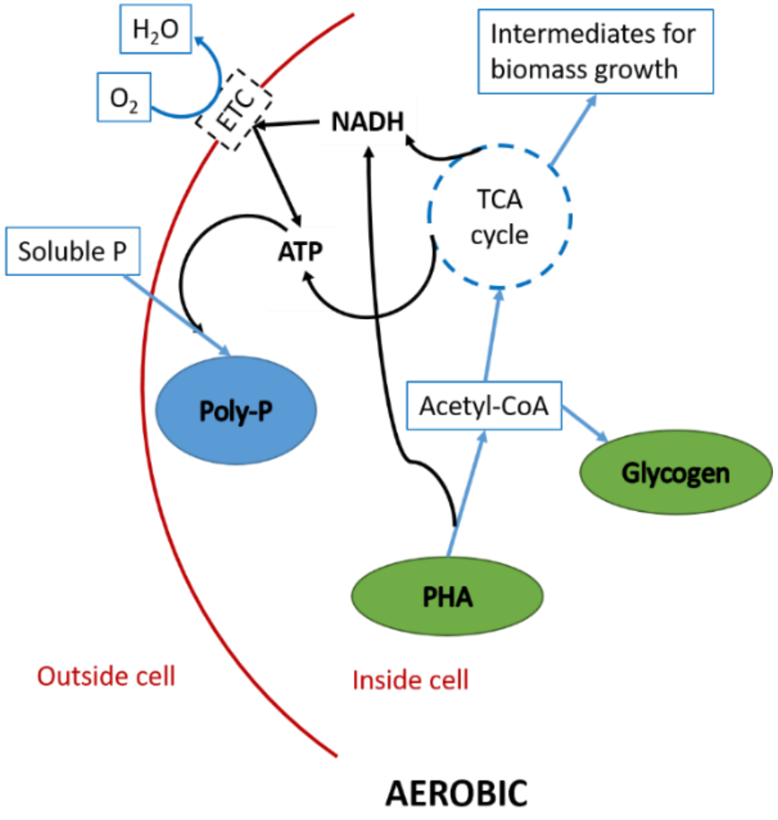
Background: carbon-storing heterotrophs

- Rates with **PHA**:
  - 1.12 - 10.8 mg N/g MLVSS/hr (Carvalho et al., 2007; Qin et al., 2005)
- Rates with **glycogen**:
  - 0.2 - 1.26 mg N/g MLVSS/hr (Coats et al., 2011; Winkler et al., 2011, Vocks et al. 2005)

...dPAOs?

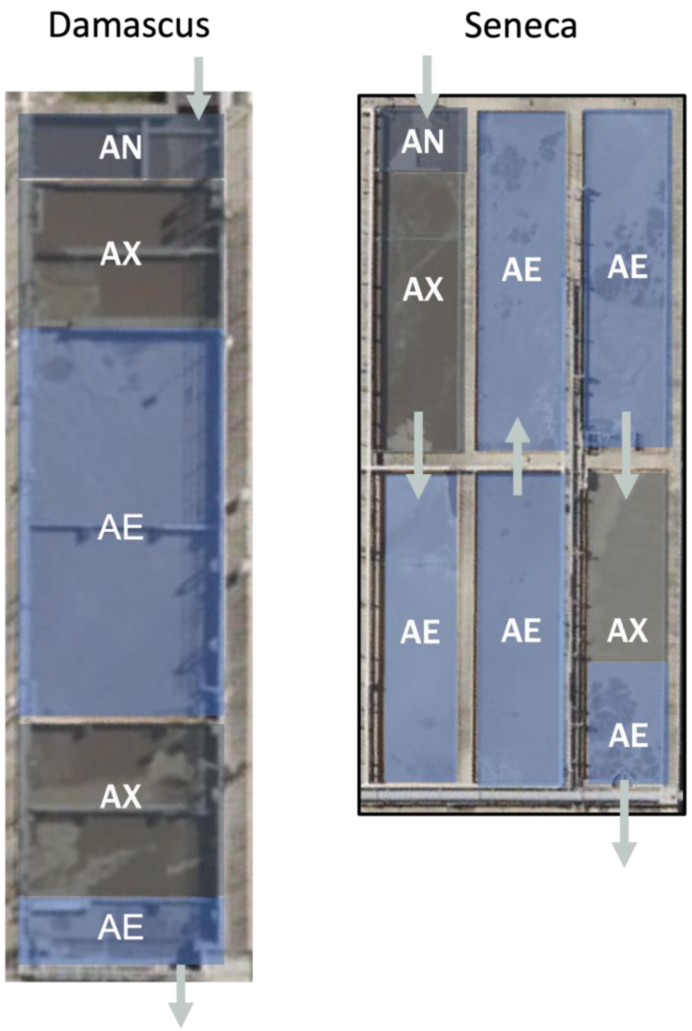
...dGAOs?





WSSC and HRSD Facilities Overview

WSSC's 5-Stage plants



- Seneca: 15 mgd, SRT 25 days, ABAC/Low DO
- Damascus: 1 mgd, SRT 25+ days, High DO
- No primaries, very small anaerobic zone

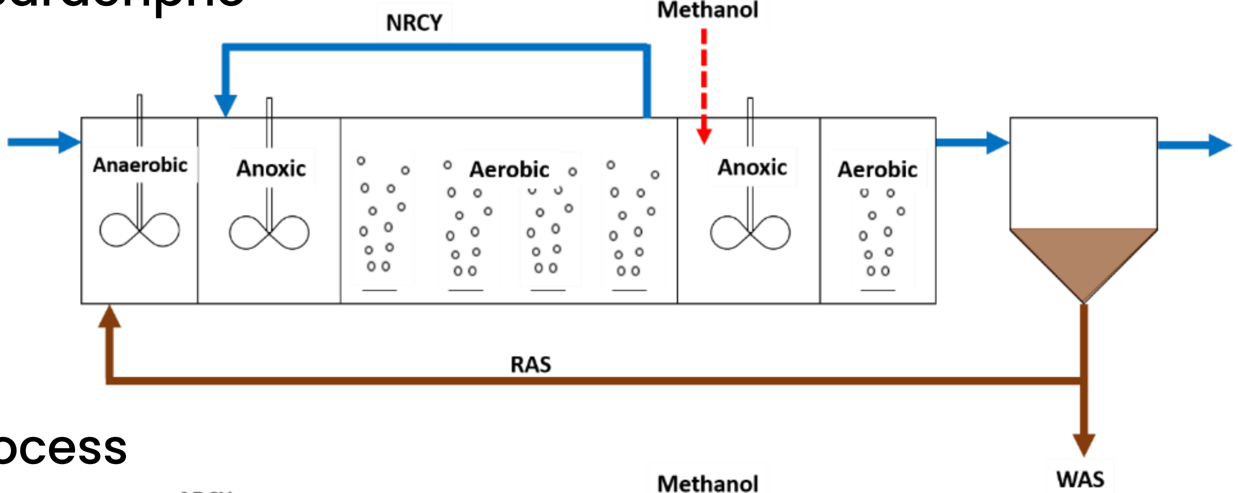
Damascus / Seneca Overview

	Seneca	Damascus
Average Flow	~12 – 13 MGD	~0.7 – 0.8 MGD
Target effluent TN	< 3 mg N/L	< 3 mg N/L
Configuration	5-stage Bardenpho	5-stage Bardenpho
Primary Clarifiers?	No	No
F/M (g BOD/g MLSS/d)	1.8	1.5
IMLR	~200 – 400%	400%
DO	Low/ABAC (0.3 mg/L)	High DO (1.5+ mg/L)
SRT	25 days	25-40 days
P removal	Bio-P Alum for polishing	Bio-P Alum for polishing
Post-anoxic NO_3 removal *(low/no methanol)*	~3.5 mg N/L	~7 mg N/L

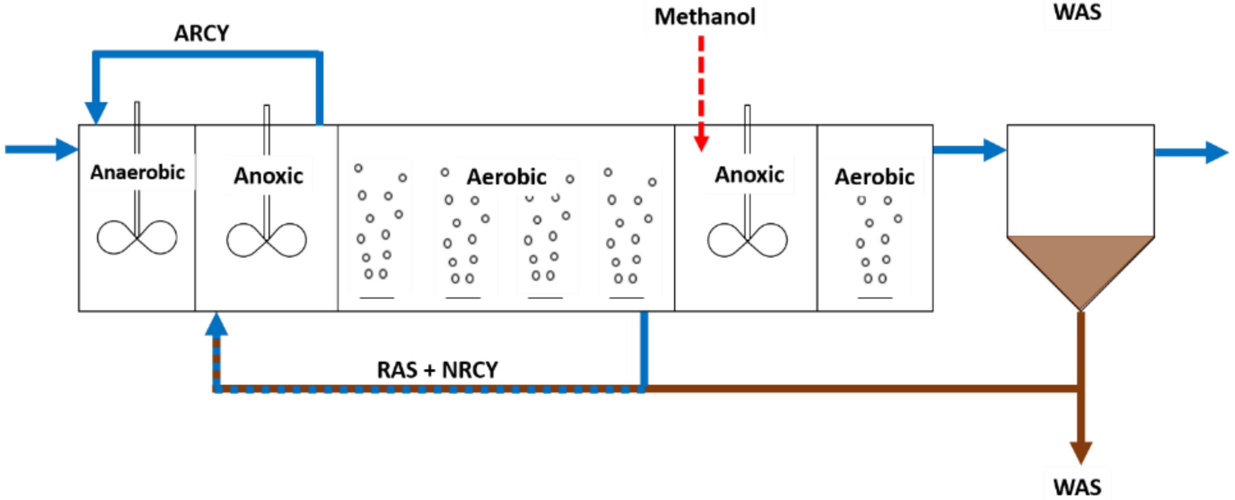
HRSD’s 5-Stage plants (with methanol addition)

