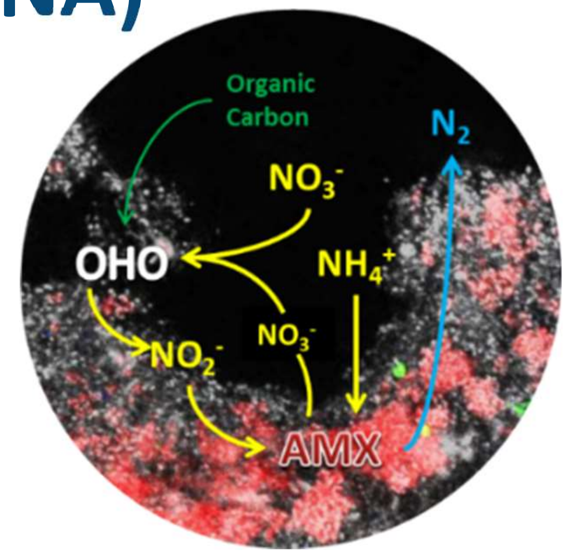
Developing and Deploying the Next Generation of Mainstream Nitrogen Removal Technology through Partial Denitrification-Anammox (PdNA)



Charles B. Bott, PhD, PE, BCEE

Director of Water Technology and Research

Hampton Roads Sanitation District

HRSD

The Water Research Foundation

Virginia Tech

Old Dominion University

swift Sustainable Water Initiative for Tomorrow

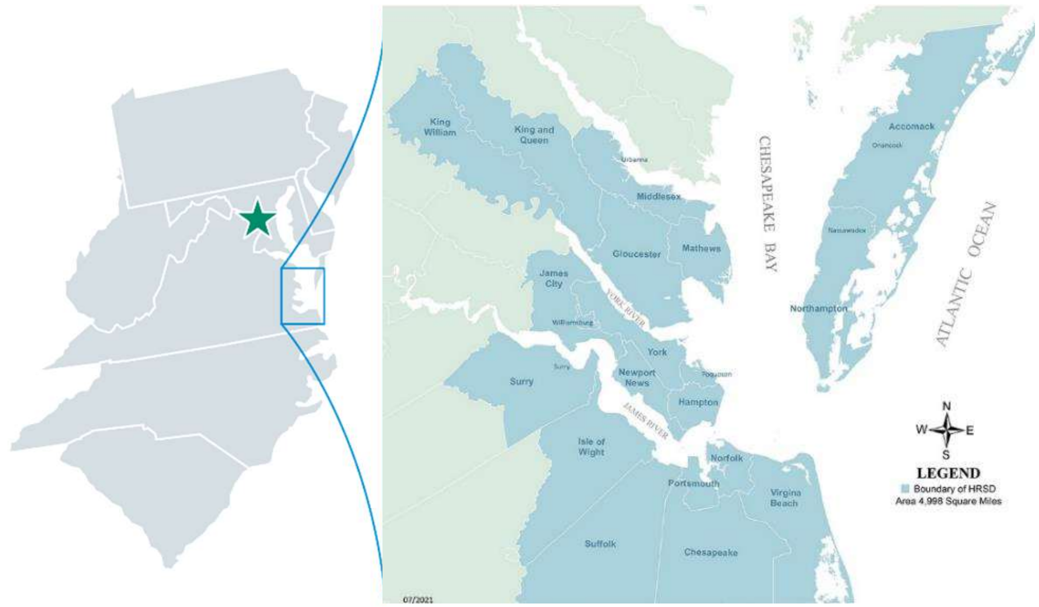
dc water is life®

Hampton Roads Sanitation District (HRSD)

Population Served ~1.9 million (20 cities and counties in SE Virginia)

We operate 8 major and 6 smaller treatment plants and more than 100 pump stations

Combined wastewater treatment capacity - 225 million gallons/day



Service area is over 5,000 square miles

HRSD Drivers for Technology Research and Innovation

- **Process Intensification**
- Virginia Enhanced Nutrient Removal Certainty Program (ENRCP)
  - Load equivalent of TN = 4 mg/L by 2026
  - Load equivalent of TP = 0.3 mg/L by 2032
- SWIFT demands on wastewater nutrient removal
- Minimizing SWIFT capital and O&M costs
- Emerging treatment issues – PFAS, 1,4-dioxane, AMR, pathogens, etc
- Biosolids – stabilization, land app, dewatering, product quality
- [Other research needs and objectives are managed by HRSD Water Quality]

THE Water Research FOUNDATION

VIRGINIA TECH.

OLD DOMINION UNIVERSITY

UNIVERSITY OF MICHIGAN

dc water is life®

EPA

HOWARD UNIVERSITY 1867

UNIVERSITÉ LAVAL

METRO WATER RECOVERY℠

U.S. DEPARTMENT OF ENERGY

Northwestern University

Hazen

CORNELL UNIVERSITY FOUNDED A.D. 1865

BUREAU OF RECLAMATION

Georgia Tech

Brown AND Caldwell

dynamita PROCESS MODELING

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

AECOM

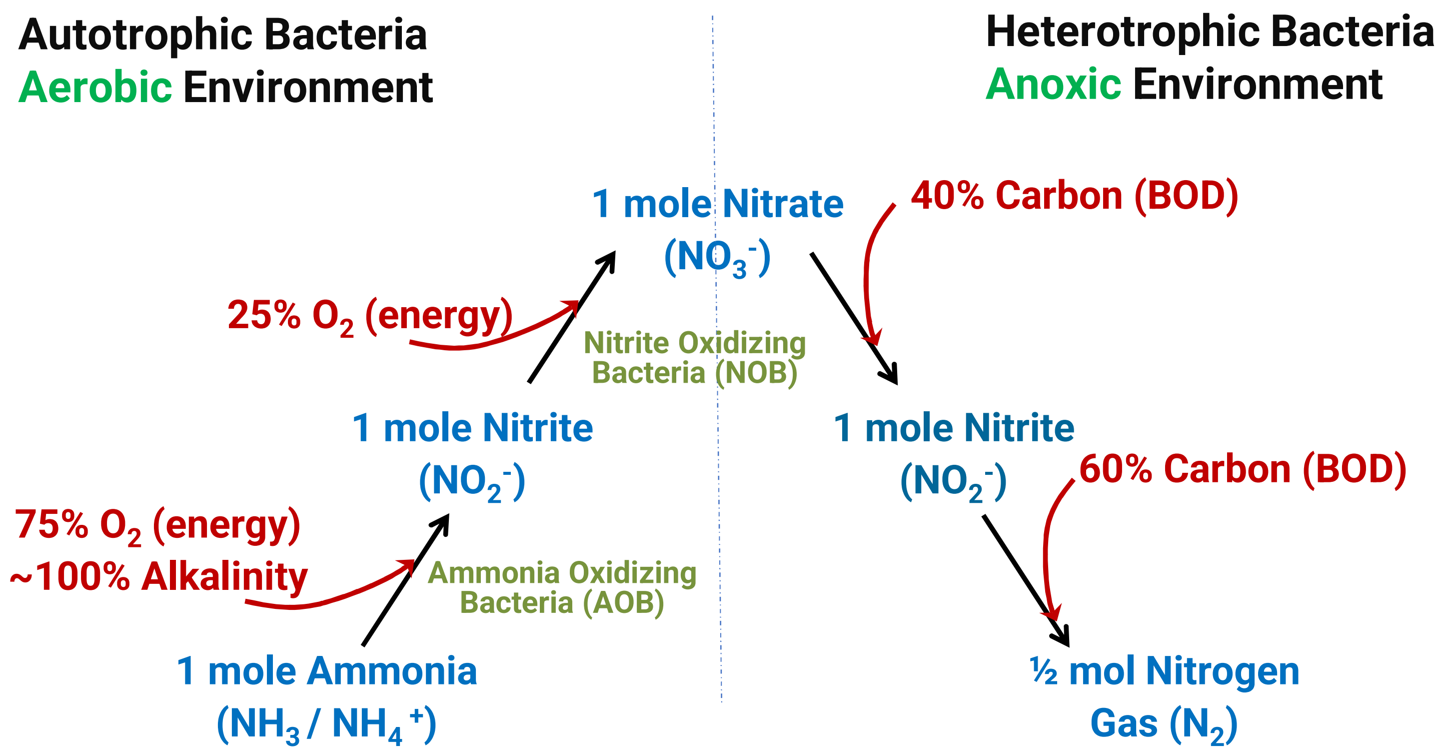
HDR

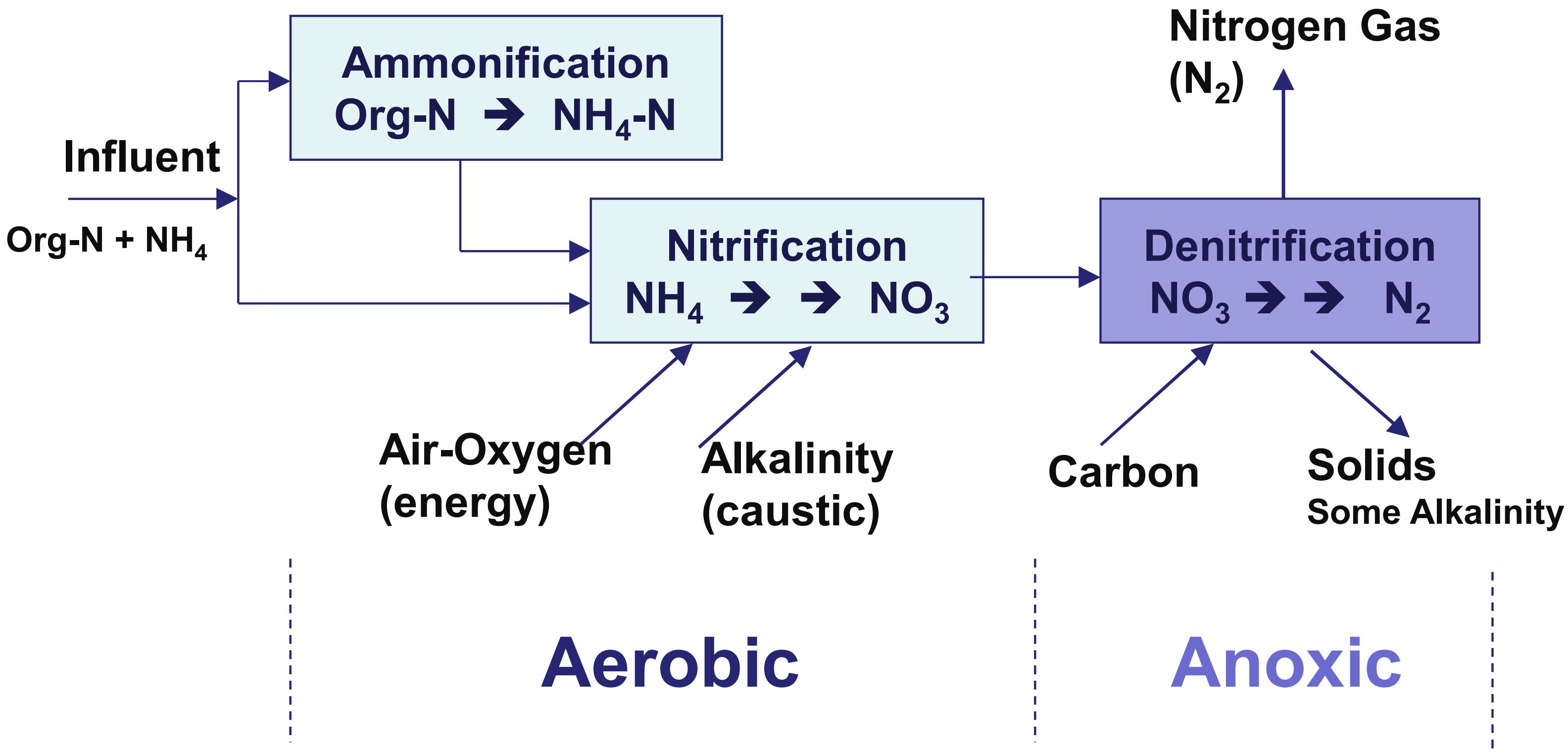
AM TEAM Advanced Modelling for process optimisation