- Virginia Initiative Plant (VIP)
- Army Base (AB)
- Nansemond Plant (NP)

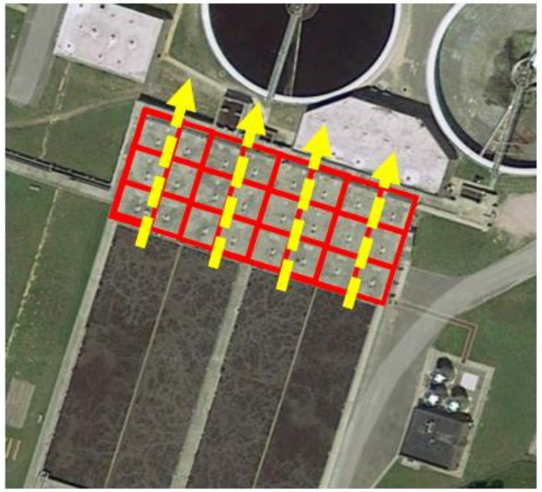
5-Stage Bardenpho



VIP + 2 process



Post-anoxic zones and relevant parameters

AB	NP	VIP
		

Flow (MGD)	10.5	17.0	27.4	
# CSTRs in series	2	3	40 (train 1)	30 (train 2)
HRT (hr)	1.0	2.4	1.8	
Mixing	Mechanical	Mechanical	Big bubble	
NRCY (%)	201 (± 3)	342 (± 4)	118 (± 2)	
Effluent TN (mg N/L)	4.90 (± 0.18)	4.73 (± 0.12)	5.01 (± 0.16)	
Methanol Dose (lb COD/lb N removed)	**2.11 (± 0.15)**	**1.48 (± 0.06)**	**0.49 (± 0.03)**	

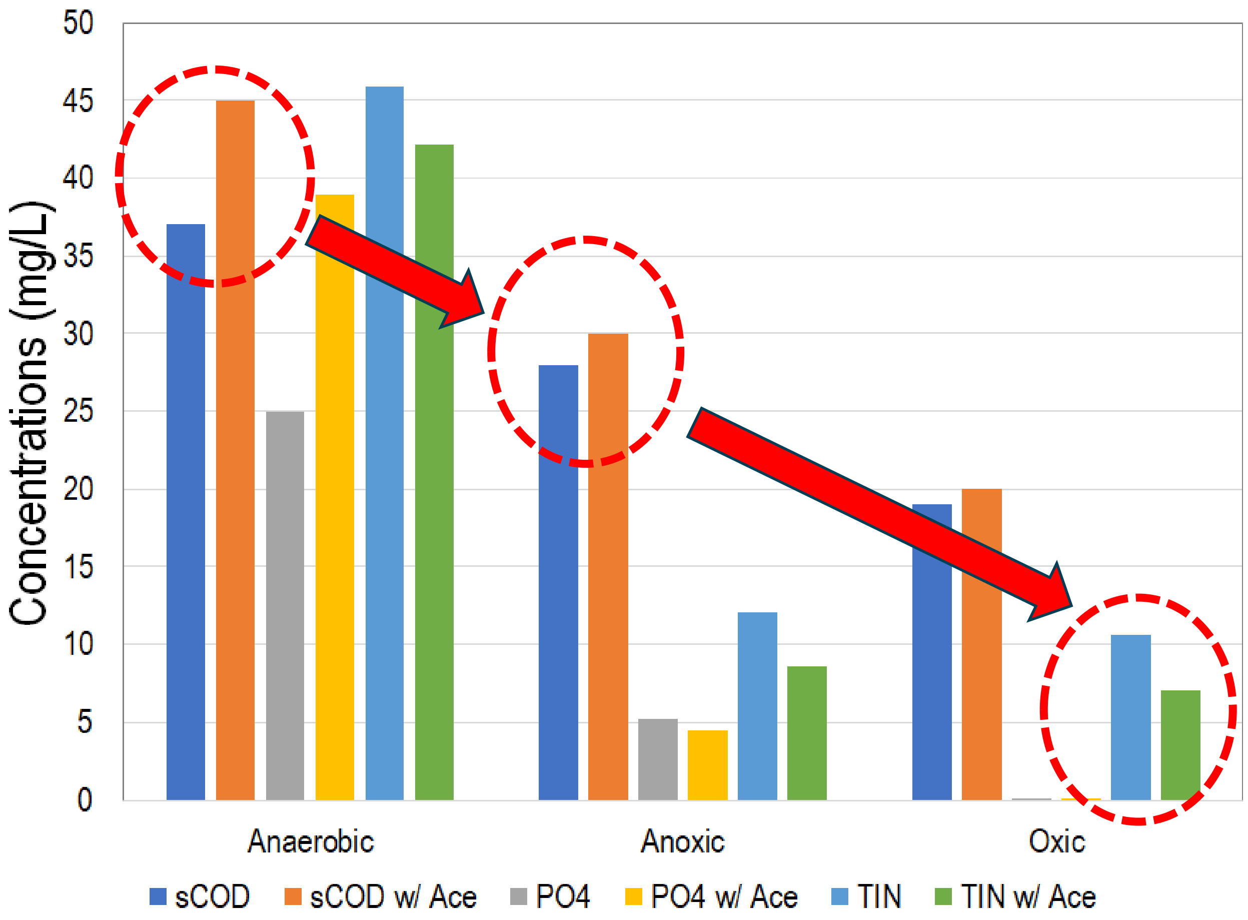
Internal carbon for post-anoxic denitrification?

Plant	Methanol Dosage (lb COD/lb N removed)	PCE rbCOD:TKN (lb/lb)	PCE rbCOD:TP (lb/lb)	F/M (mg rbCOD/mg MLVSS/d)
VIP	**0.49 (± 0.03)**	4.12 (± 0.65)	31.0 (± 4.3)	3.57 (± 0.57)
NP	**1.48 (± 0.06)**	2.00 (± 0.26)	10.4 (± 1.2)	0.66 (± 0.09)
AB	**2.11 (± 0.15)**	1.63 (± 0.32)	10.4 (± 1.7)	0.79 (± 0.14)

(± 95% confidence interval for the average)

Which conditions favor ISC for BNR?