KU

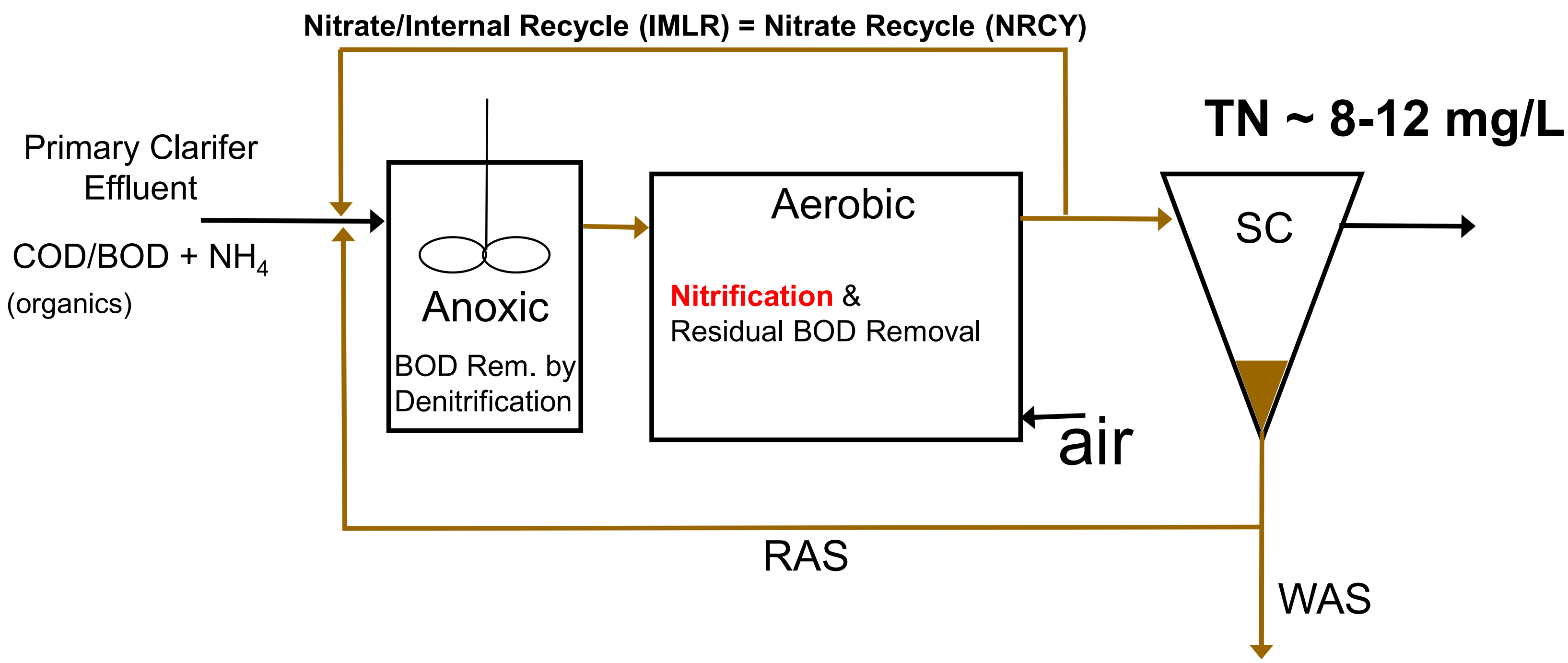
carollo®

Conventional Nitrification-Denitrification



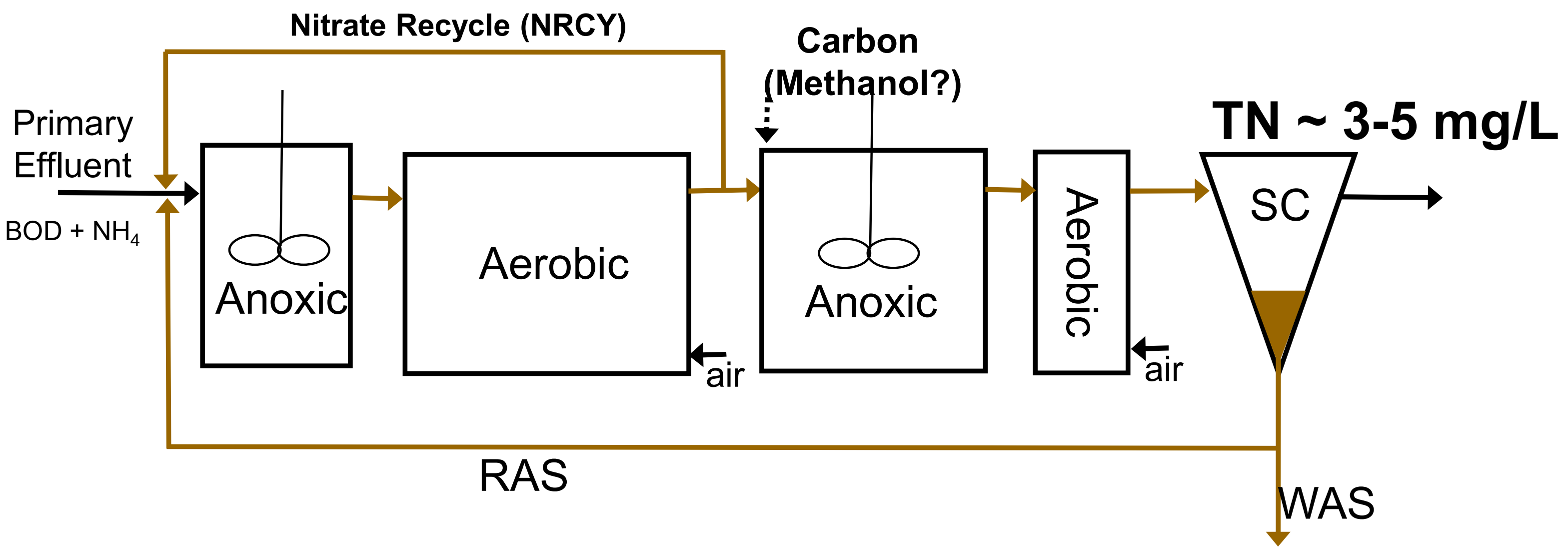

Ammonification
Org-N ➔ NH4-N
Influent
Org-N + NH4
Nitrification
NH4 ➔ ➔ NO3
Nitrogen Gas
(N2)
Denitrification
NO3 ➔ ➔ N2
Air-Oxygen
(energy)
Alkalinity
(caustic)
Carbon
Solids
Some Alkalinity
Aerobic
Anoxic

MLE Process (N Removal)



HRSD York River Plant – 15 MGD

4-Stage Bardenpho (Better N Removal)



HRSD Army Base Plant – 18 MGD

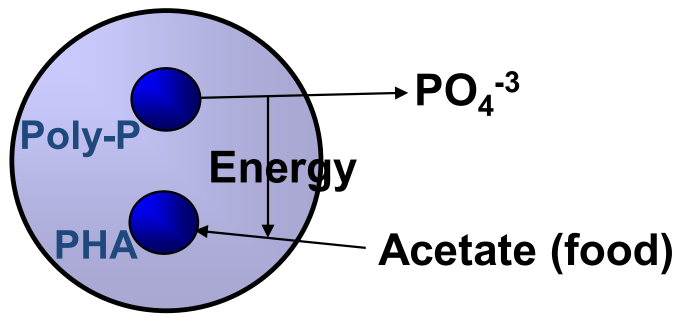
What about phosphorus removal?

- Chemical precipitation
  - Alum = aluminum sulfate
  - Ferric = ferric sulfate OR ferric chloride
  - consumes alkalinity, generates solids
- Biological P removal (bio-P, EBPR, etc)

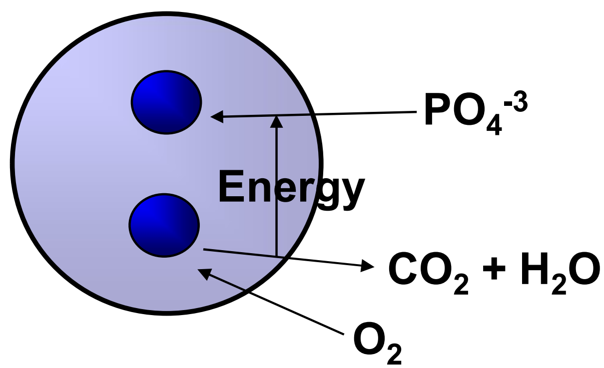
Biological Phosphorus Removal (Bio-P)

Phosphorus accumulating organisms (PAOs) have a unique anaerobic/aerobic metabolism

Anaerobic Conditions



Aerobic Conditions

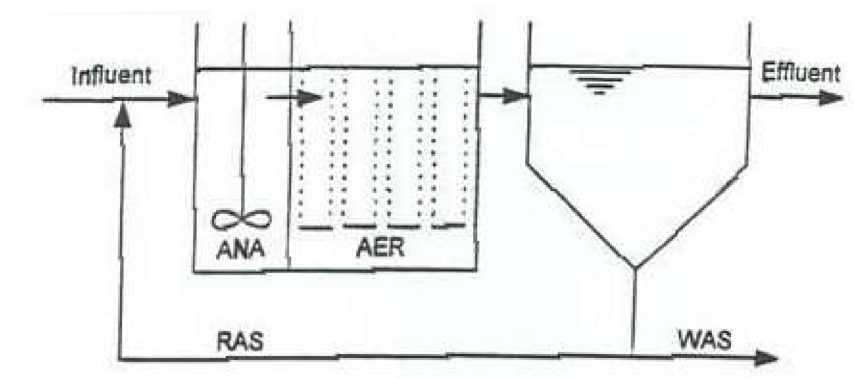


Poly-P = granule of poly-phosphate

PHA = granule of polyhydroxyalkanoate

Bio-P in A/O Process

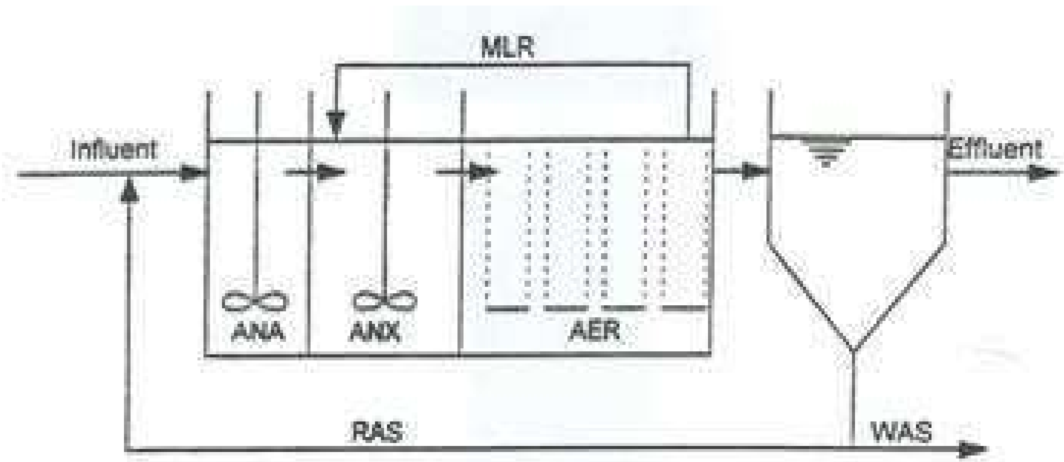
A/O Process



ANA = Anaerobic
AER = Aerobic

Addition of an anaerobic selector…

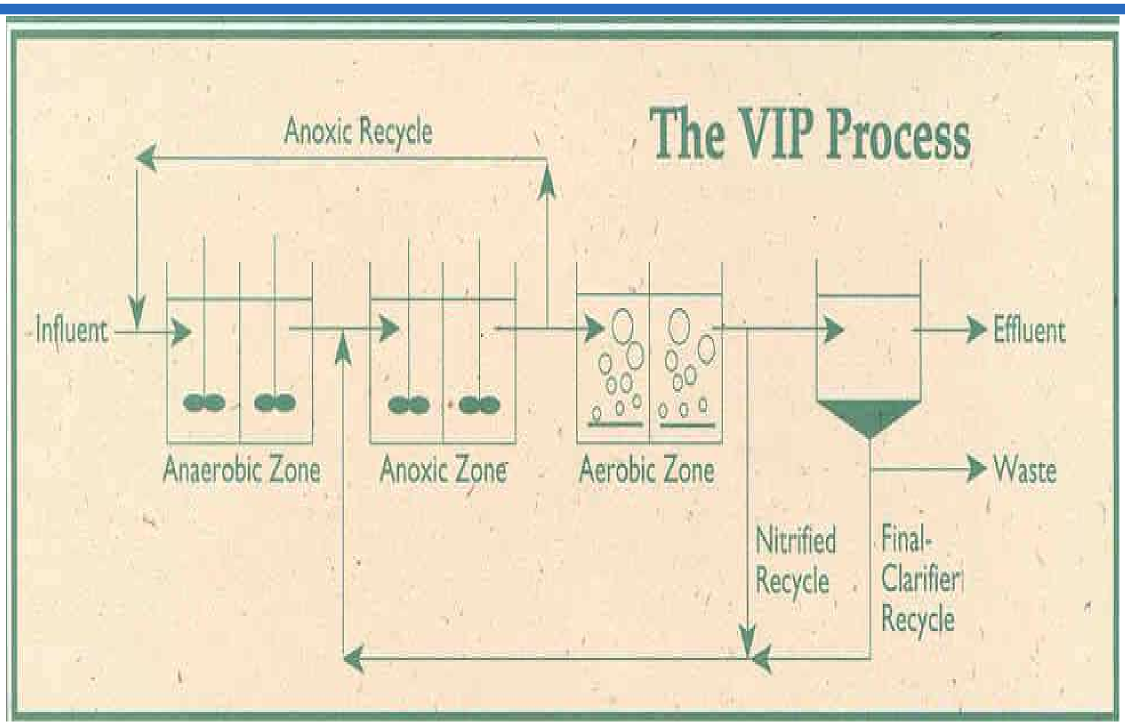
Add Bio-P to MLE… "A2O Process"



A^2/O or Phoredox Process

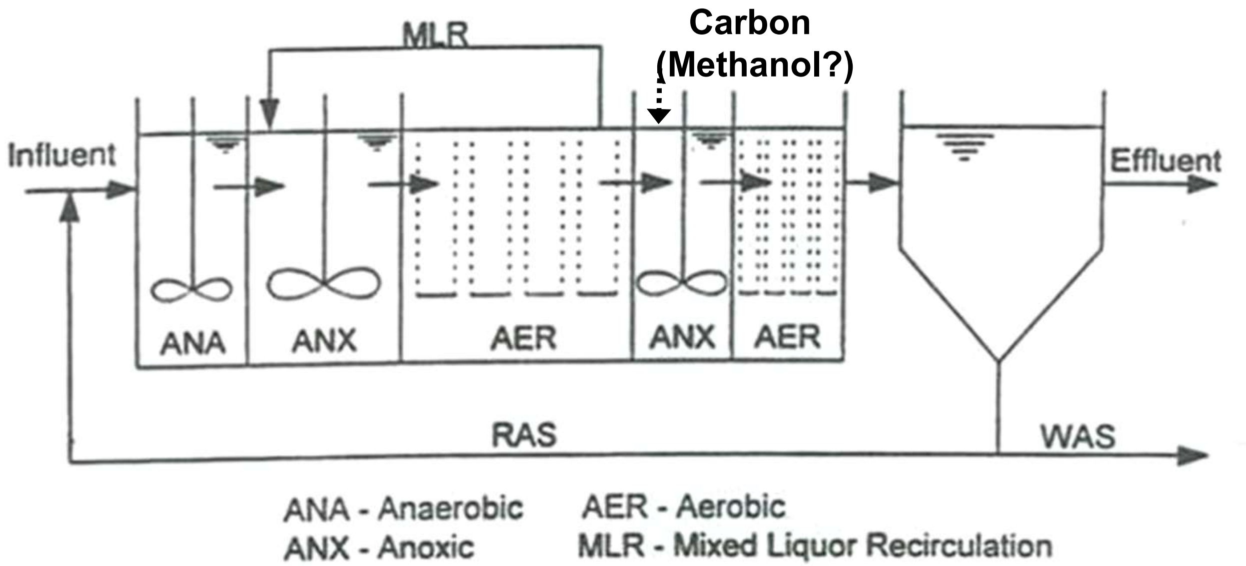
ANA = Anaerobic
ANX = Anoxic
AER = Aerobic

Virginia Initiative Process (VIP)



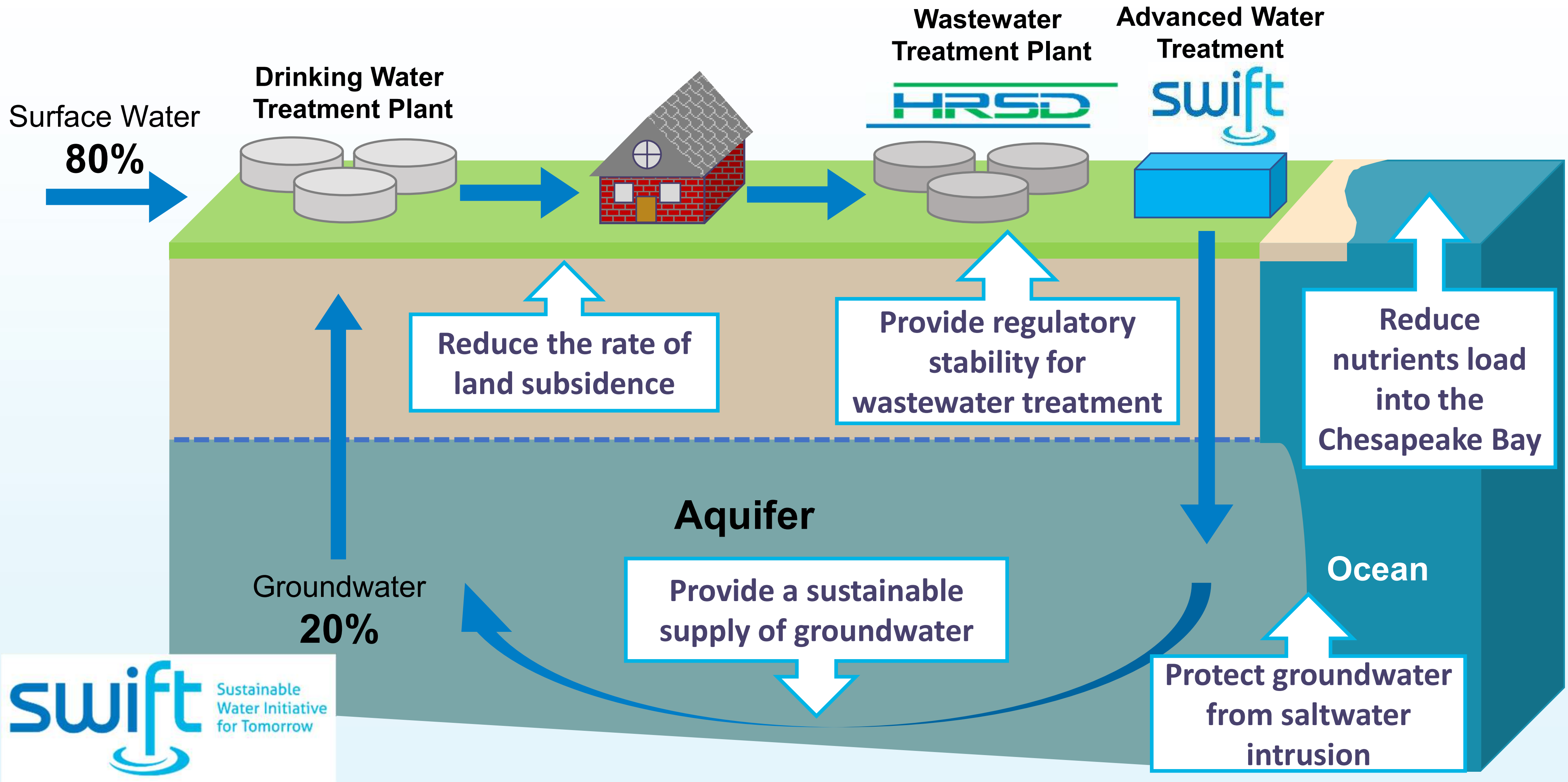
- **Developed collaboratively by HRSD, Virginia Tech, and CH2M Hill**
- **Biological N and P removal**

5-Stage Bardenpho

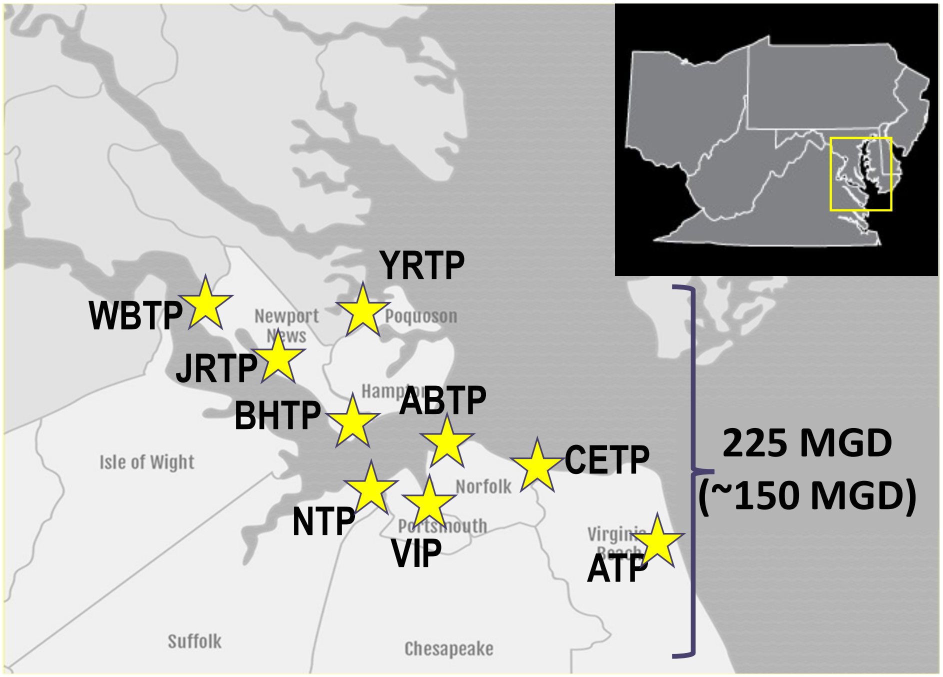


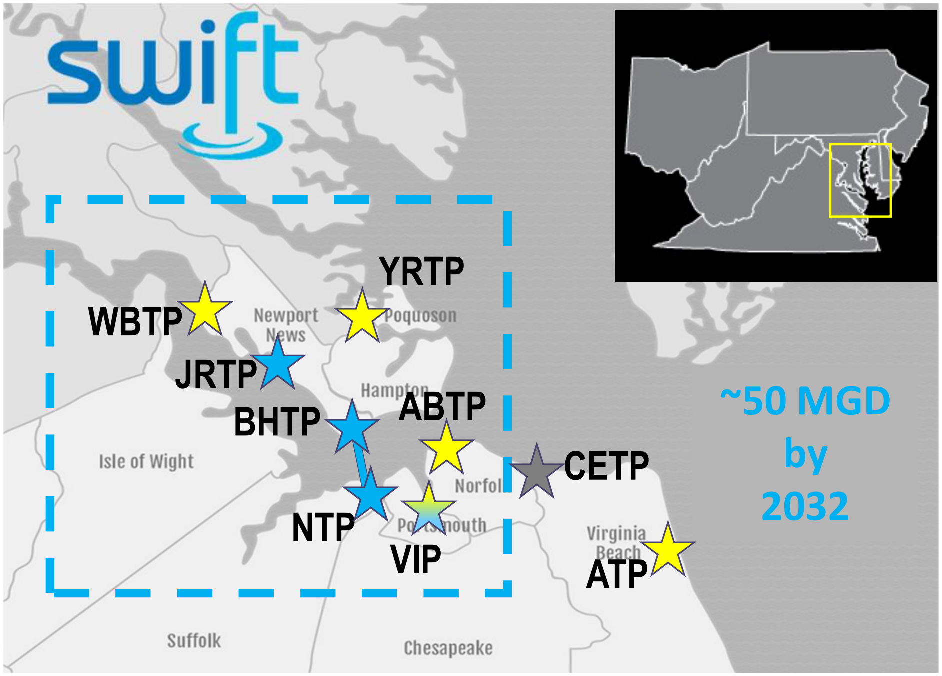
Generally - “5-stage BNR”
Add second anoxic zone to a Bio-P processes
(for example VIP + 2, MUCT+2, A2O+2, etc)

SWIFT will provide multiple regional benefits



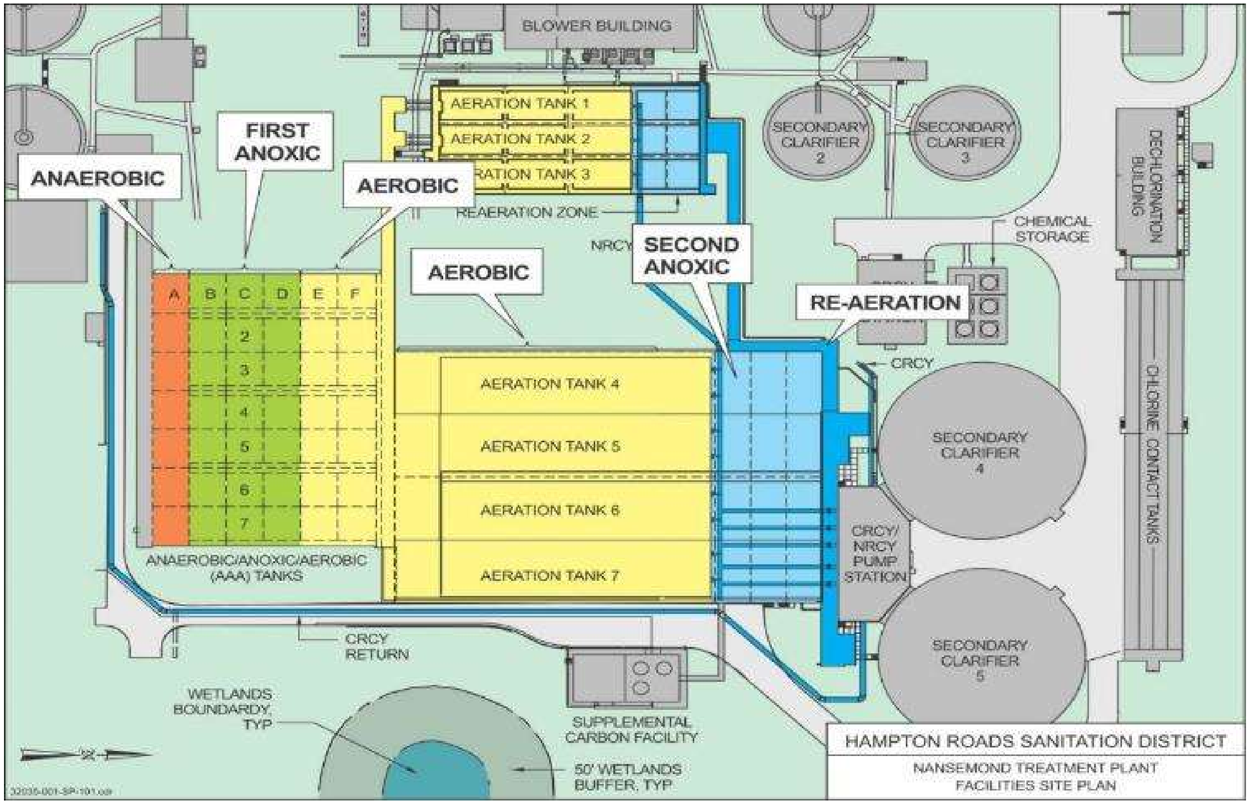
SWIFT Goal: ~50 MGD by 2032; ~$1.2B





SWIFT Research Center (1 MGD) at HRSD Nansemond Treatment Plant (30 MGD)

Nansemond Plant - 5-Stage Bardenpho Configuration
Stable and reliable TN removal is a must!

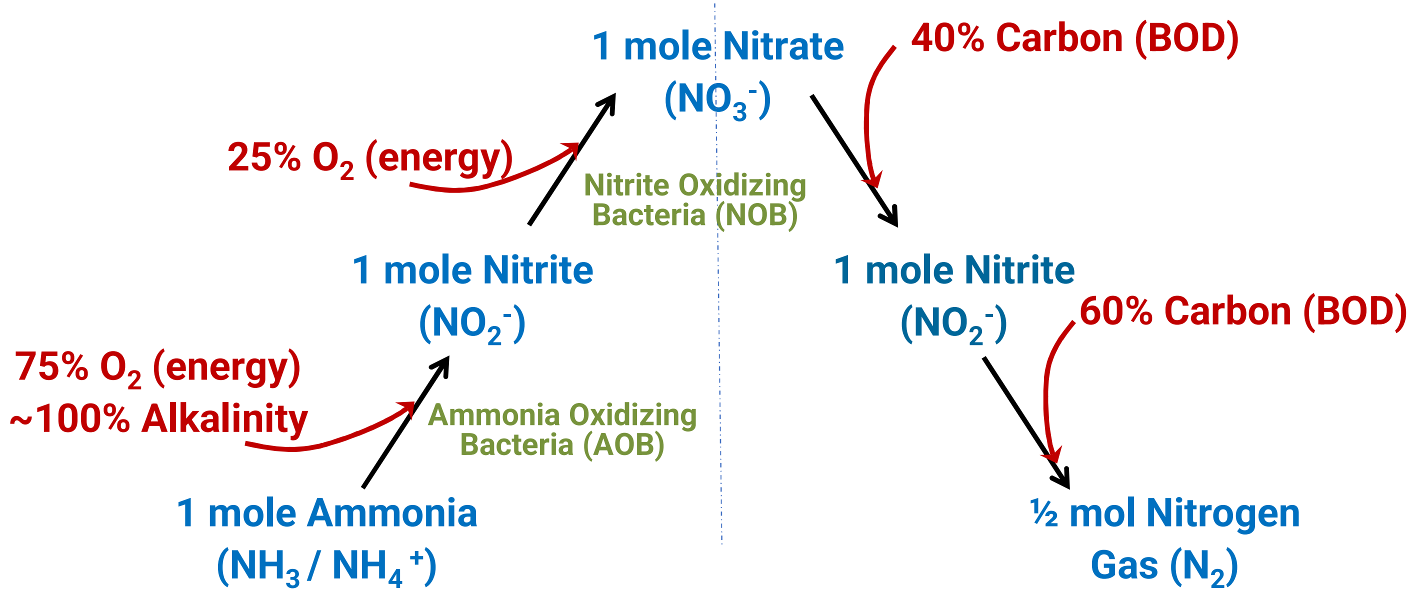


- Feedback ammonia-base aeration control
- Feedback nitrate-based internal mixed liquor recycle (NRCY) flow control
- Feedforward/feedback methanol feed control

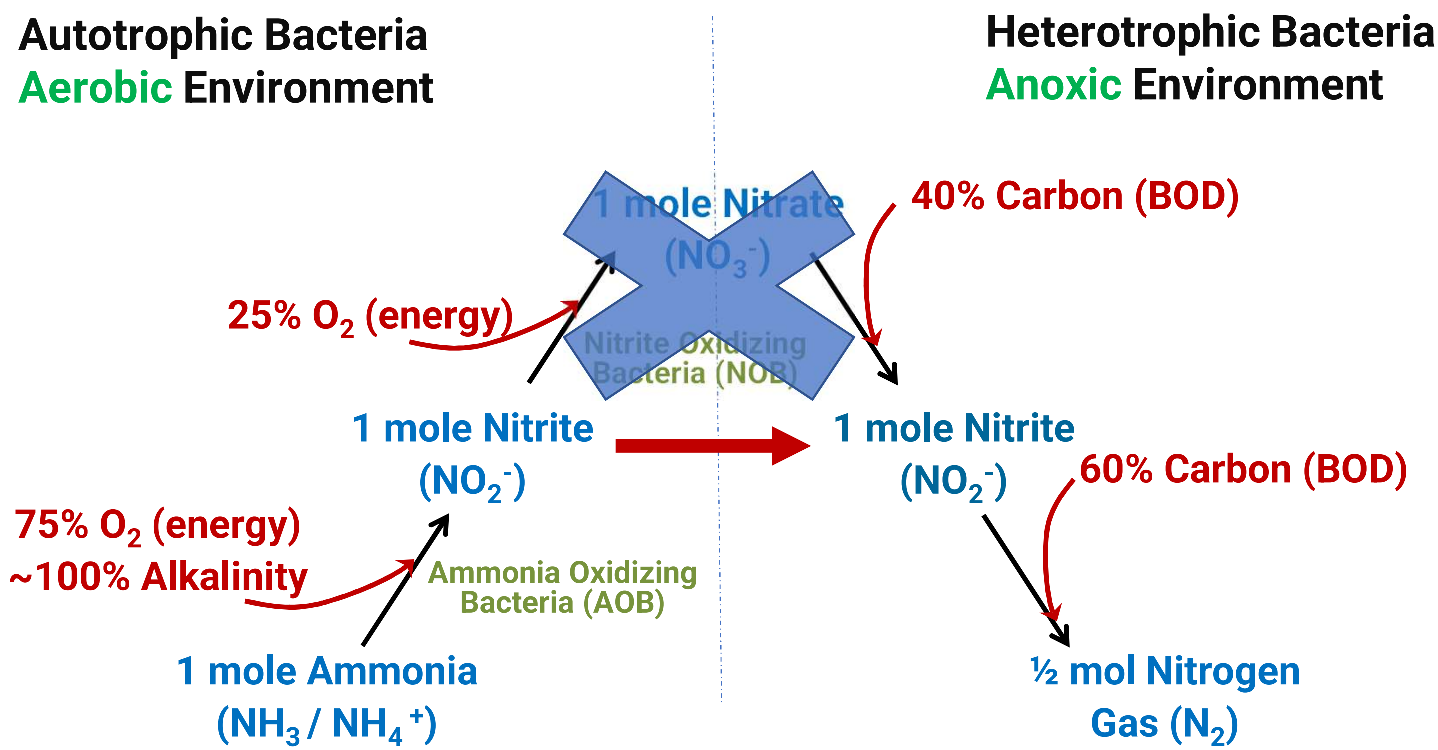
Conventional Nitrification-Denitrification