Selector Zone Carbon

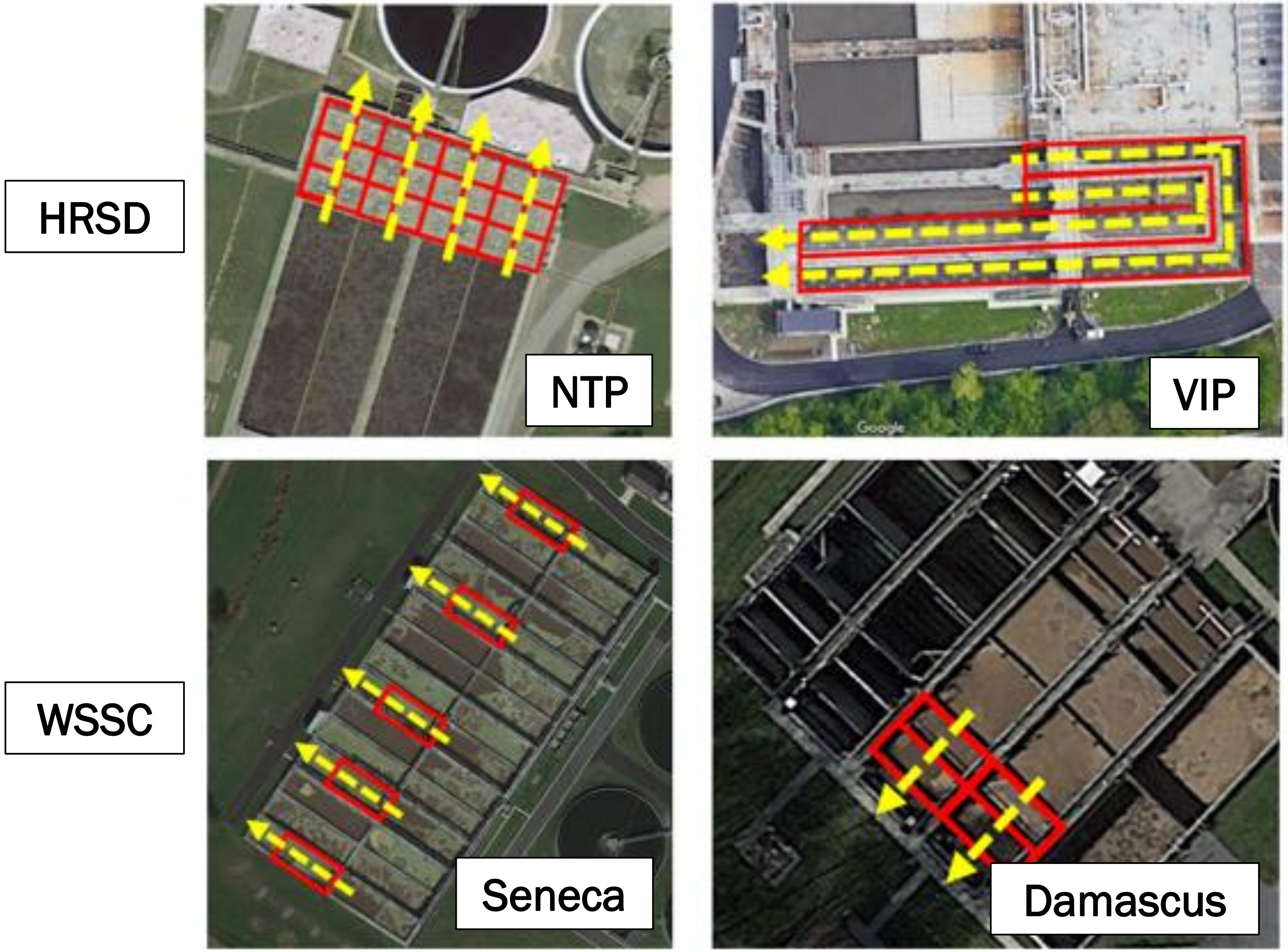


JD WRF – Pueblo, CO

1. Extra anaerobic acetate consumption
2. …led to lower effluent TIN

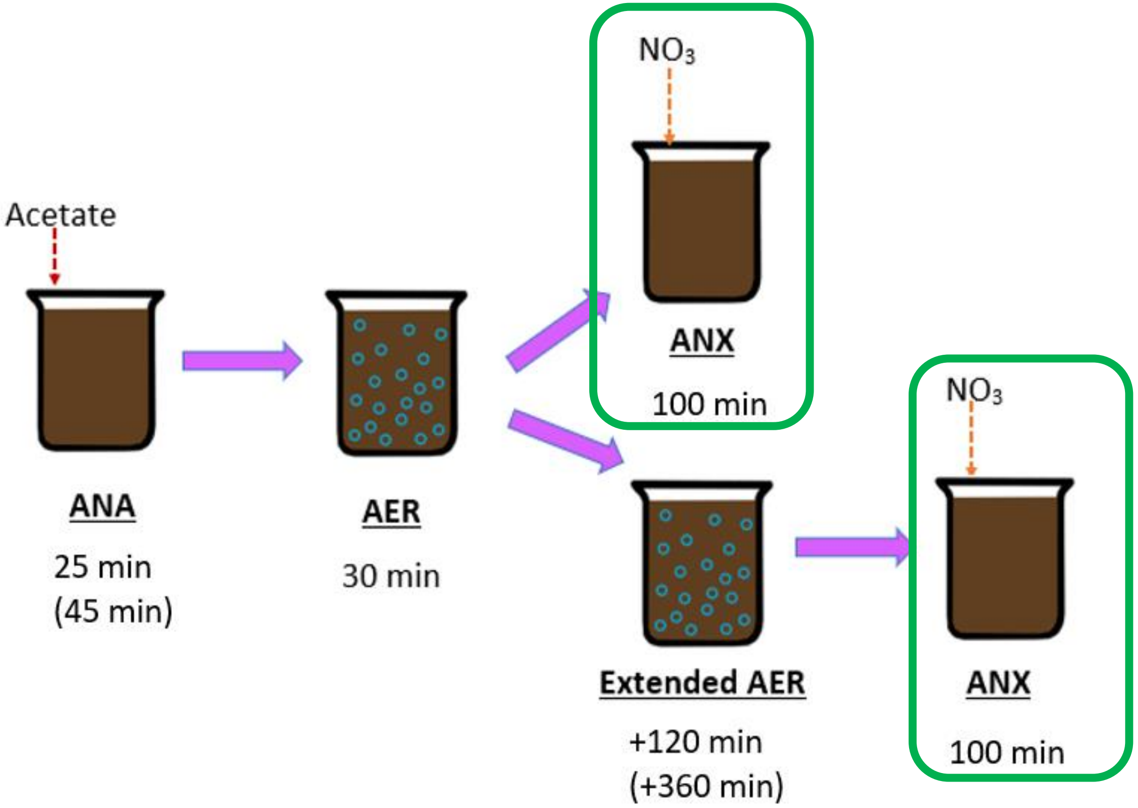
Plug Flow

- Internal carbon denitrification all except NTP…
- Higher NO_3 half-saturation for ISC denitrifiers?



Reduced DO

“Long vs. short aeration” batch test



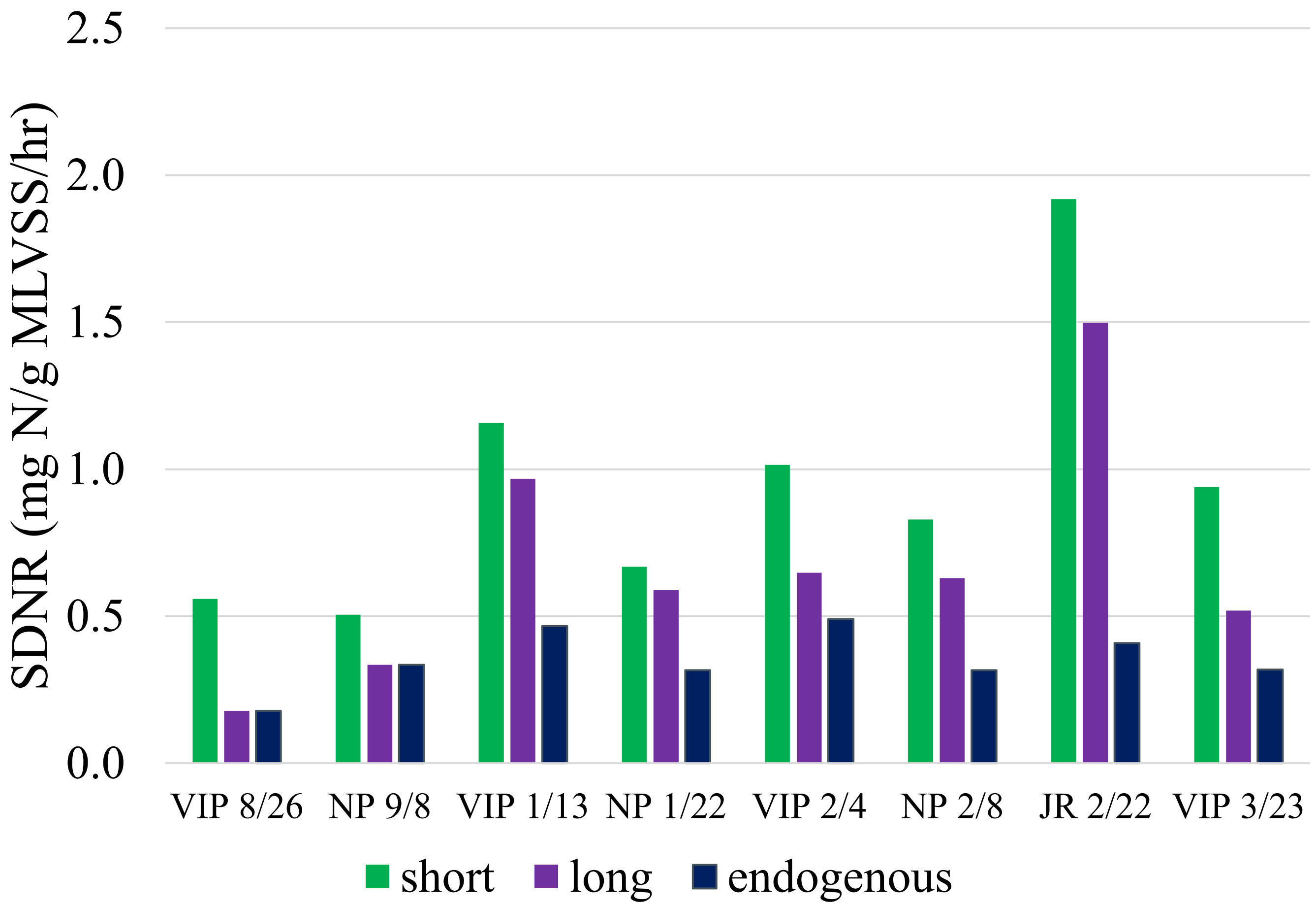
Short AER

- 0.5 hour to ensure VFA oxidized prior to ANX phase
- Assume **PHA** used…or more of other carbon source?

Long AER

- 2.5-4.5 hour to mimic actual HRT
- Assume **glycogen** used…or less of other carbon source?

Reduced DO (cont.)



Batch tests - HRSD 5-stage WRRFs

- Shorter aerobic HRT increases post-anoxic SDNRs
- PHA rather than glycogen?

Increased Bio-P Activity

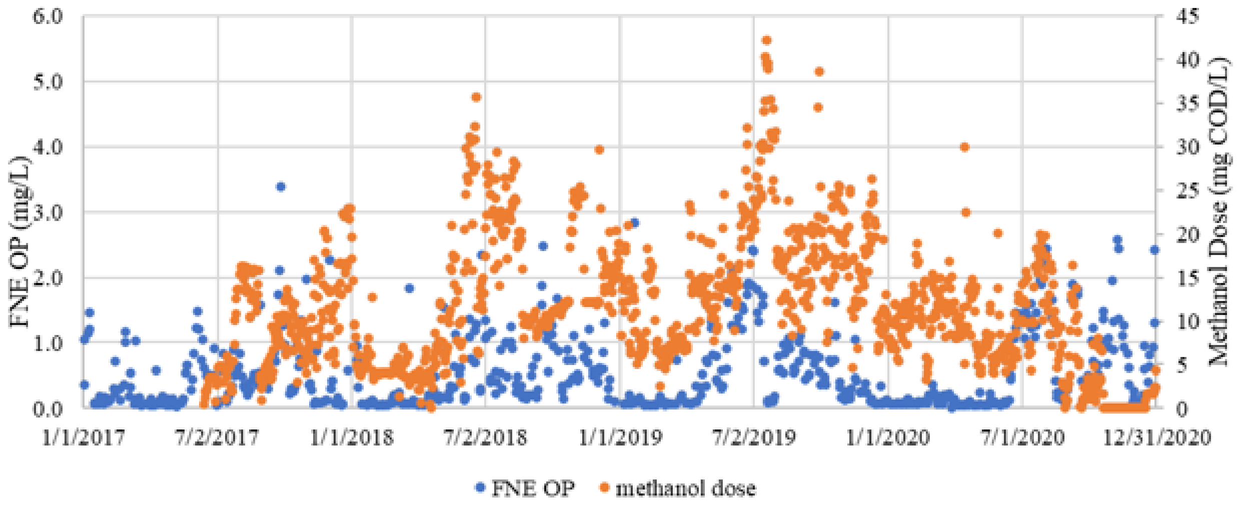
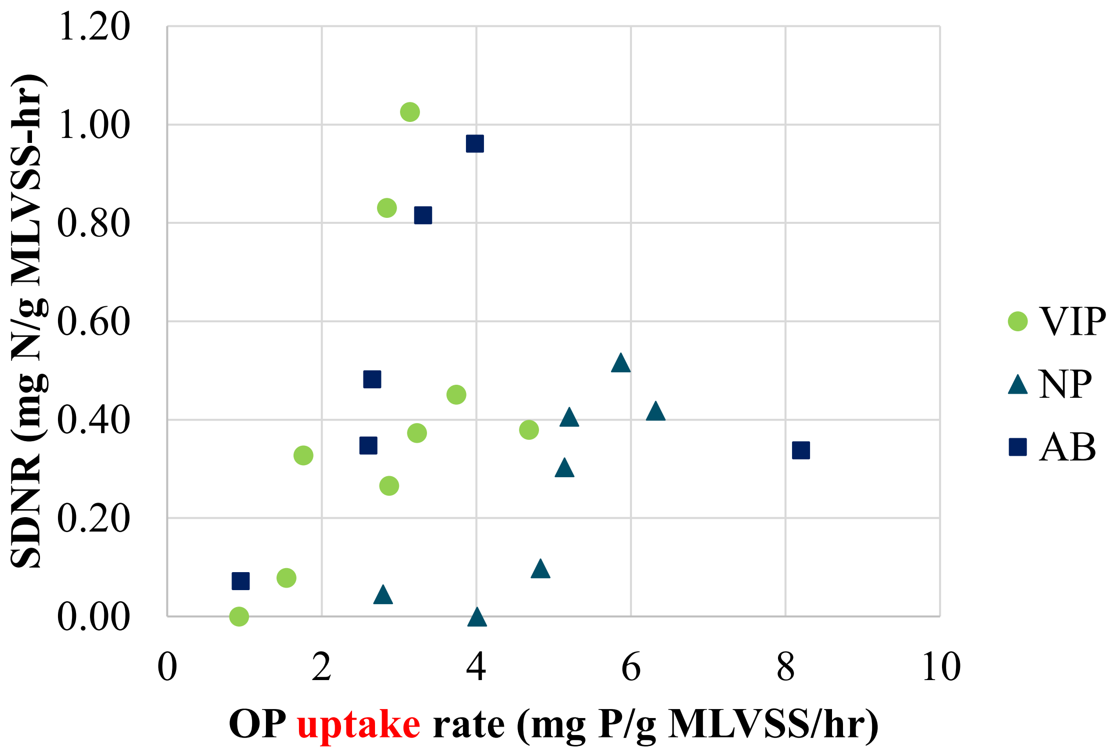


Figure 3: Seasonal variation of final effluent OP concentrations (FNE OP) and methanol dose at VIP.



Summary of observations (so far…)

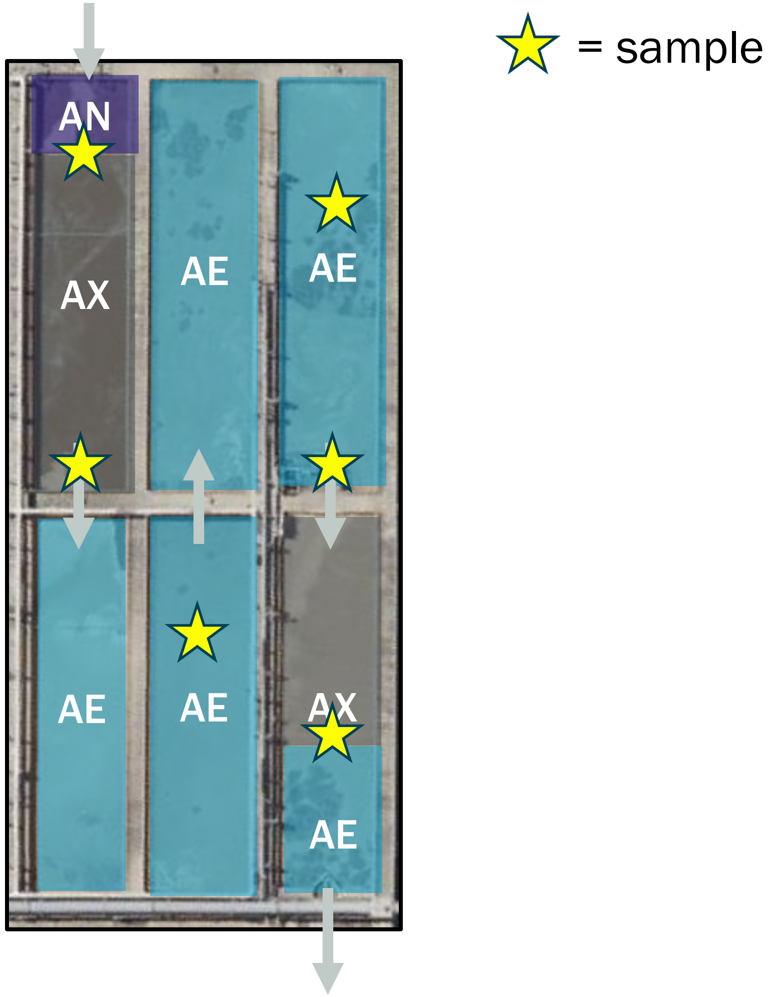
- **Indicators of ISC denitrification**
  - Low/no external carbon addition
  - Plant profiles show post-anoxic NOx removal above expected
  - Reduced effluent TIN
- **Factors that promote ISC denitrification**
  - Selector zone carbon
  - Plug flow
  - Reduced DO
  - Increased Bio-P Activity
  - Reduced IMLR? – Case Study: Seneca WRRF
  - No Primary Clarifiers? – Case Study: Damascus WRRF

Case Study – Seneca WRRF

Brown AND Caldwell

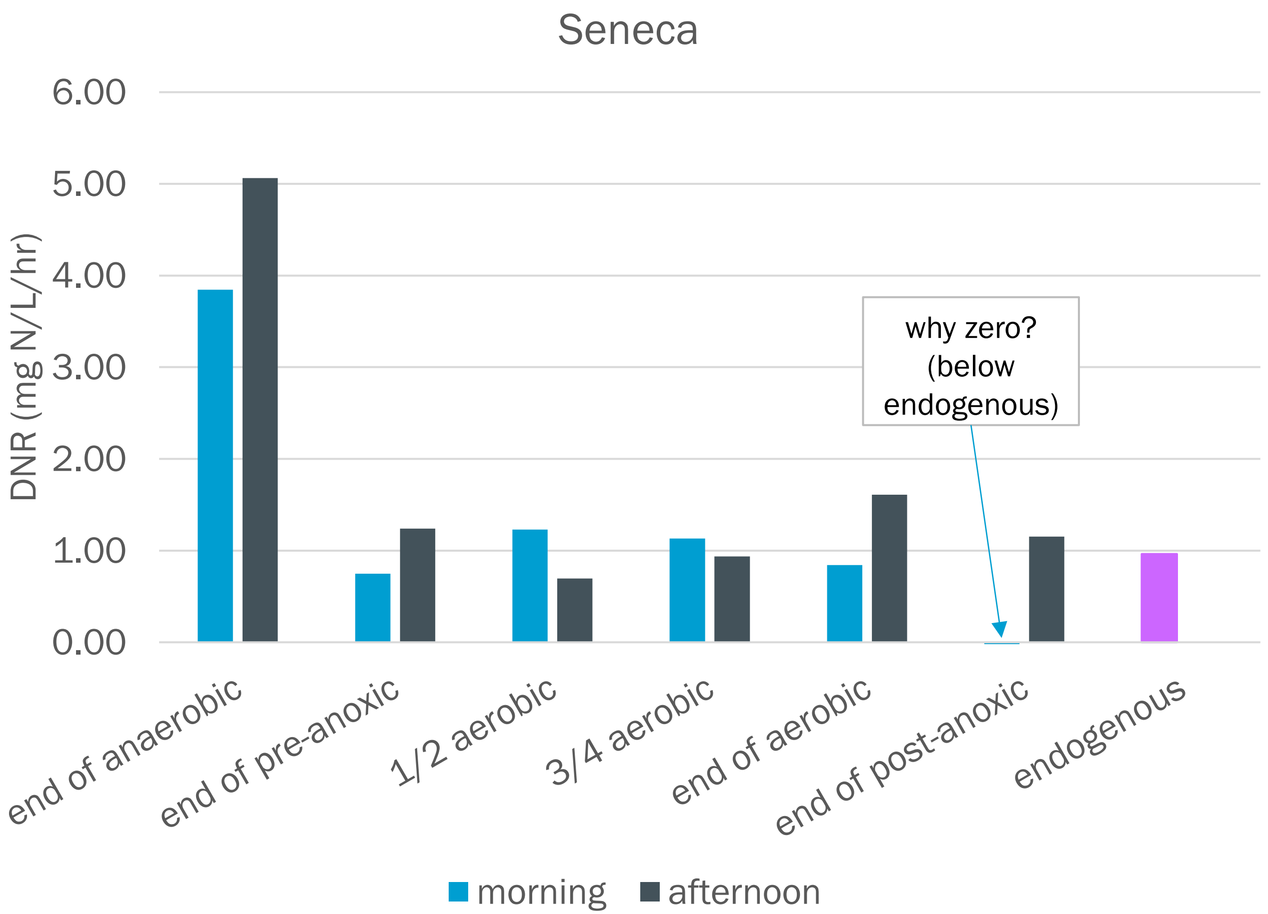
Batch testing at Seneca WRRF (WSSC)