Autotrophic Bacteria
Aerobic Environment

Heterotrophic Bacteria
Anoxic Environment



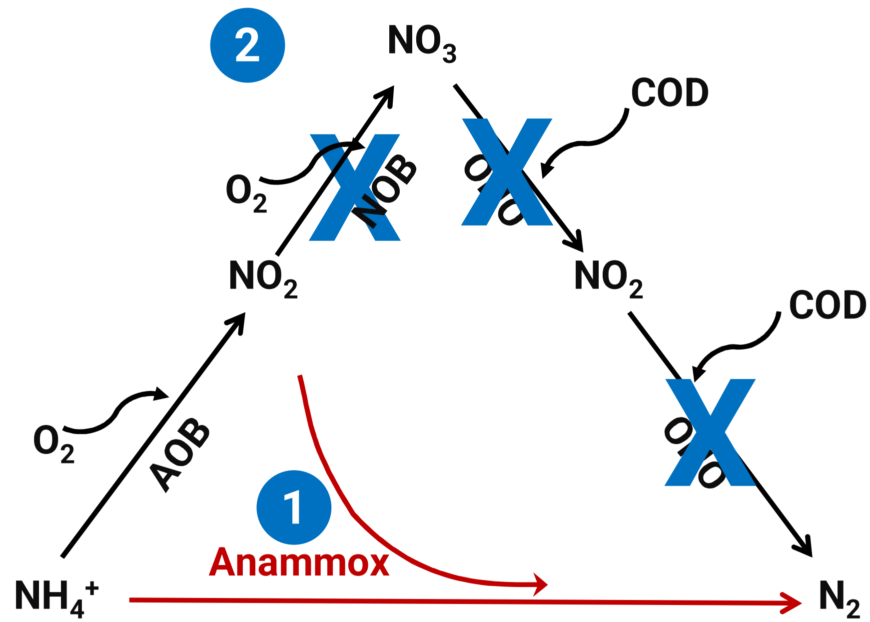
Nitrite Shunt - a form of "Shortcut Nitrogen Removal"



Deammonification through Partial Nitritation-Anammox (PNA)
{PNA is the "best" form of Shortcut Nitrogen Removal}

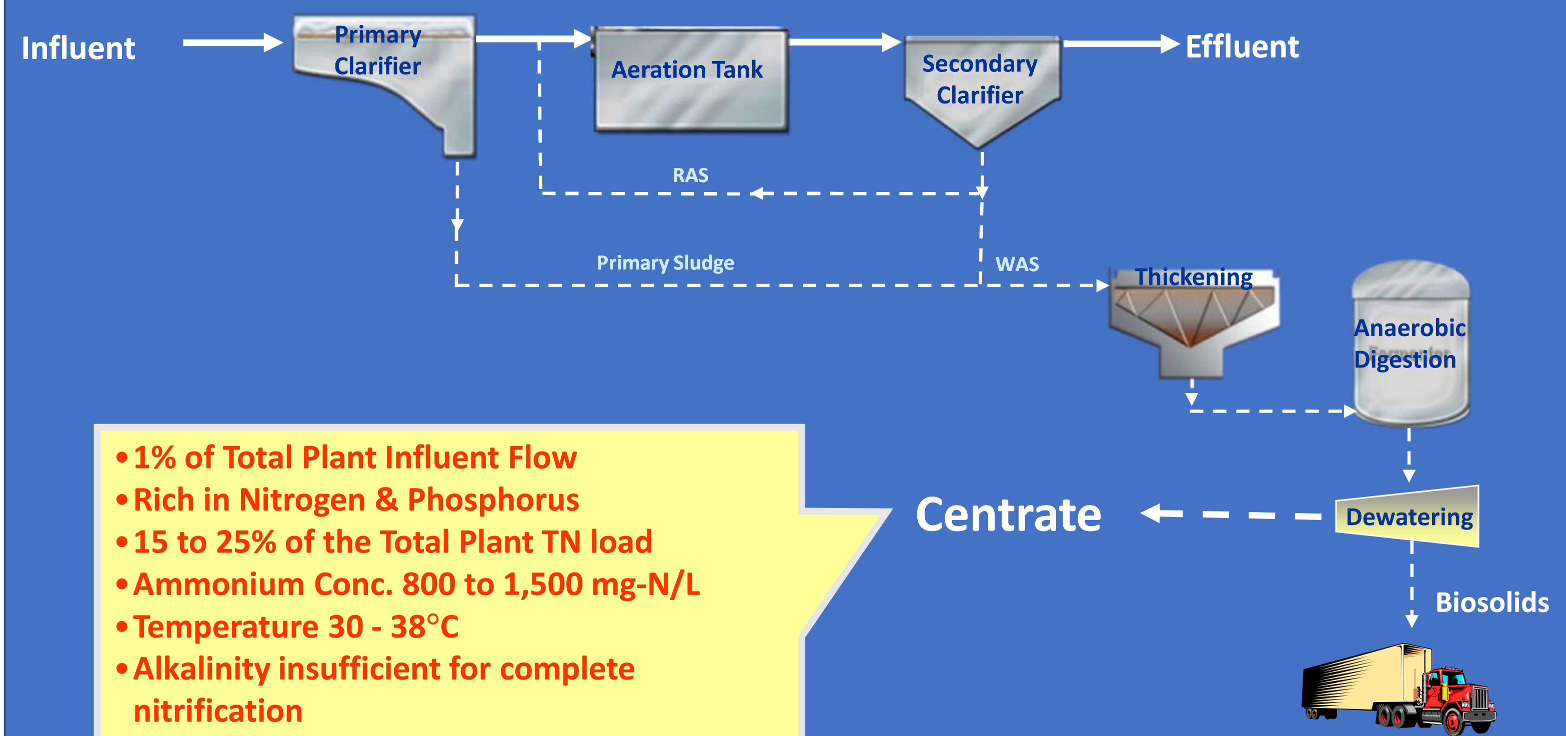
Main challenges:

1. Sufficient **retention of anammox** while allowing for SRT pressure on other organisms
2. Nitrite availability for anammox through **NOB out-selection**



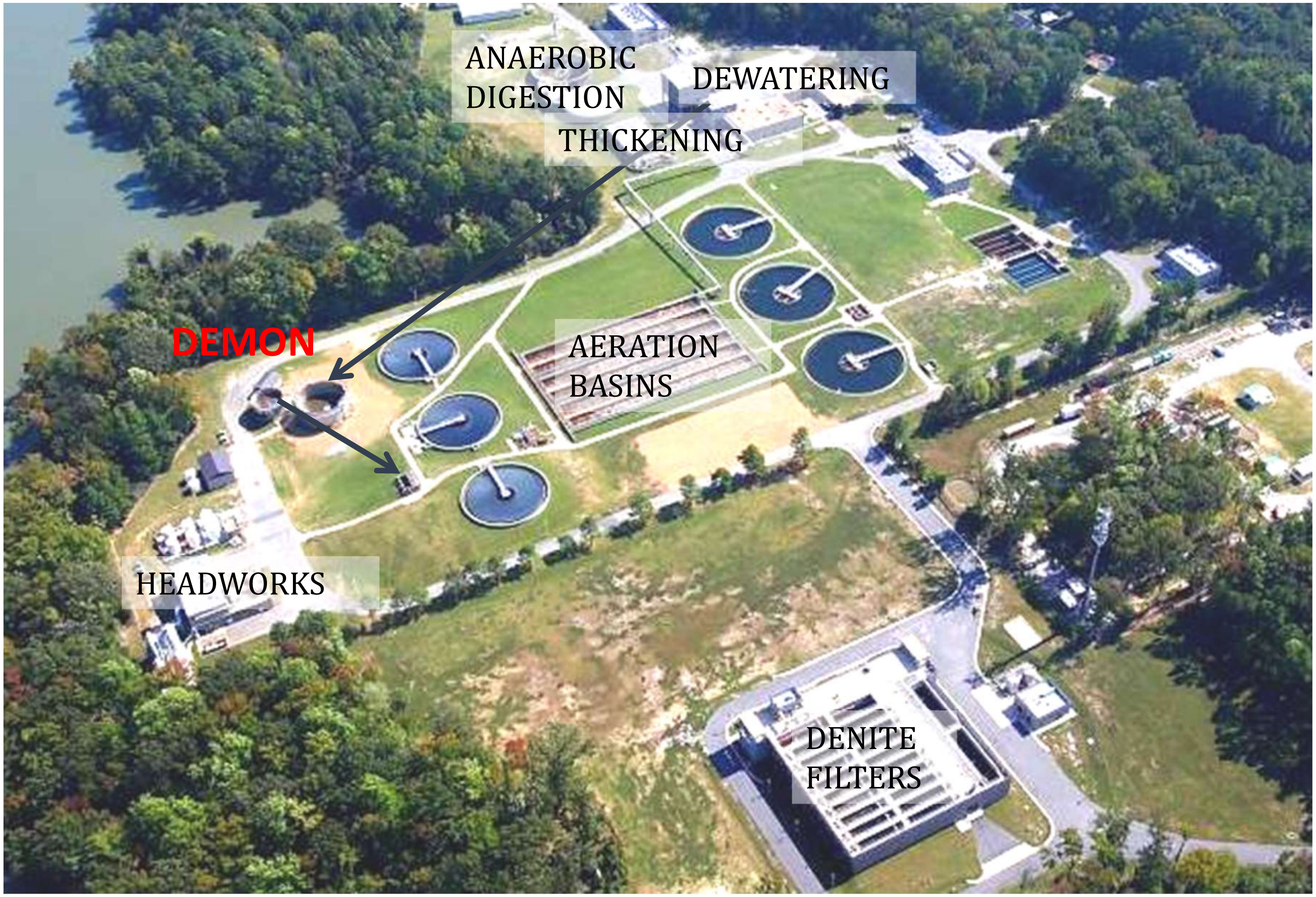
Mainstream Partial Nitritation/Anammox

Sidestream Treatment – N & P



- 1% of Total Plant Influent Flow
- Rich in Nitrogen & Phosphorus
- 15 to 25% of the Total Plant TN load
- Ammonium Conc. 800 to 1,500 mg-N/L
- Temperature 30 - 38°C
- Alkalinity insufficient for complete nitrification
- Insufficient carbon for denitrification

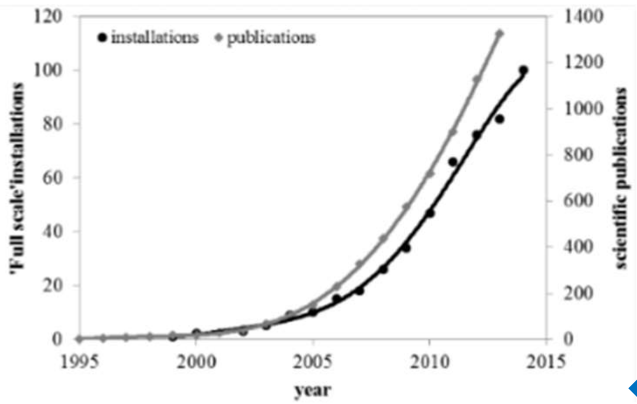
- For a Bio-P plant with no iron addition:
  - Centrate TP = 200-800 mg/L



DEMON® PNA at HRSD York River (15 MGD) - 2012

Partial Nitritation-Anammox (PNA) Sidestream vs. Mainstream

Sidestream

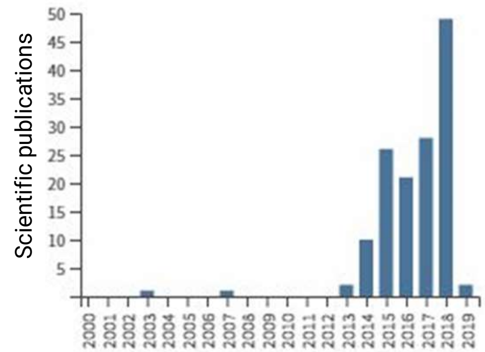


Lackner et al., 2014, WR

Mature and robust process with 200-300 Full-Scale installations including:

- HRSD York River TP Demon (2012)
- HRSD James River TP AnitaMox (2013)

Mainstream



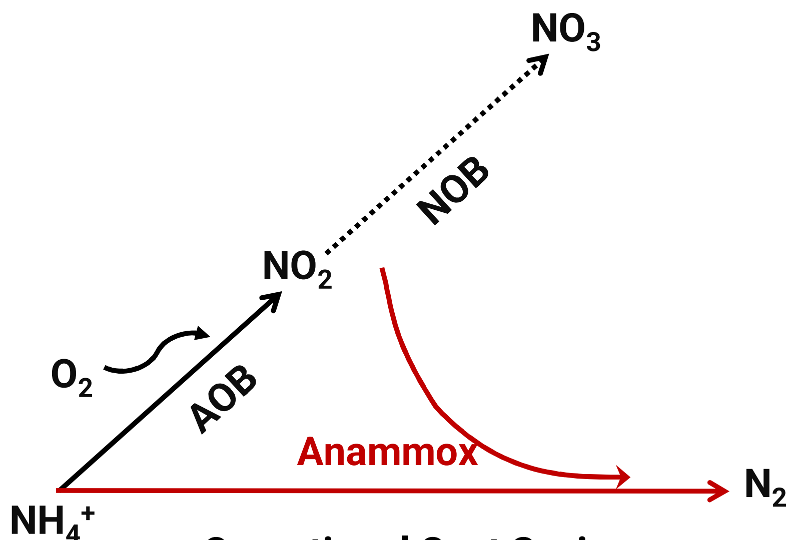
Limited full-scale reports of mainstream PNA:

- Strass, Austria (Wett et al, 2013)
- PUB Changi, Singapore (Cao et al, 2016)
- Xi'an, China (Li et al, 2019)

The complexity of NOB out-selection limits full scale implementation of mainstream PNA

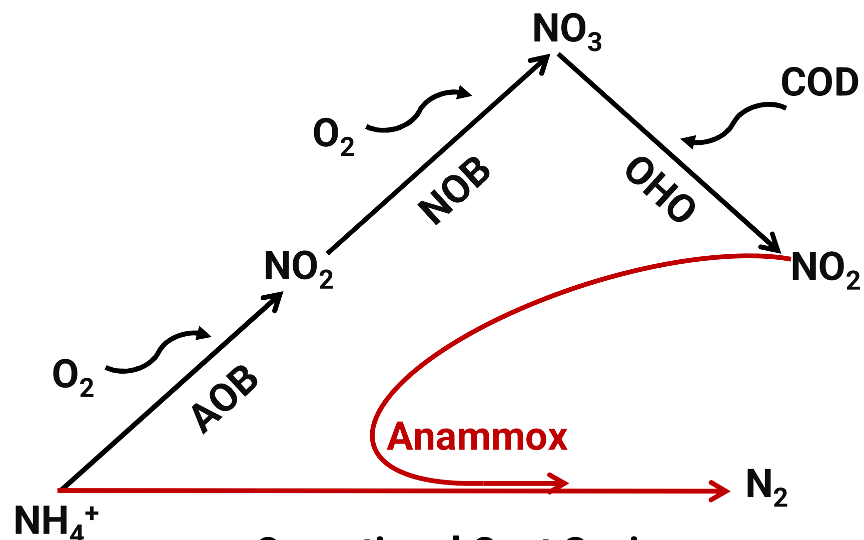
Taking a DETOUR to achieve mainstream shortcut N removal – Partial Denitrification-Anammox (PdNA)