- Previous observations
  - No methanol addition in post-anoxic zone
  - batch post-anoxic SDNRs >> endogenous SDNRs
- Plant had since converted all trains to optimized configuration (ABAC, etc.)
- Aim to track ISC throughout treatment train via SDNRs



Seneca – all sample points vs. endogenous

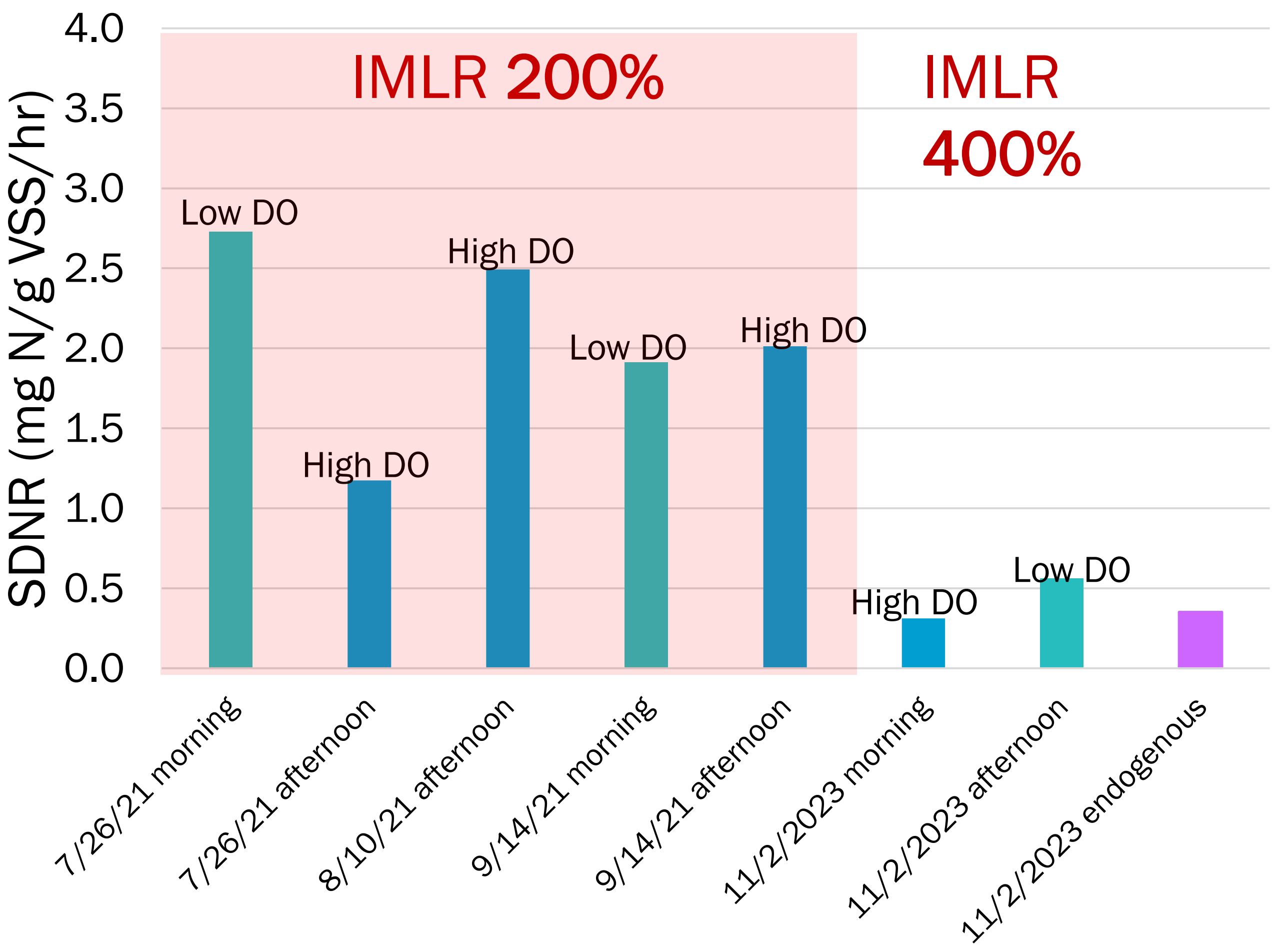
- Most rates right around endogenous
  - Carbon is likely mostly utilized in pre-anoxic due to recycle
- IMLR at 400%



Reduced Internal Recycle

WSSC Seneca WRRF

- Less recycled NO_3 = more ISC storage
- Balance pre-anoxic vs. post-anoxic denitrification
- Post-anoxic benefits:
  - Bio-P (less NO_3 = more P release)
  - Energy (less recycle pumping)



Conclusion

- Seneca still meeting effluent TN requirements suggests high C/N is key and operations just changes how/where the C is used:
  - High IMLR/high DO: used pre-anoxically (with endogenous denite in post-anoxic)
  - Low IMLR/low DO*: used via SND and post-anoxically

    saves recycle and aeration energy

Case Study – Damascus WRRF

Brown AND Caldwell

Damascus / Seneca Overview

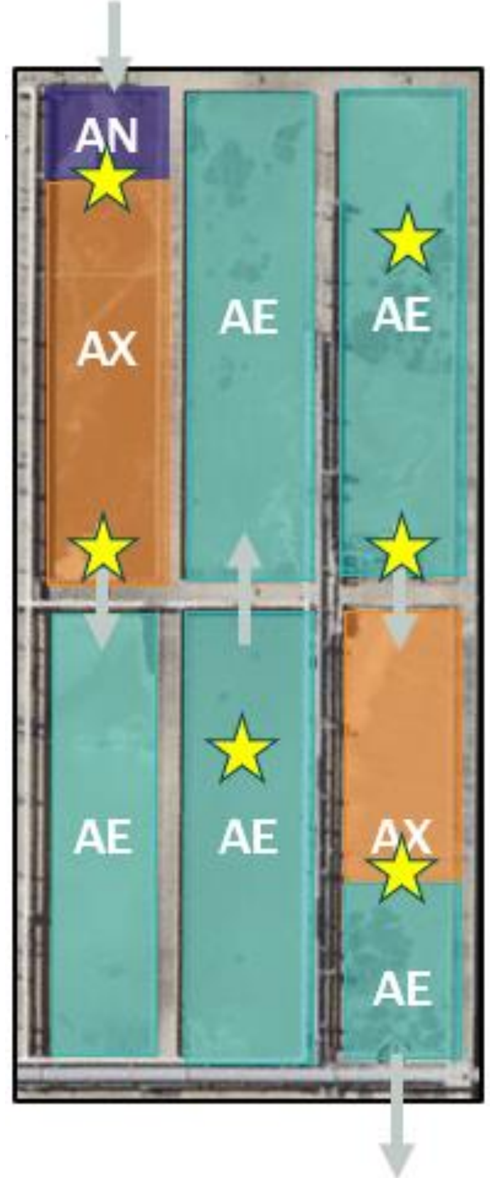
	Seneca	Damascus
Flow	~12 – 13 MGD	~0.7 – 0.8 MGD
Target effluent TN	< 3 mg N/L	< 3 mg N/L
Configuration	5-stage Bardenpho	5-stage Bardenpho
Primary Clarifiers?	No	No
F/M (g BOD/g MLSS/d)	1.8	1.5
IMLR	~200 – 400%	400%
DO	Low/ABAC (0.3 mg/L)	High DO (1.5+ mg/L)
SRT	25 days	40 days
P removal	Bio-P Alum for polishing	Bio-P Alum for polishing
Post-anoxic NO_3 removal *(low/no methanol)*	~3.5 mg N/L	~7 mg N/L

Why so much ISC denitrification even at high DO and high IMLR?