PNA = NOB Out-Selection Route



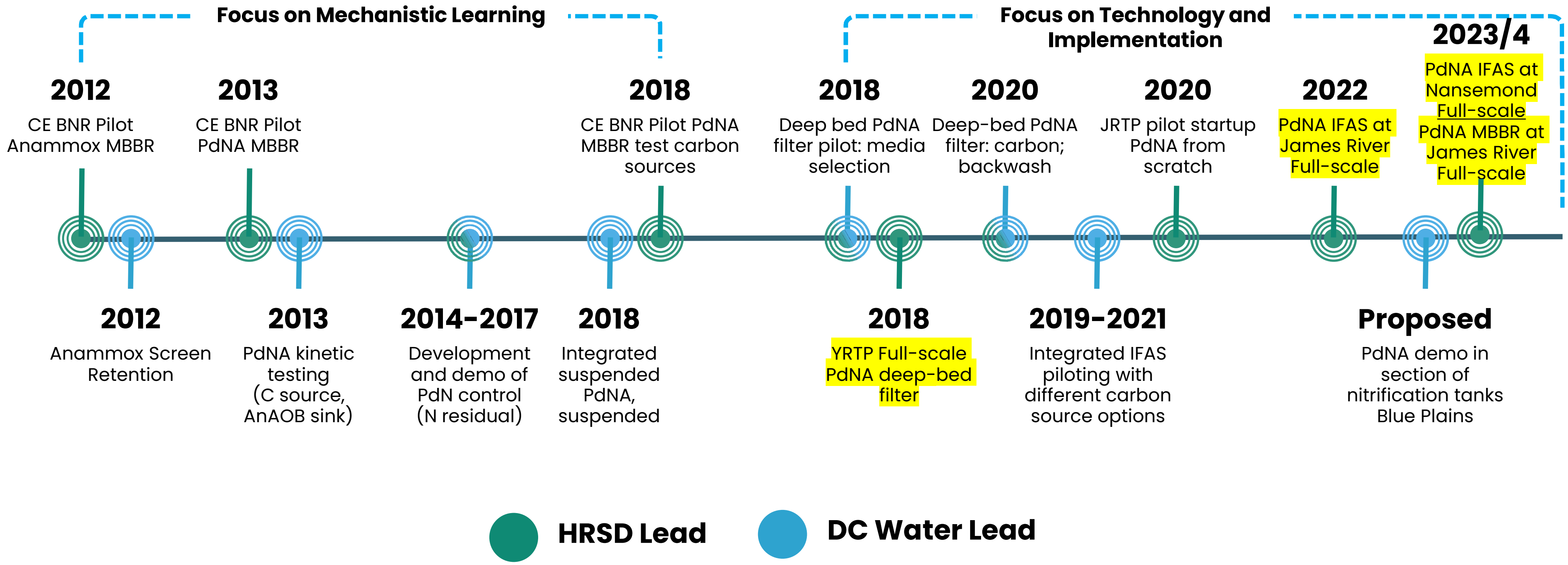
Operational Cost Savings:
- 60% in aeration
- 100% in carbon

PdNA Route



Operational Cost Savings:
- 50% in aeration
- 80% in carbon

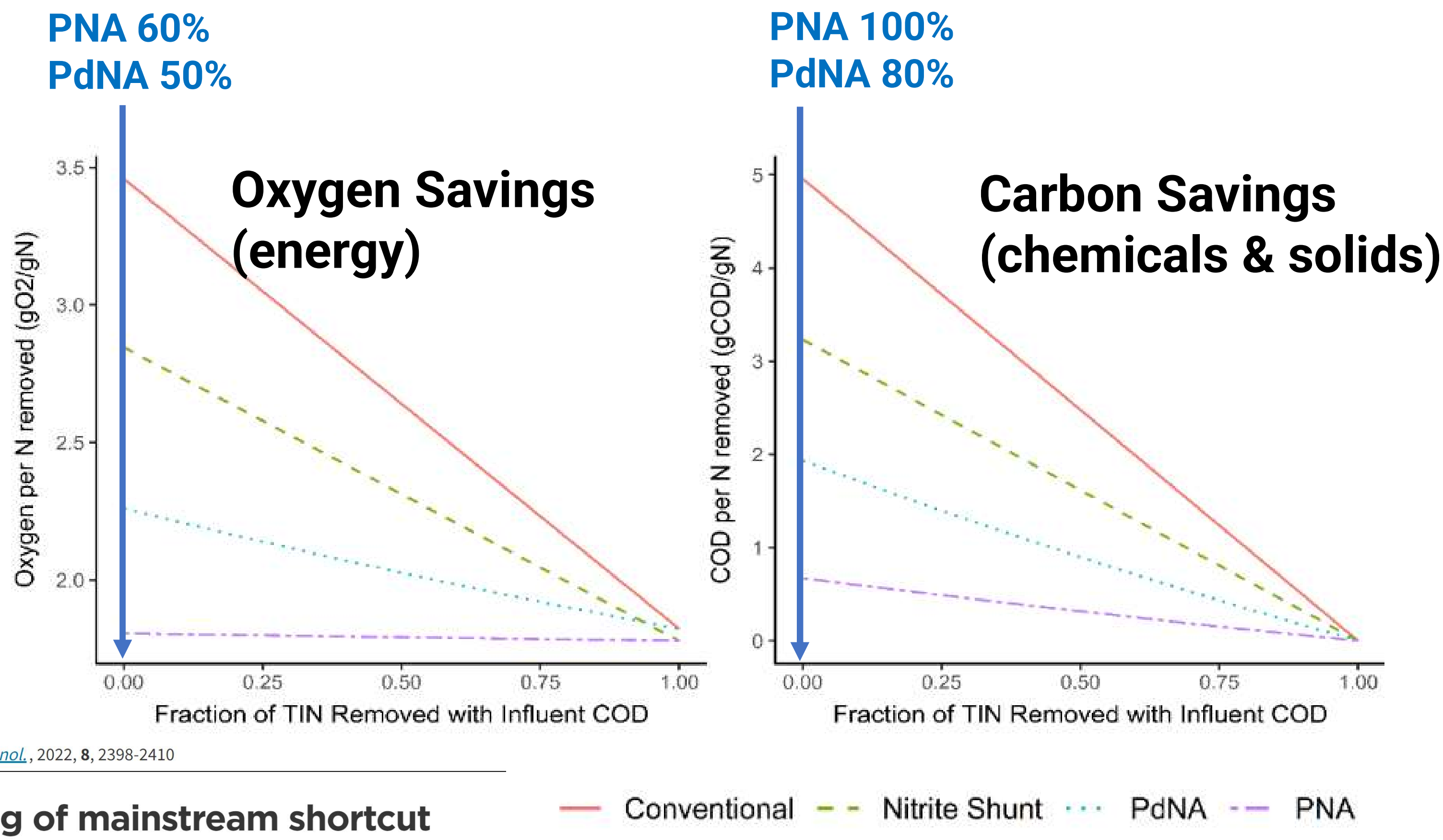
Partial Denitrification/Anammox (PdNA) Development Timeline



HRSD Chesapeake-Elizabeth Plant - BNR Pilot


HRSD
Chesapeake Elizabeth
Treatment Plant

Benefits of Shortcut N Removal



DOI: 10.1039/D2EW00247G (Paper) *Environ. Sci.: Water Res. Technol.*, 2022, **8**, 2398-2410

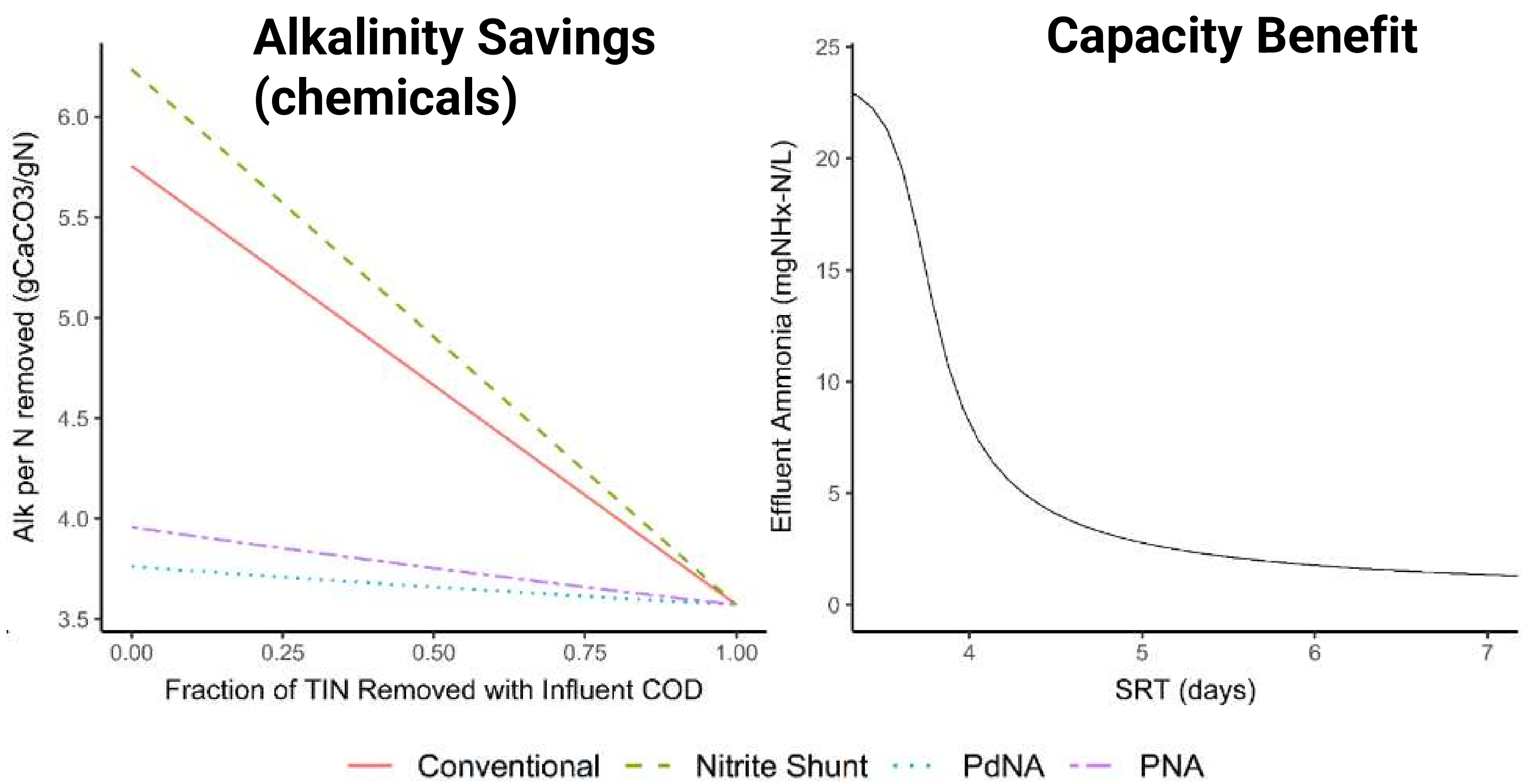
Advancing the understanding of mainstream shortcut nitrogen removal: resource efficiency, carbon redirection, and plant capacity†

Kester McCullough *[a,b], **Stephanie Klaus** [a], **Michael Parsons** [a], **Christopher Wilson** [a] **and Charles B. Bott** [a]

[a] *ModelEAU, Département de génie civil, Pavillon Pouliot, Université Laval, Québec G1K 7P4, QC, Canada*

[b] *Hampton Roads Sanitation District, 1434 Air Rail Avenue, Virginia Beach, VA 23455, USA*

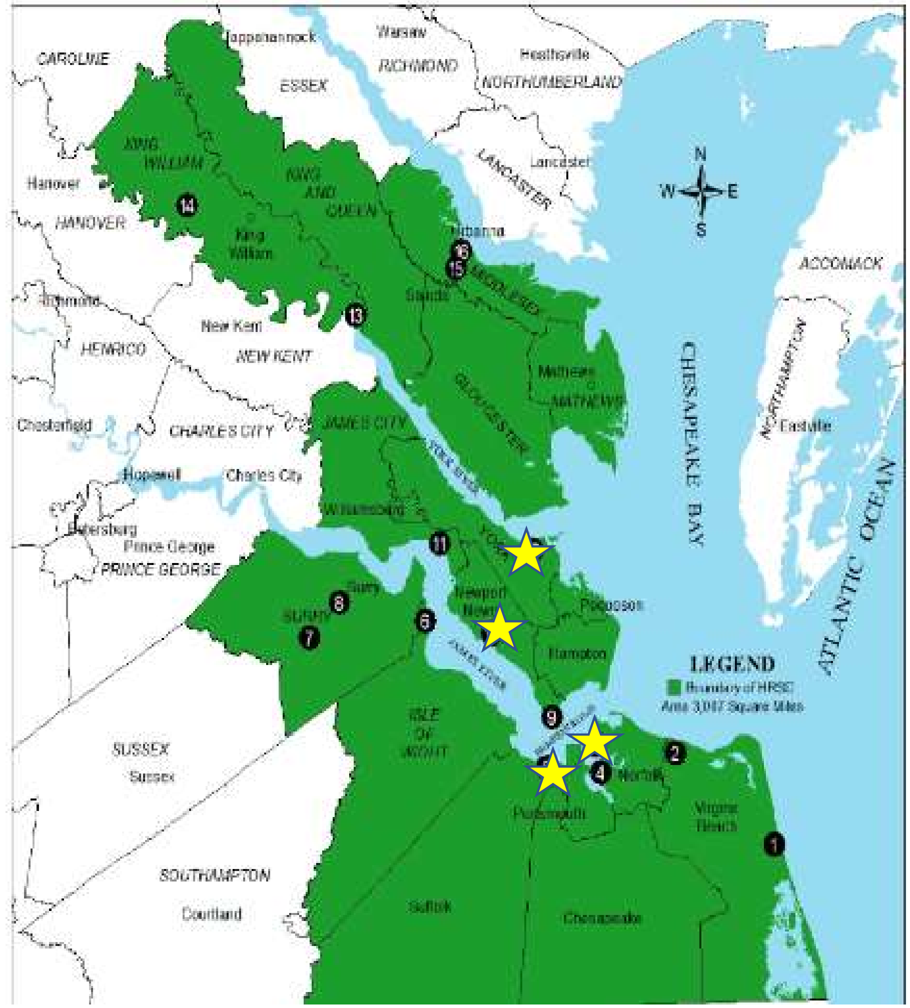
Benefits of Shortcut N Removal



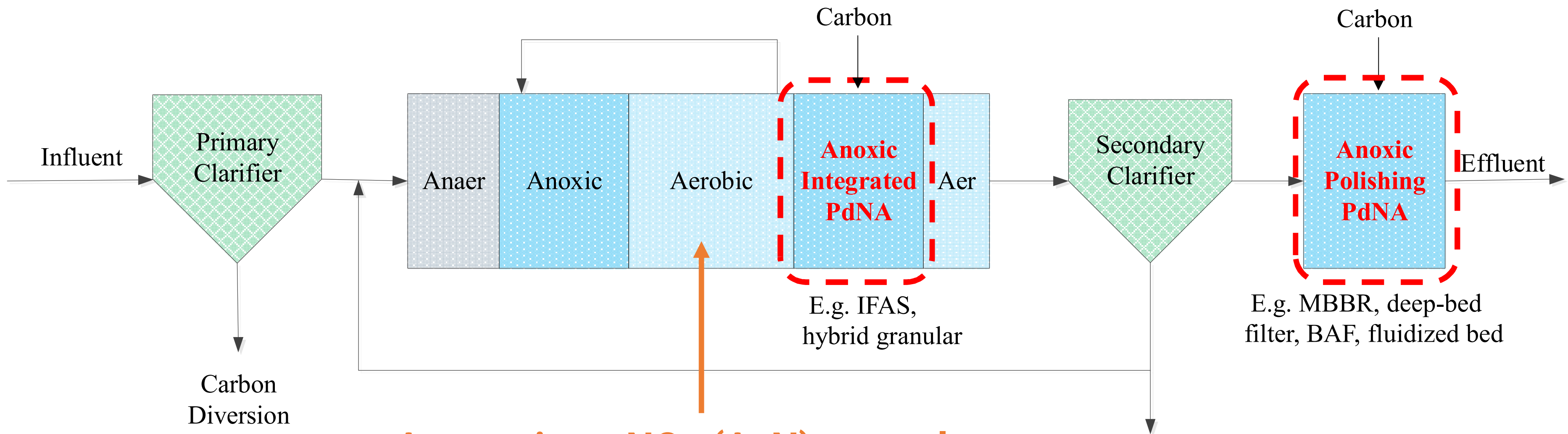
PdNA @ HRSD

- PdNA pilot work:
  - A/B BNR pilot polishing MBBR (2012-2018)
  - York River filter pilot (2020-2021)
  - James River MBBR & IFAS (2020-present)