Configuration

Damascus

Seneca



Anaerobic

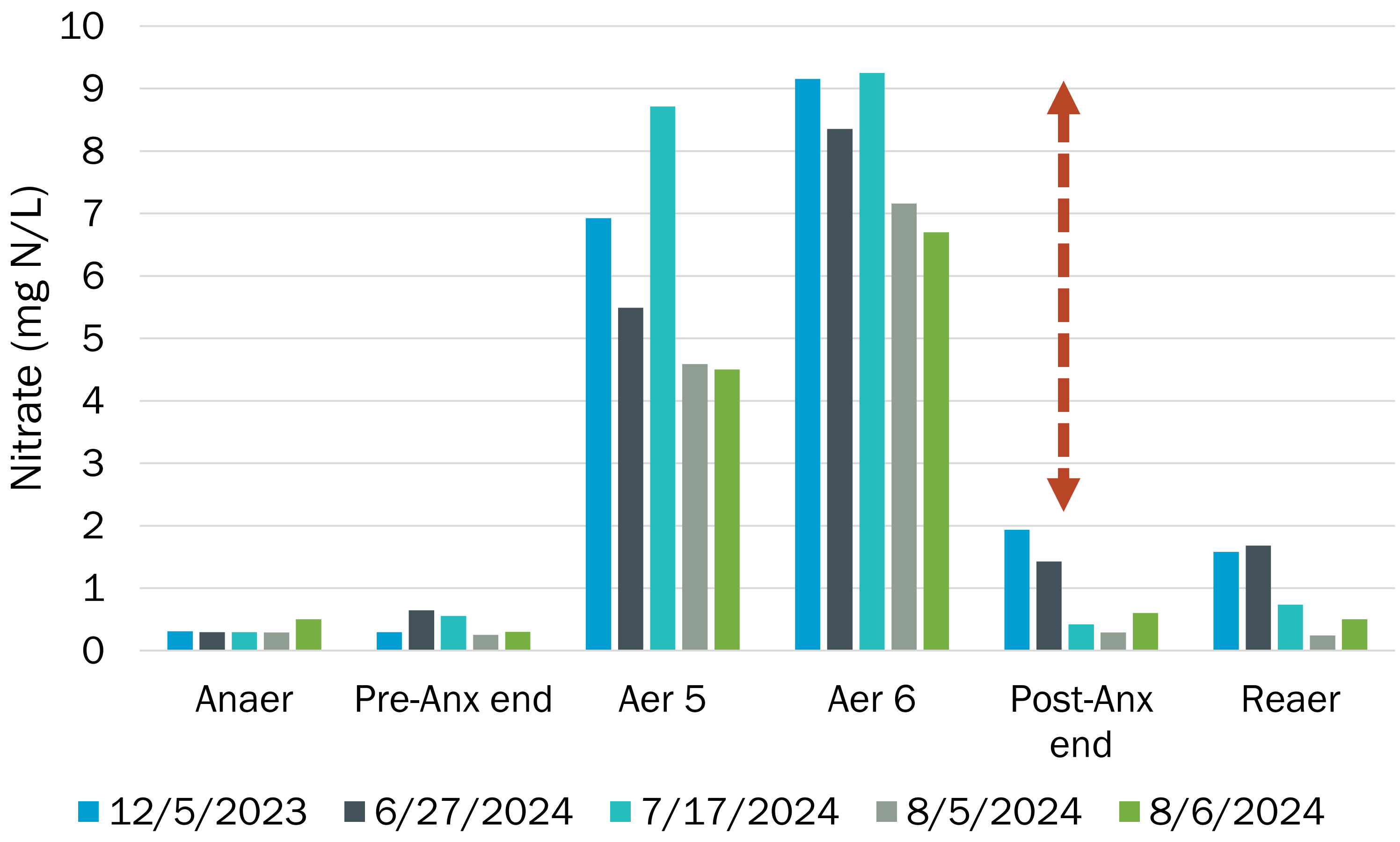
Anoxic

Anoxic (Swing)

Aerobic

★ = sample

Damascus Nitrate Profiles



Average 7 mg N/L NO_3 removal in post-anoxic zone

Research Question: What mechanisms enable post-anoxic denitrification in Damascus WRRF despite high DO?

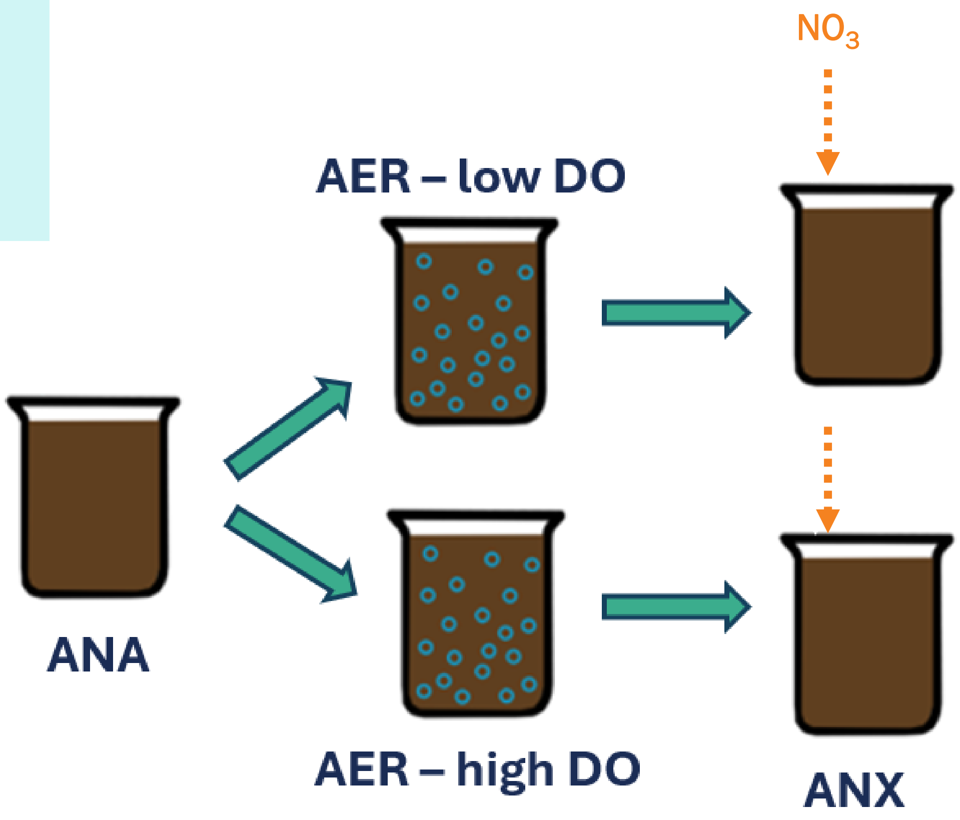
Hypothesis: Without primary clarification, the elevated levels of sbCOD support denitrification even under high DO.

Activity Testing

Activity Test – high vs. low DO

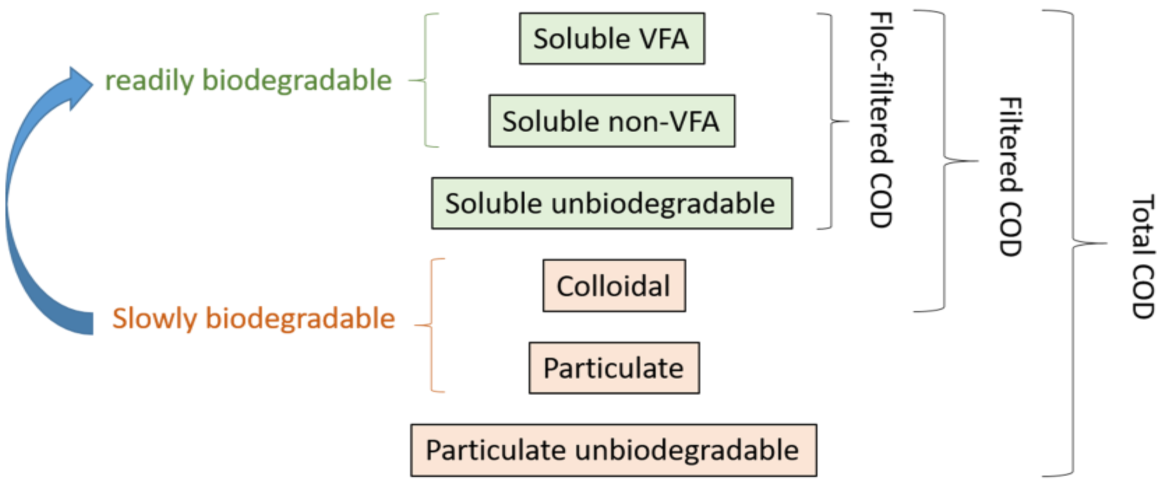
- Compare **high vs. low DO** before post-anoxic denitrification with ISC
- Does DO make any difference for Damascus?

1. Combine RAS and influent
2. Run anaerobic storage phase
3. Split sample into two reactors
    - aerate one at 2 mg/L (high DO)
    - aerate other at 0.2 mg/L (low DO)
4. Aerate for 2 hours
5. Stop aeration, spike nitrate, measure post-anoxic SDNR