- PdNA full-scale status
  - York River filter 2018
  - James River IFAS 2022
  - Nansemond IFAS full plant design/construction 2024 startup
  - James River MBBR in construction 2025 startup
  - Army Base IFAS feasibility study



Polishing PdNA Implementation – Post Anoxic (we know how to do this; now it's just an engineering challenge)



Ammonia vs NOx (AvN) control =
Maintain target NH3/NOx ratio based on controlling:
- DO
- Aeration time
- Step feeding
- etc

York River Plant (15 MGD) Denitrification Filters

Deep-bed filters with 2 to 3 mm silica sand and NOx-based feedforward-feedback methanol dosing control

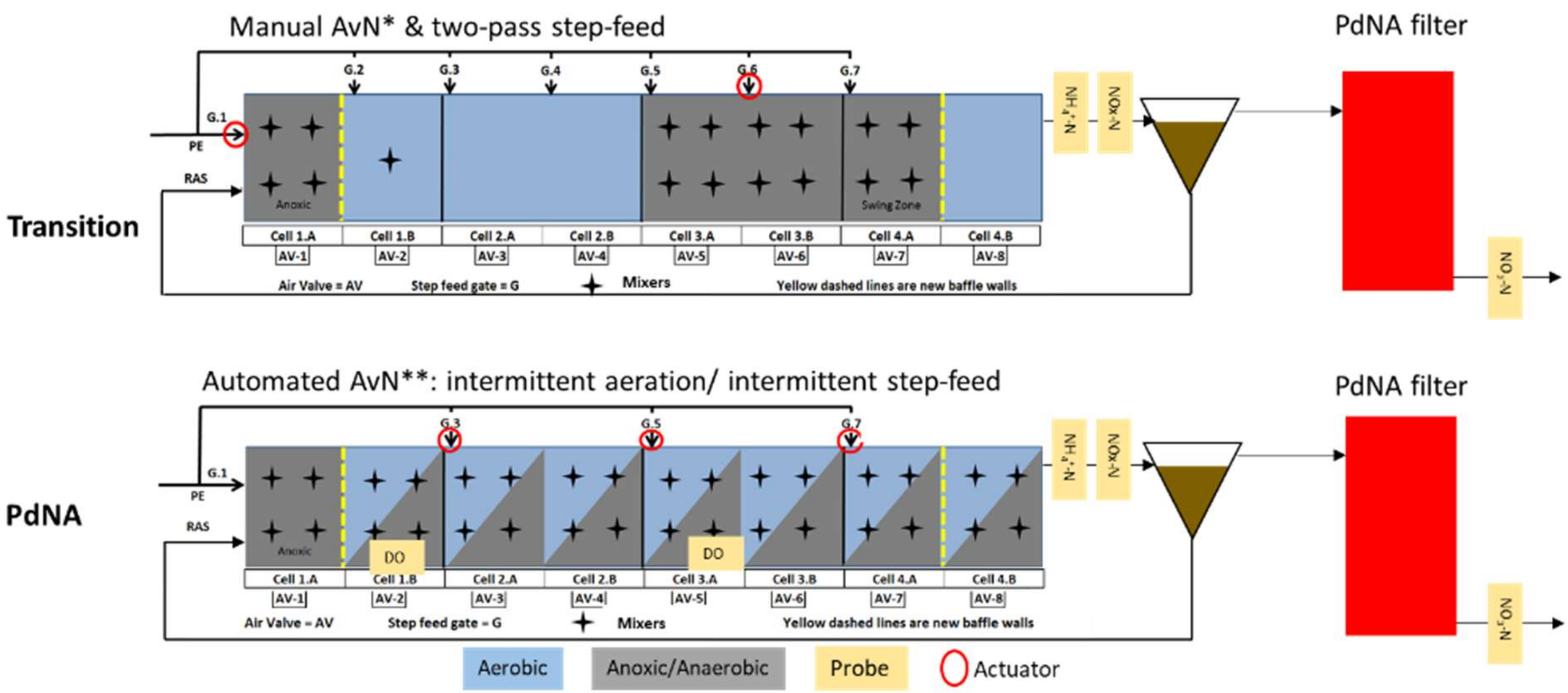
The Problem

1. Limited aerobic capacity
2. Excessive energy/chemical usage
   - Sodium hydroxide
   - Ferric
   - Methanol

York River Full-Scale Filters Transition to PdNA

How did we grow mainstream anammox?

1. Tight methanol dosing control (provide stable nitrate residual)
2. Ammonia vs NOX (AvN) control upstream
3. Minimize backwash and air scour
4. Wait patiently



Fofana et al., 2022

York River Plant

O&M Savings = ~$1M/year
Capital Cost avoided = ~$80M

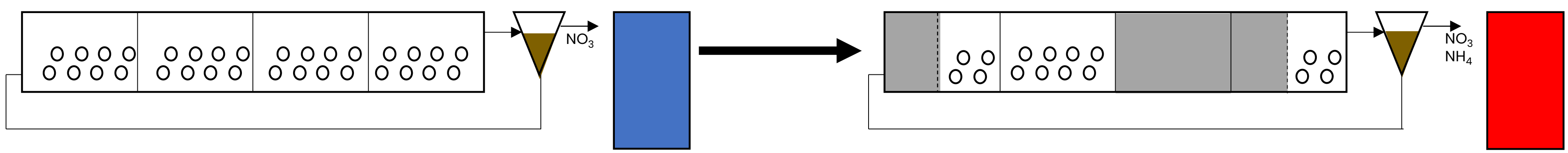
The Solution
1. Update aeration tanks for AvN
2. Convert denite filter to PdNA

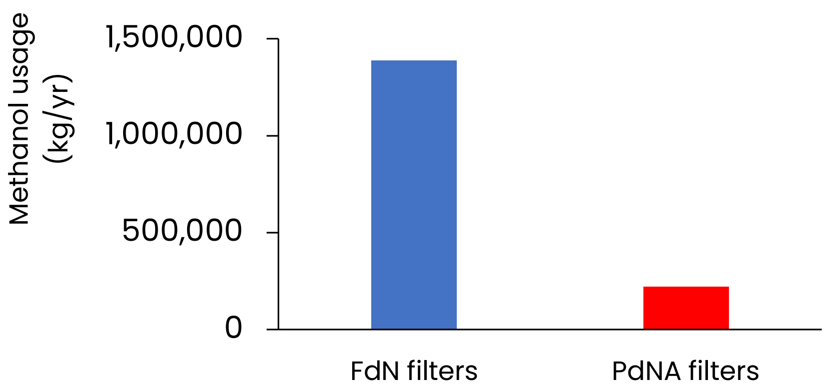
Full Nitrification
with manual blower control

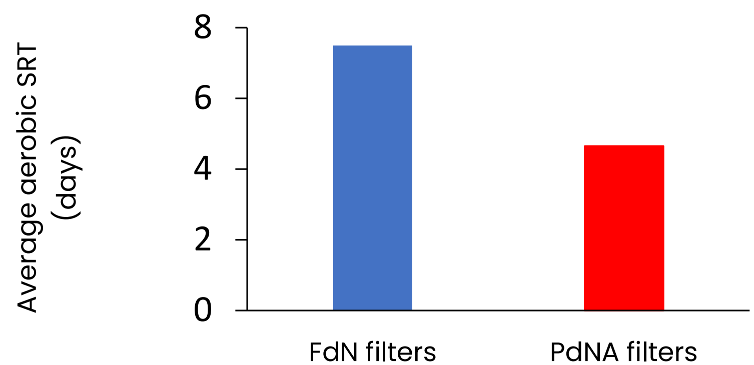
+FdN filters

BNR
with AvN Control

+PdNA filters





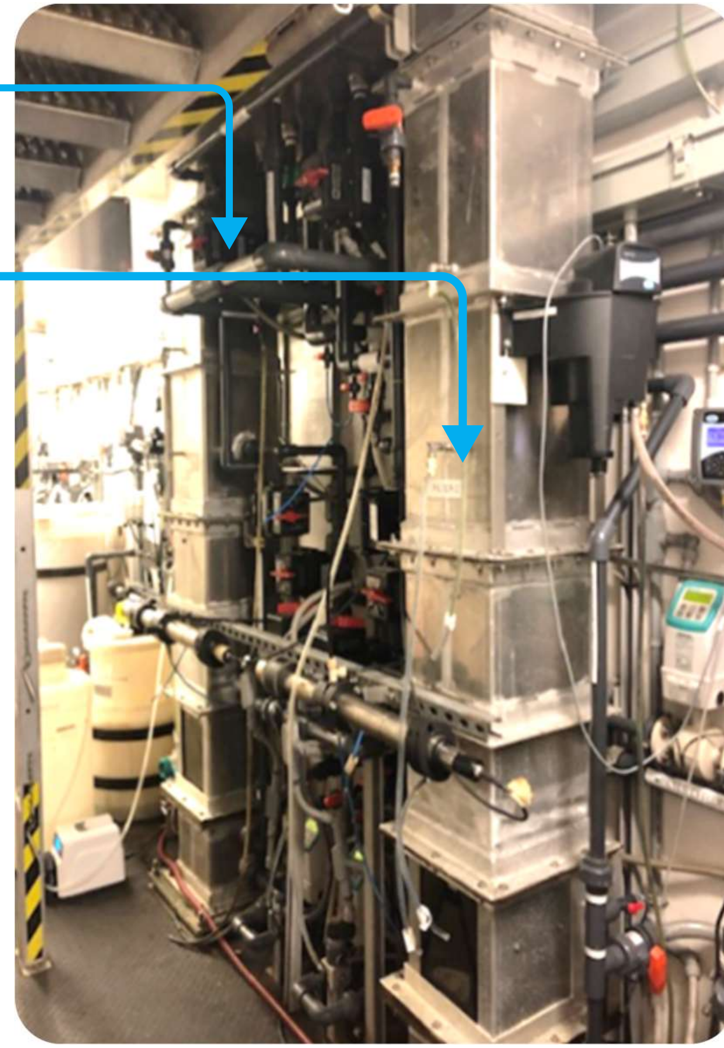


Fofana et al., 2022

York River PdNA Filter Pilot (HRSD/DCWater/Xylem)

Glycerol
vs
Methanol

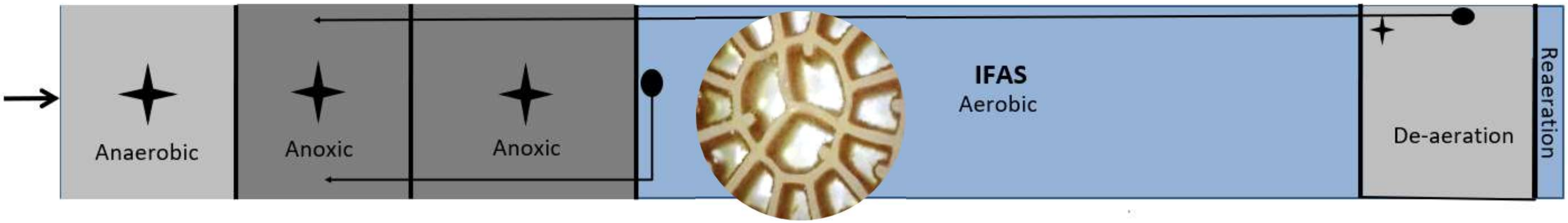
- Two downflow filters
- 6 ft deep bed x 1 ft^2
- Feedback carbon dosing control
- Seeded media from full-scale filters



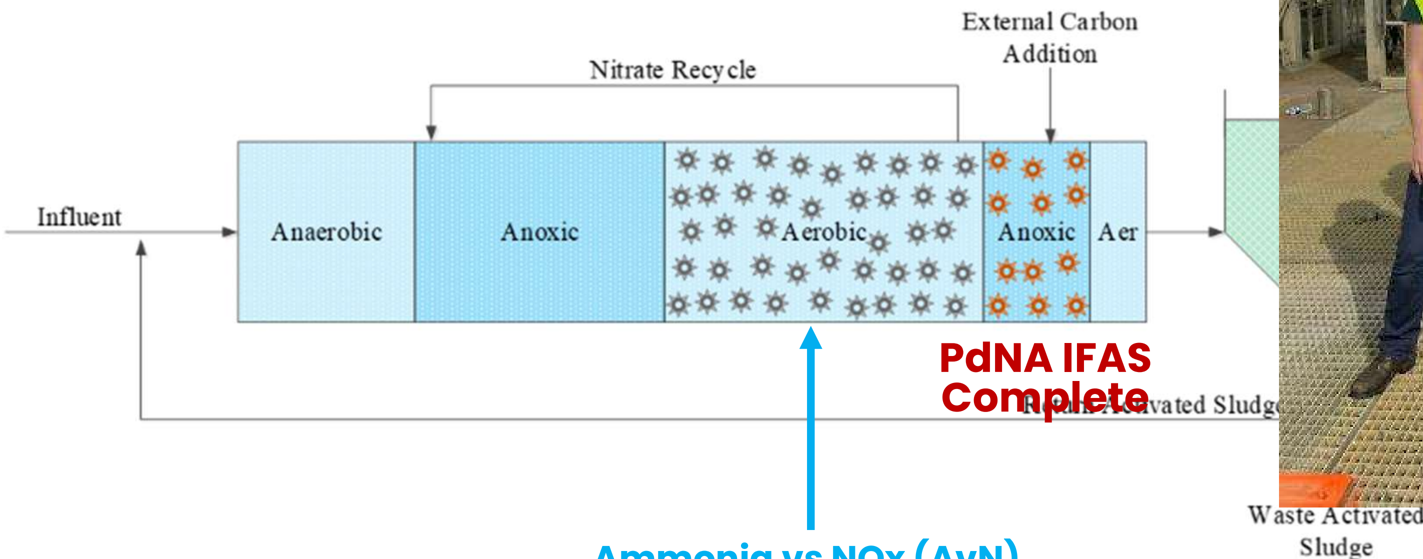
James River Plant (20 MGD)
A2O w/aerobic IFAS

The Problem

1. Limited aerobic capacity in existing tanks
2. Existing A2O will not meet future TN limits



PdNA Plans for the James River Plant TN Upgrade – 20 MGD

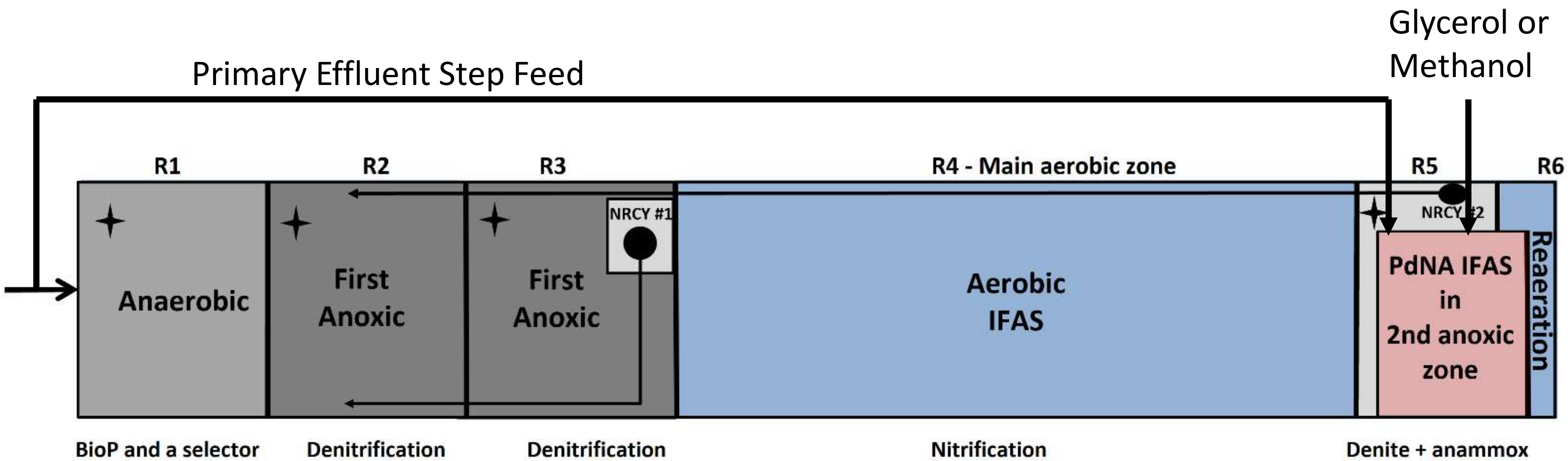


PdNA IFAS Complete

Ammonia vs NOx (AvN) aeration control

PdNA MBBR and IFAS Pilot Facility

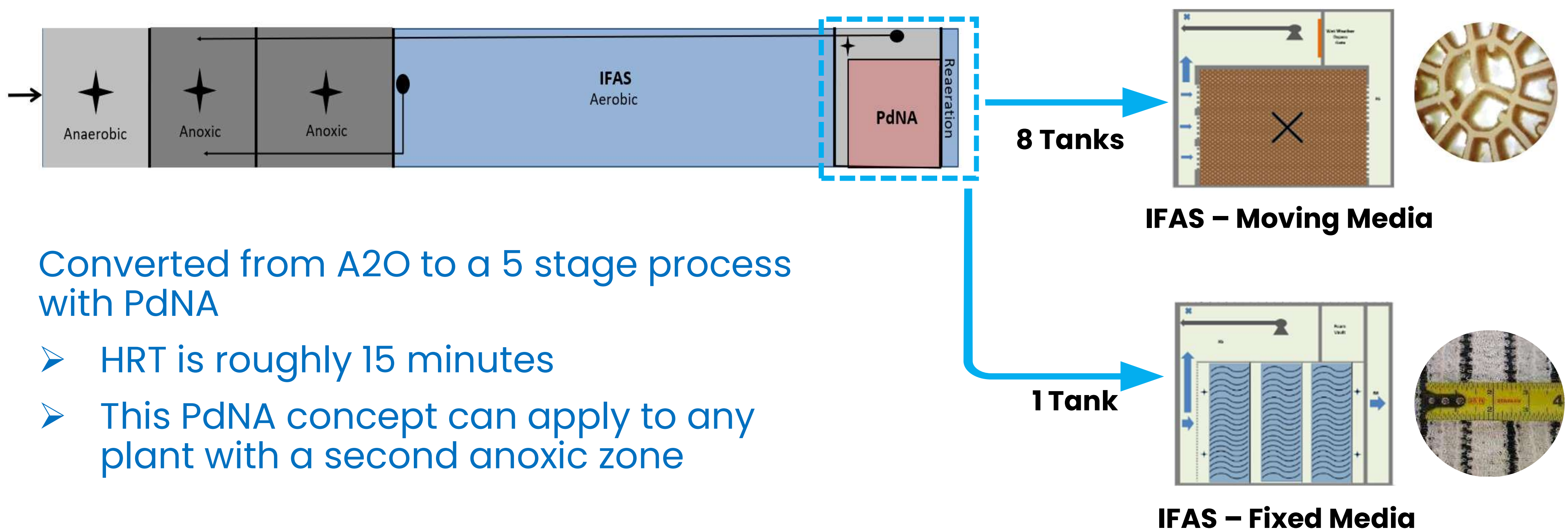
James River Integrated PdNA



James River Plant PdNA IFAS Upgrade

The Solution

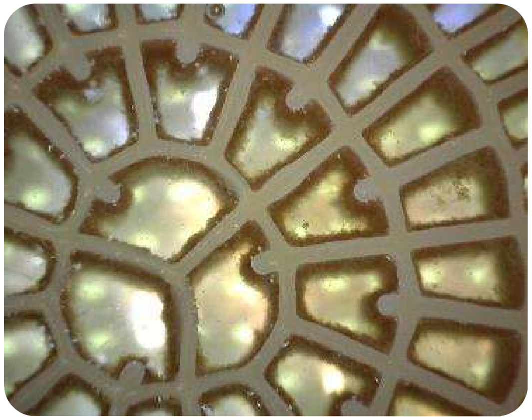
1. Update aeration control to AvN
2. Convert A2O to a 5-stage process
3. PdNA in the second anoxic zone



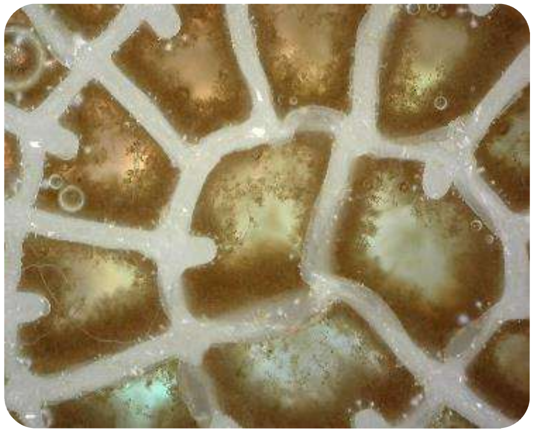
Converted from A2O to a 5 stage process with PdNA

- HRT is roughly 15 minutes
- This PdNA concept can apply to any plant with a second anoxic zone

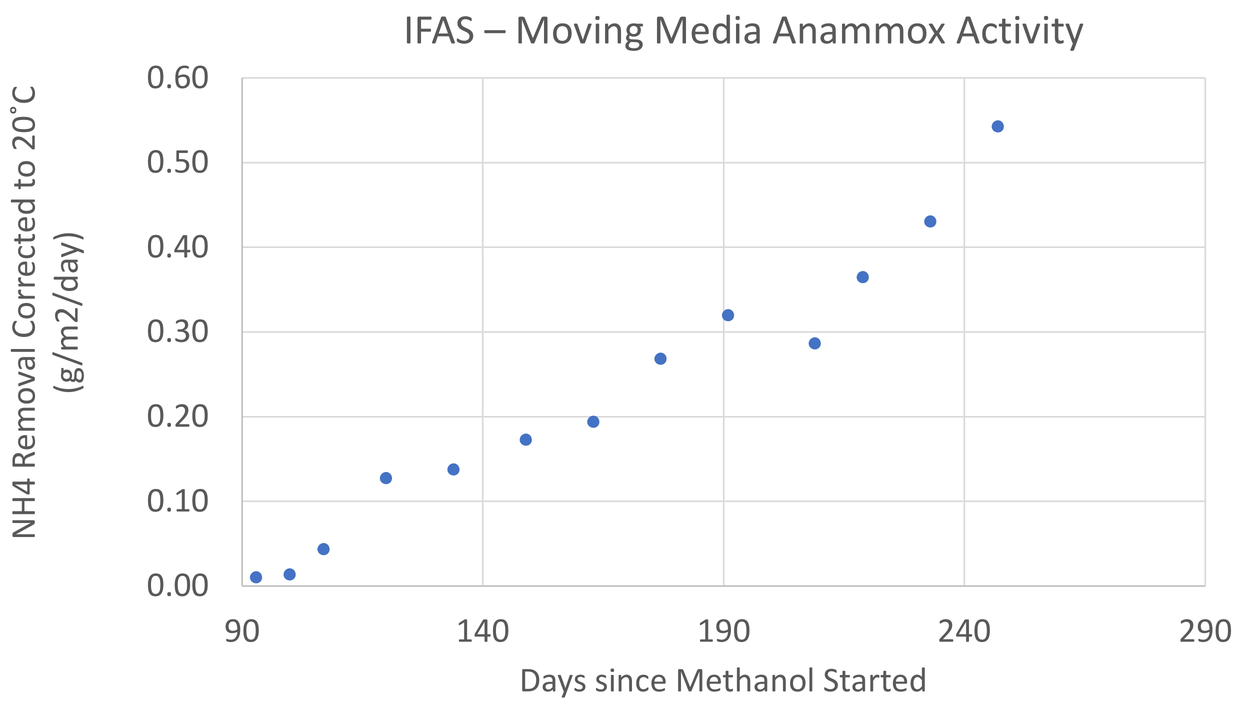
Moving Media IFAS

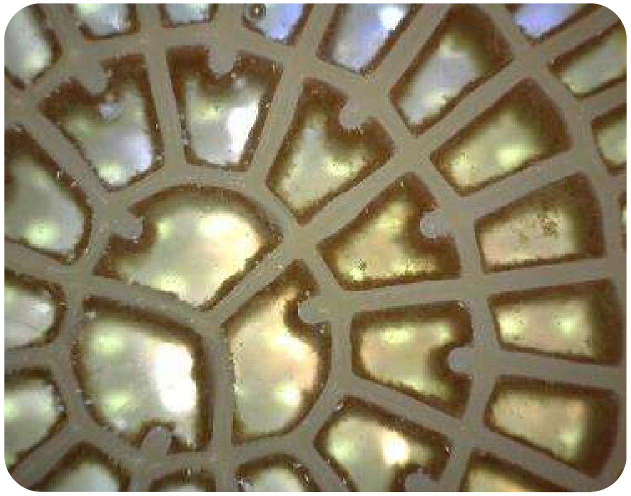


WWW2 MEDIA

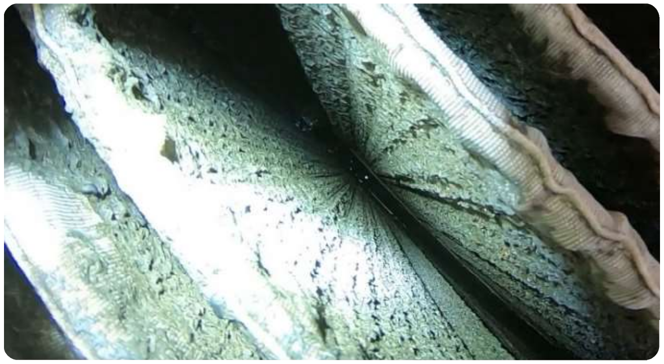


Anammox activity confirmed in IFAS



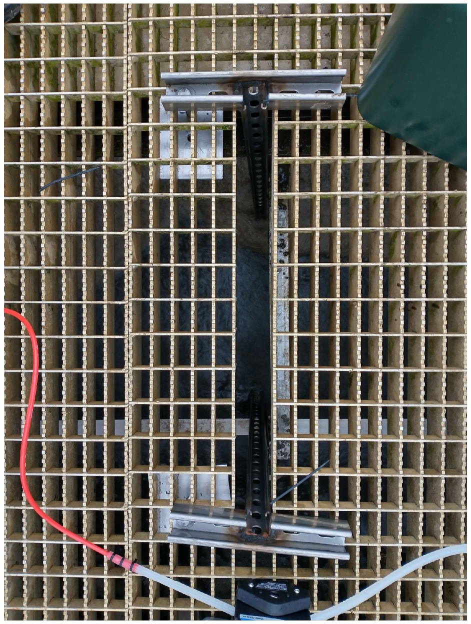


Fixed Media IFAS



Fixed Media IFAS

- Installed in November
- Just started step-feeding and glycerol
- Removable sheets for batch testing

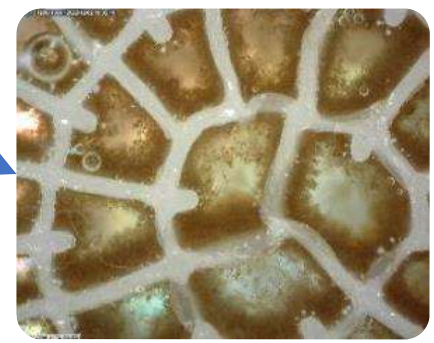


Nansemond Plant
5-stage Bardenpho
30 to 50 MGD Expansion

The Problem:
Low influent C/N leading to excessive methanol usage

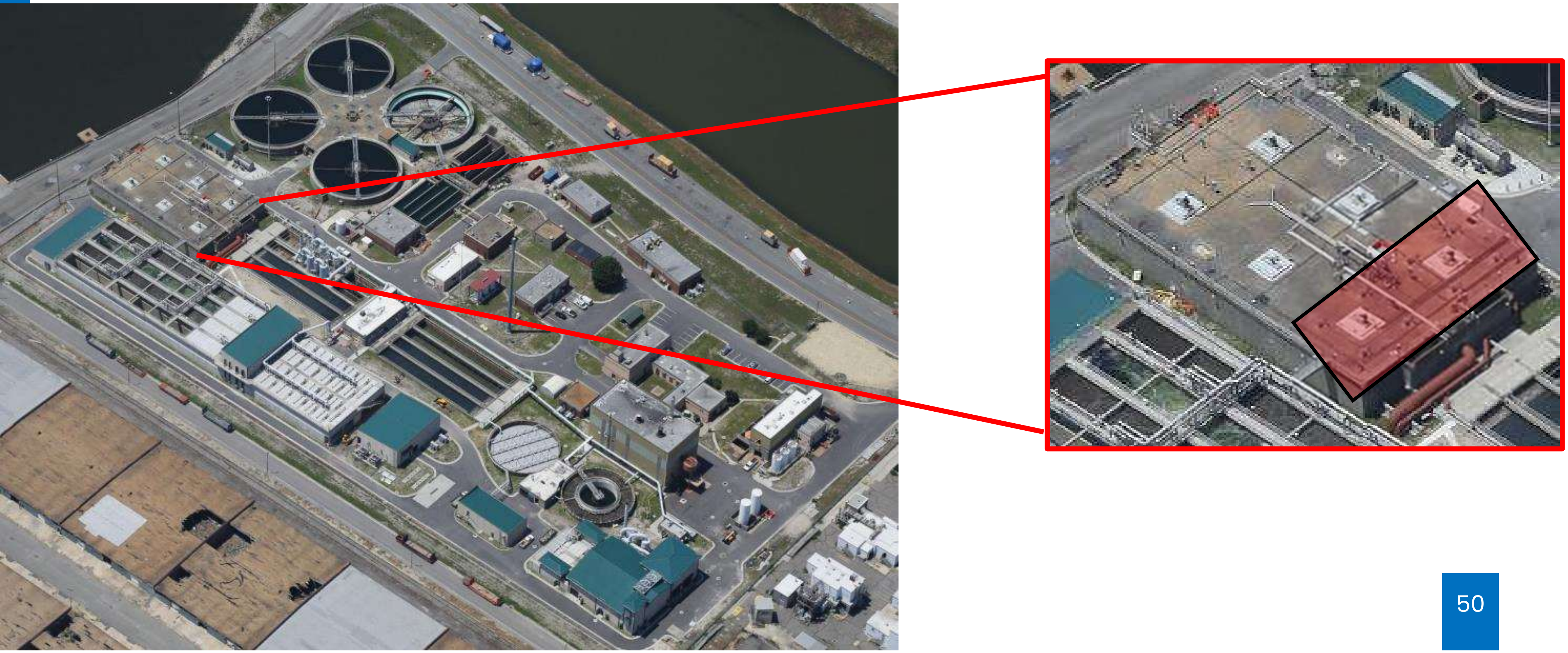
Nansemond Plant Expansion
5-stage Bardenpho

The Solution:
PdNA IFAS in second anoxic zone
- First cell for PdNA
- Cells 2 and 3 for full denite polishing