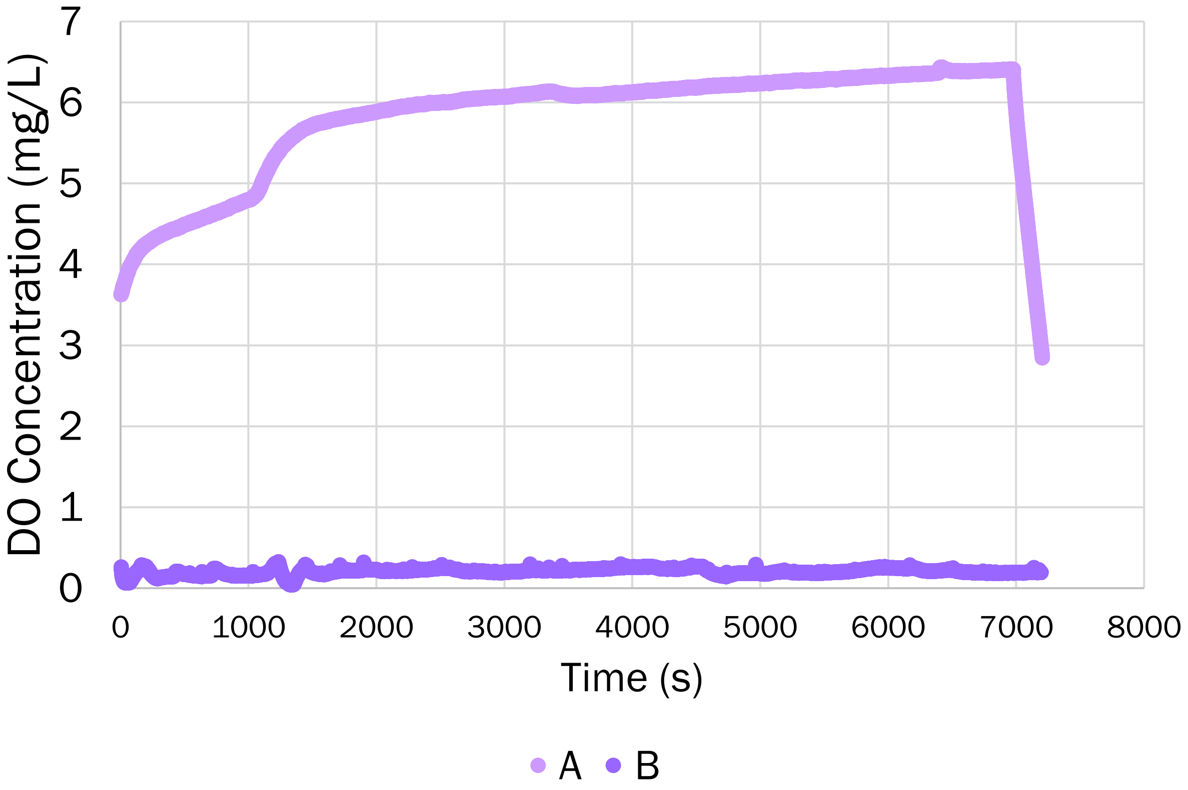


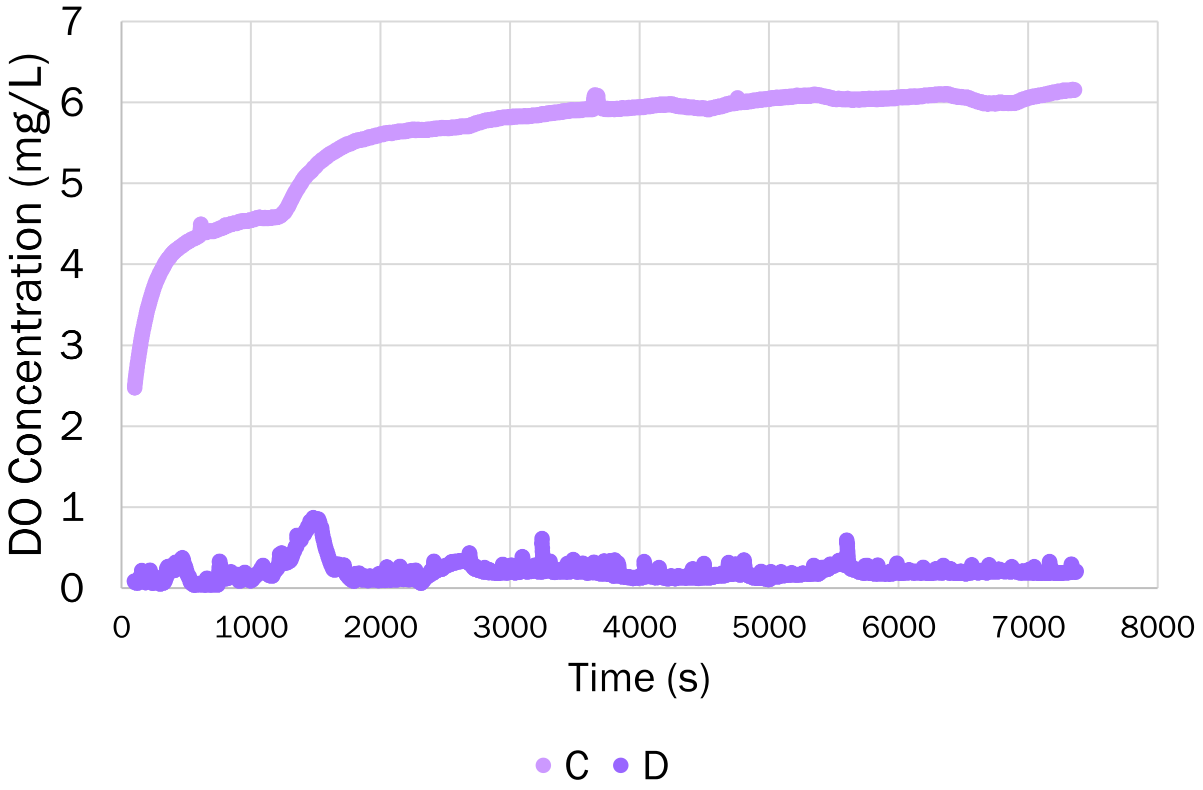
Effect of DO…and sbCOD

- No primaries at Damascus (or Seneca)
- Excess sbCOD may contribute to post-anoxic denitrification
- **Is low DO critical for ISC preservation if sbCOD available?**
- Compare non-settled influent to decant of settled influent



DO Control


DO Concentration (mg/L)
0
1
2
3
4
5
6
7
0
1000
2000
3000
4000
5000
6000
7000
8000
Time (s)
A
B


DO Concentration (mg/L)
0
1
2
3
4
5
6
7
0
1000
2000
3000
4000
5000
6000
7000
8000
Time (s)
C
D

Effect of DO and sbCOD – Results

Reactor	Influent Type	DO	SDNR (mg N/g VSS/hr)	ISC SDNR ** (mg N/g VSS/hr)
A	Non-settled	High DO	**1.53**	**0.76**
B	Non-settled	Low DO	**1.69**	**0.91**
C	Settled (decant)	High DO	**1.16**	**0.76**
D	Settled (decant)	Low DO	**1.62**	**1.22**
			endogenous	*0.41*
			*sbCOD**	*0.37*
			Maximum (acetate spike)	*2.65*
			In-basin (calculated from profile data)	*1.15*

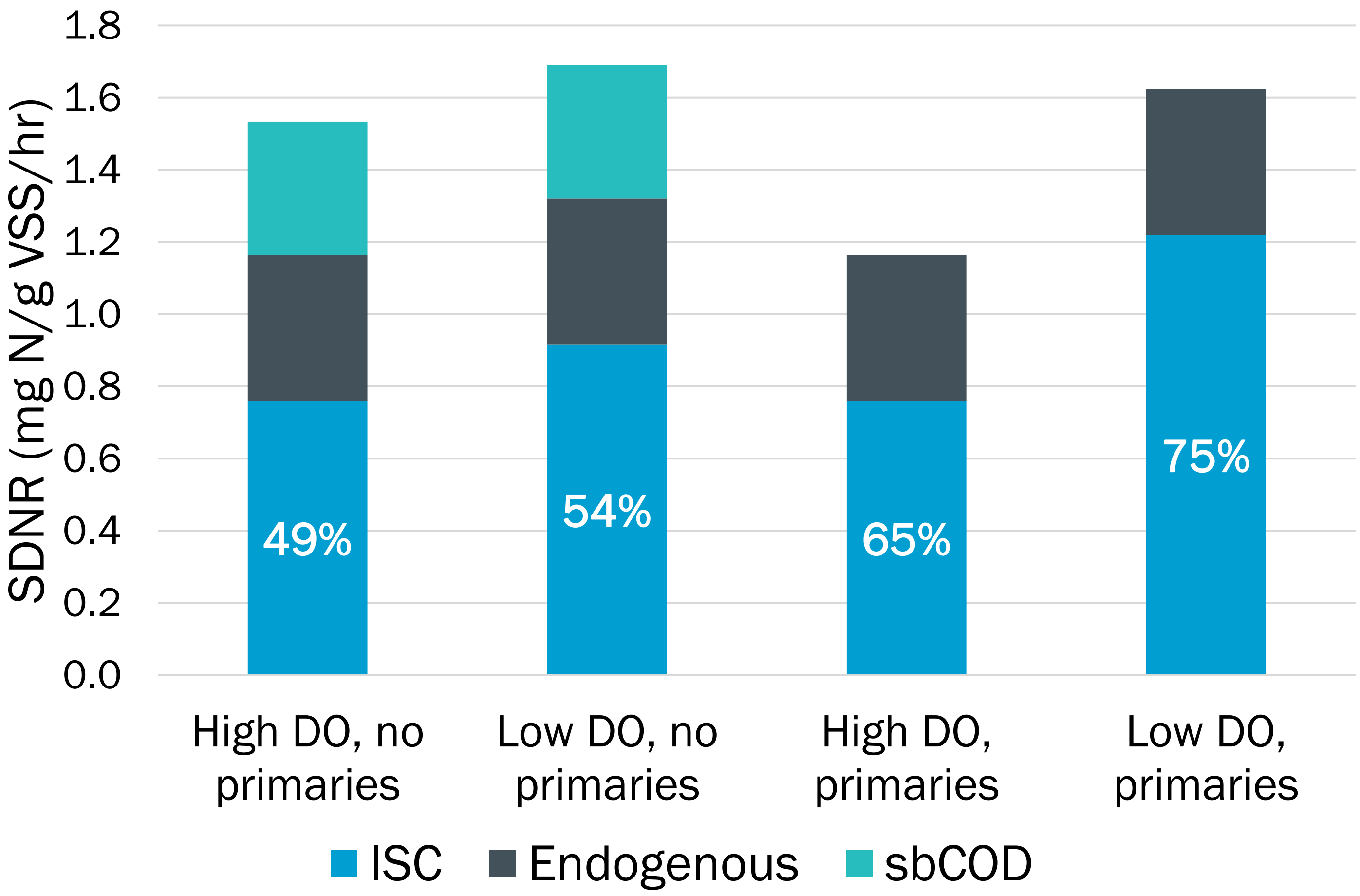
- Greater difference in SDNRs for settled influent decant (less sbCOD)
- All rates are still far above endogenous

** Calculated as the difference between Reactor A and Reactor C (both high DO; only difference is sbCOD)*

*** Calculated as the total SDNR minus endogenous and sbCOD (as relevant) rates*

Low DO is less critical when there are no primaries

- Higher overall SDNR at low DO
- Low DO: similar SDNR with vs. without primaries
  - ISC contributes more when there is lack of sbCOD
- WITHOUT primaries: smaller difference in high vs. low DO SDNRs
  - Post-anoxic denitrification less dependent on ISC



Activity Test – Key Takeaways

- The experiment compared denitrification rates at high and low DO, with and without primary clarification.
- For plants **with** primary clarifiers, low DO operation is better for denitrification rates compared to high DO.
  - Lack of sbCOD is compensated by low DO operation
- **Without** primary clarification, there was no significant difference in denitrification rates between high and low DO.