Army Base (18 MGD)
5-stage Bardenpho
PdNA IFAS Feasibility study

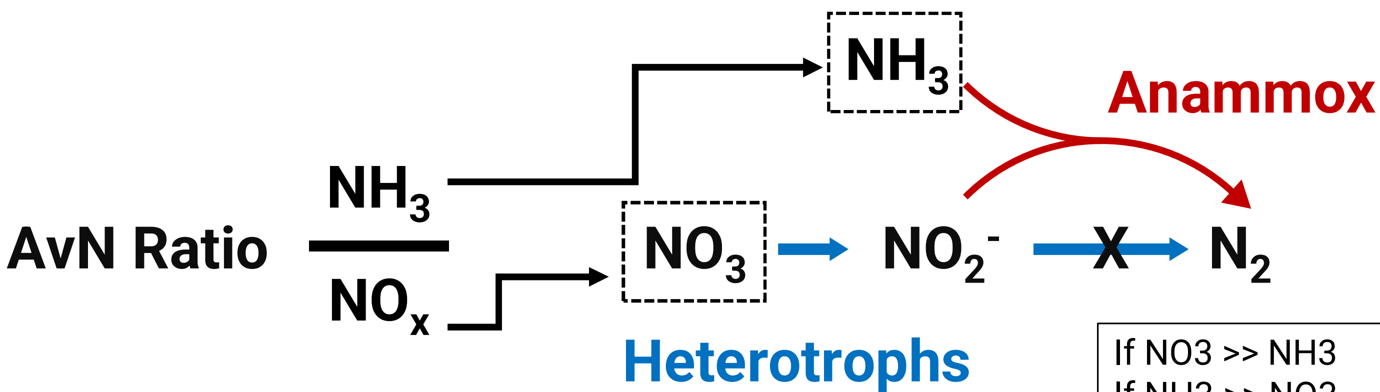
The Problem:
High methanol usage



NOB Outselection (PNA) is hard… PdNA is "easy"

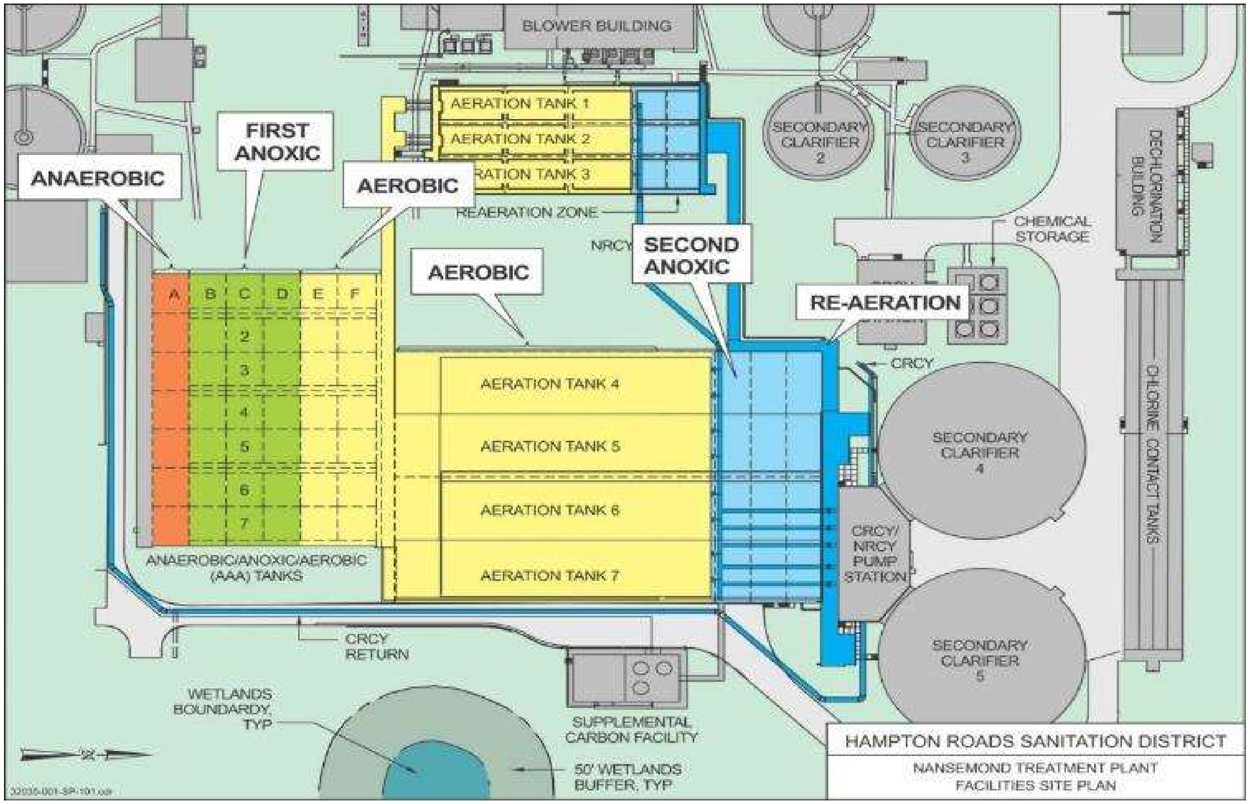
Challenge:

The biggest challenge for polishing PdNA is operating AvN aeration control to consistently meet the required effluent targets out of the PdNA zone



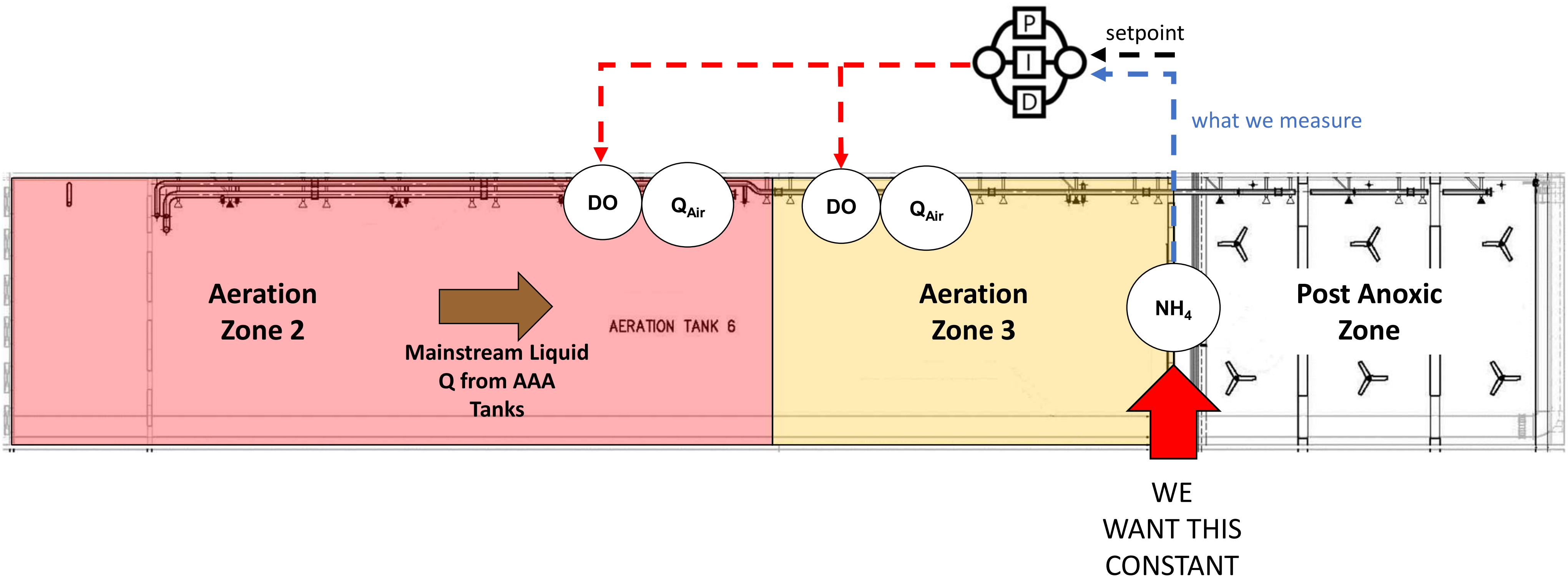
If NO3 >> NH3	wastes carbon, NO2 breakthrough
If NH3 >> NO3	NH3 breakthrough

Nansemond Plant - 5-Stage Bardenpho Configuration
Stable and reliable TN removal is a must!

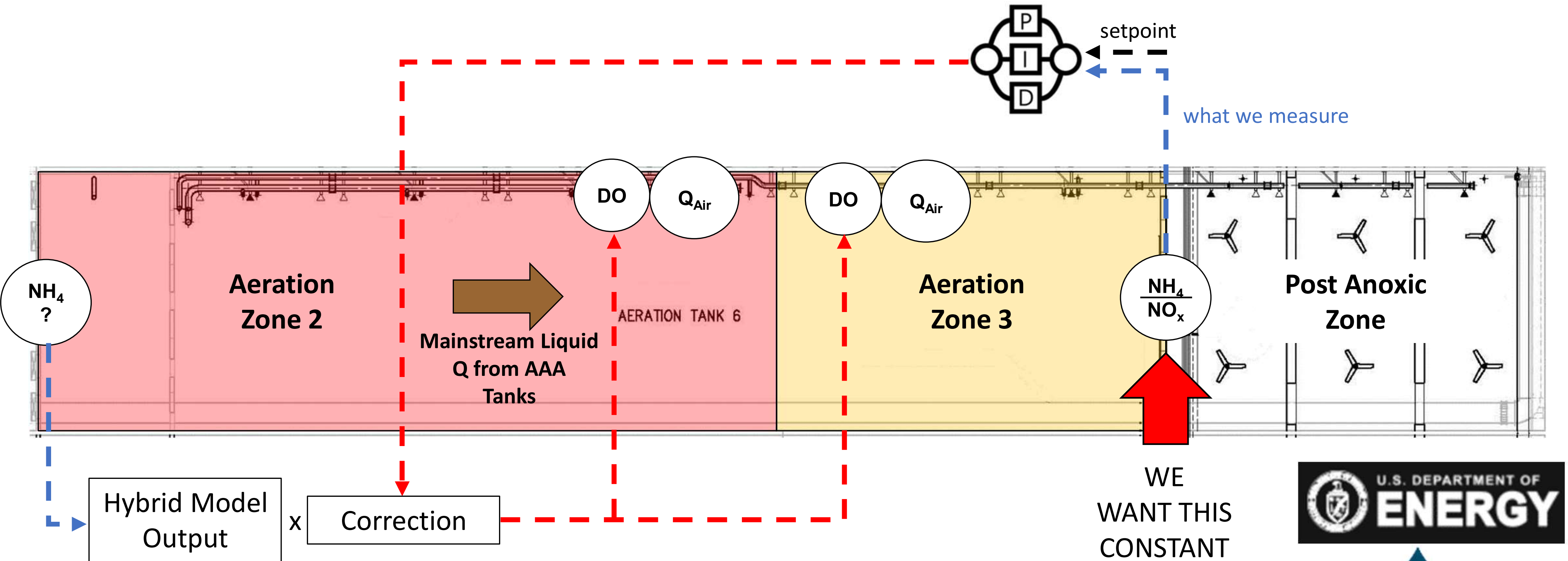


- Feedback ammonia-base aeration control
- Feedback nitrate-based internal mixed liquor recycle (NRCY) flow control
- Feedforward/feedback methanol feed control

Existing ABAC – Feedback only, PI control



Upgraded ABAC (to be extended to AvN – future)



<u>Feedforward – three approaches being evaluated at HRSD</u>:

1. Controller adjusts for changes in influent flow only (already applied to AvN) – Mike Parsons, James River (AvN)
2. Feedforward model predictive controller from regression analysis of calibrated process model simulations (no additional sensors) – Ali Gagnon, VIP (ABAC now, soon to AvN)
3. Hybrid mechanistic and data/ML model with added NH4 sensor – Jeff Sparks, Nansemond (ABAC soon to AvN)

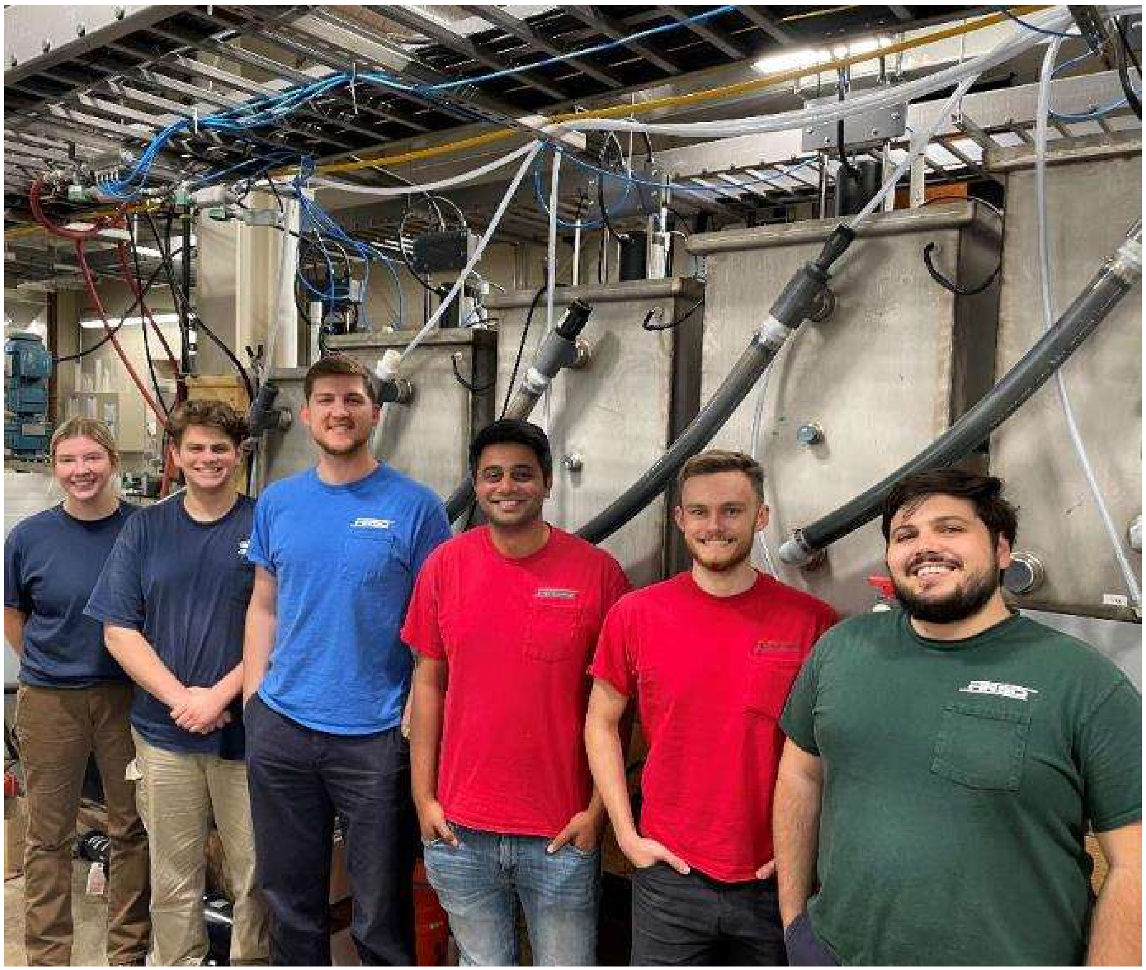
All of this requires good sensors!

- Good NH_4 measurement, even at low concentrations
- Discrimination of NO_3 and NO_2 without interferences

- Standard commercial sensors:
  - Dissolved oxygen – optical probes are reasonably good
  - Orthophosphate – wet chemical colorimetric
  - NH_4
    - ion selective electrode
    - wet chemical gas sensitive electrode analyzer
  - NO_3 and NO_2
    - UV spectroscopy in probe or analyzer common, nitrite]wet chemical colorimetric rare still

HRSD’s Online Analyzer – “Jarbalyzer” NH4, NO3, NO2, OP

Our new VIP BNR Pilot Facility



Low DO – Mechanistic Understanding of Acclimation of Autotrophs and Heterotrophs

(and other practical issues)