Summary

Brown AND Caldwell

How do we promote ISC denitrification?

	HRSD – VIP	HRSD – NTP	WSSC – Seneca	WSSC – Damascus
Anaerobic selector	Yes	Yes	Yes	Yes
High F/M	Yes (7 g BOD/g MLSS/d)	No (1.3 g BOD/g MLSS/d)	No (2.3 g BOD/g MLSS/d)	No (1.7 g BOD/g MLSS/d)
High C/N	Yes (>12)	No (<12)	Yes (>12)	Yes (>12)
Low DO	No	No	Yes (~0.3 mg/L)	No
Plug flow	Yes (> 30 CSTRs in series)	No	Yes	No
Bio-P*	Yes	Yes	Yes	Yes
Low IMLR	Yes (200%)	No (>300%)	Yes (200%)	No (300-500%)
Reduced MeOH	Yes	No	Yes	Yes
Skip Primary Clarification	No	No	Yes	Yes
ISC for Denitrification?	**Yes**	**No**	**Yes**	**Yes**

Enhanced post-anoxic (ISC) denitrification is a combination of many factors.

Benefits

- Chemical savings
  - Less external carbon
- Energy Savings
  - Pumping – lower IMLR
  - Aeration – low DO operation
- Process Simplification
  - Reduce IMLR…or eliminate?
  - Low DO SND with ISC…eliminate post-anoxic?
- Settleability Improvements?
  - Selector zones for ISC storage hand in hand with biological selection for densification

Remaining Questions

- Source of carbon
  - ISC (PHA, glycogen)?…EPS?…other?
- Selector zone
  - Role and type (anaerobic vs. anoxic)
- System resiliency
  - Can we eliminate external C backup?
- **Fundamentals** of carbon storage and utilization mechanisms

Summary (...so far)

- **Indicators of ISC denite**
  - Low/no methanol addition
  - Extra anaerobic acetate consumption with lower effluent TIN
  - Plant profiles
- **Factors that promote ISC denite**
  - High anaerobic carbon (feast conditions)
  - Plug flow
  - Low DO
  - Reduced IMLR
- **Remaining questions/next steps**
  - Confirm PHA (vs. glycogen or other)
  - Microbial analysis
  - How to model?

WRF 5245: Unlocking the Advantages of Internally Stored Carbon for Nutrient Removal

Plans for future study – WRF 5245

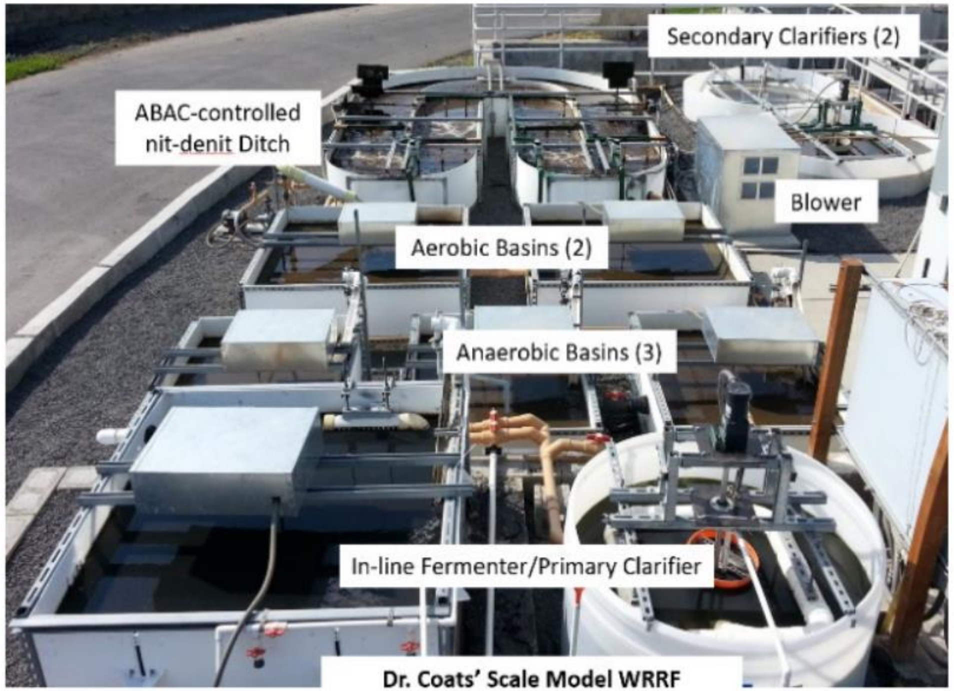
Brown AND Caldwell

WRF 5245: Unlocking the Advantages of Internally Stored Carbon for Nutrient Removal

- Bench-, pilot-, and full-scale setups
- Improve understanding of mechanisms
- Quantify benefits of ISC BNR
- Focus on full-scale implementation guidance

List of Full-Scale Participating WRRFs:

- HRSD's VIP: VIP+2 process (EBPR)
- WSSC's Seneca: 5-stage Bardenpho (low DO) (EBPR)
- WSSC's Damascus: 5-stage Bardenpho (non-EBPR)
- Denver MWR: A_2O with hydrocyclones (EBPR)
- Clean Water Services: A2O EBPR
- CLT Water's McDowell Creek: 5-stage Bardenpho (high DO) (non-EBRR)
- Durham's NDWRF: 5-stage Bardenpho



WRF 5245: Unlocking the Advantages of Internally Stored Carbon for Nutrient Removal

Key factors to address:

- Establish **standard method** for PHA/glycogen measurement
- Effect of **EPBR** vs. non-EBPR
- **Substrate type** (VFA, rbCOD, sbCOD)
- Dependence on anaerobic **HRT**
- Aerobic ISC depletion / effect of **DO**
- Limits of **effluent quality**
- Ties to **densification**/settleability
- Effect on **N2O**
- Microbial **ecology**
- **SRT** guidance
- Reliability for **PdNA**

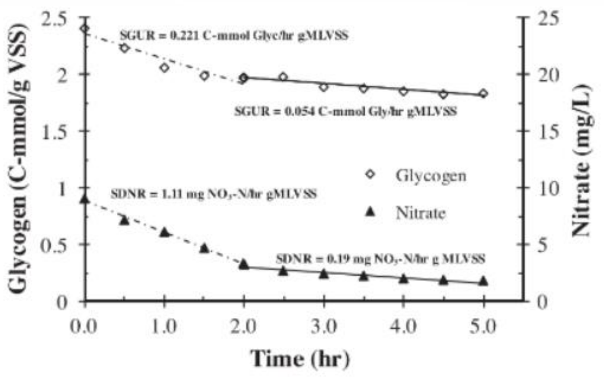


Figure 3.5 // Relationship between SDNR and SGUR.

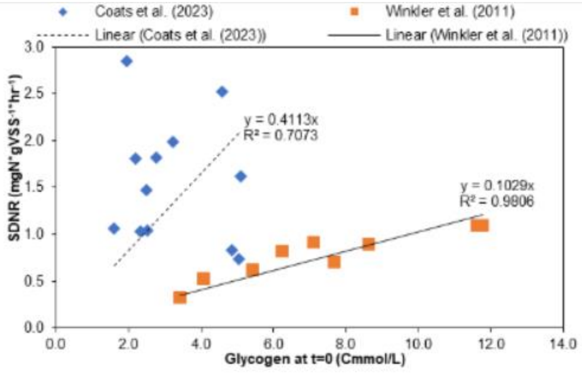


Figure 3.6 // SDNR as a function of glycogen concentration.

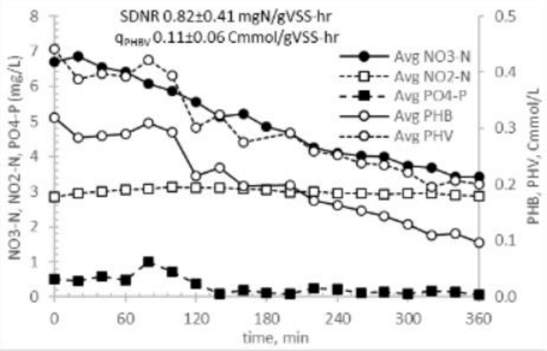


Figure 3.4 // Denitrification and PHB, PHV utilization with acetate addition.

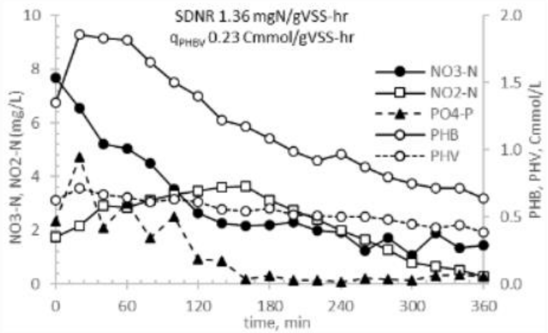


Figure 3.3 // Denitrification and PHB, PHV utilization.

Thank you.

Questions?

Brown AND Caldwell