Design of Permeable Reactive Barriers to Reduce Nitrogen Flux

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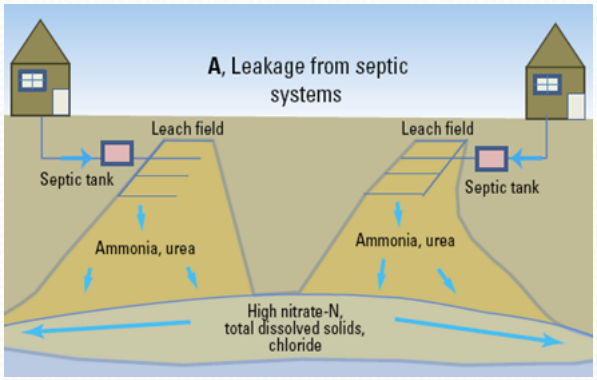
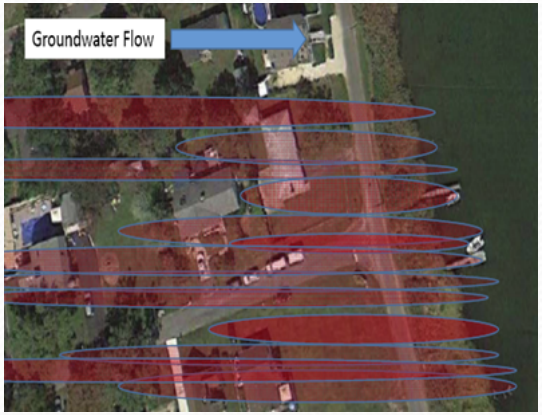
Nitrogen Impact of Cape Cod Salt Ponds

- **Septic systems used for ~85% of wastewater treatment on Cape Cod**



Modified from USGS 2013

- **Multiple smaller plumes that can combine into larger nitrate groundwater plumes that discharge into coastal waters and cause eutrophication and algae blooms.**
- **Remedial goal is to reduce nitrogen load in order to achieve TMDL (total maximum daily load).**



MT Environmental Restoration

Regional Cape Cod 208 Water Quality Plan

Watershed-based approach to restore embayments and achieve Regional Cape Cod 208 Water Quality Plan

- **Combine traditional wastewater (sewer) and non-traditional treatments**
- **Sewer infrastructure in high density areas**
- **In-situ groundwater treatment with permeable reactive barriers (PRBs)**
- **Increased shellfish aquaculture operations**
- **Monitoring to assure achievement of TMDLs**
- **Goal: minimize the proposed area of towns and properties to be sewered ($)**

(Cape Cod Commission 2015)

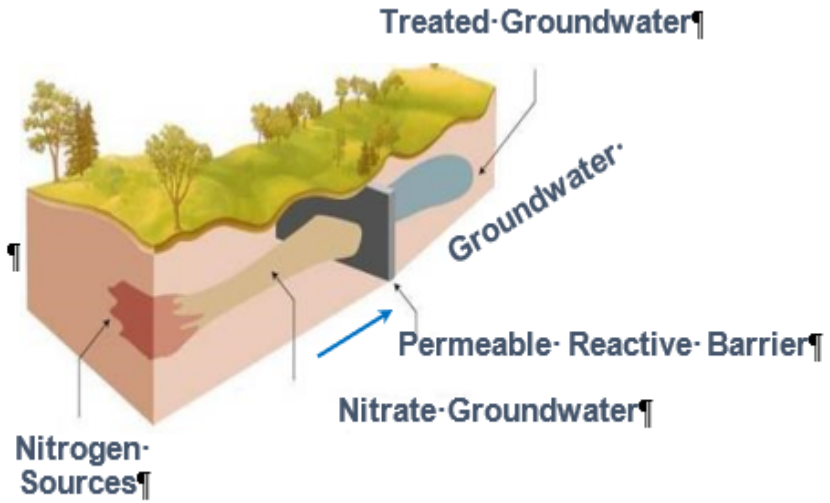
Denitrification

Well understood process for wastewater treatment

- **Bacteria convert nitrate to inert nitrogen gas (N2)**

$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$ (g)

- **Denitrifying bacteria are ubiquitous in soil**
- **Anaerobic bacteria**



- **PRBs – accepted groundwater treatment approach**
- **Permeable - groundwater flows through (passive)**
- **Reactive - promotes biological denitrification**
- **Barrier - prevents nitrate migration to coastal waters**

Cape Cod and Island PRB Pilots

- AECOM Orleans Eldredge Park –Nov. 2016 and June 2018
- Verdantas and MT Environmental - Eastham – April 2020
- WHOI Falmouth – July 2020
- SMAST Martha Vineyards – November 2020

AECOM Orleans Eldredge Field Pilot Test Design

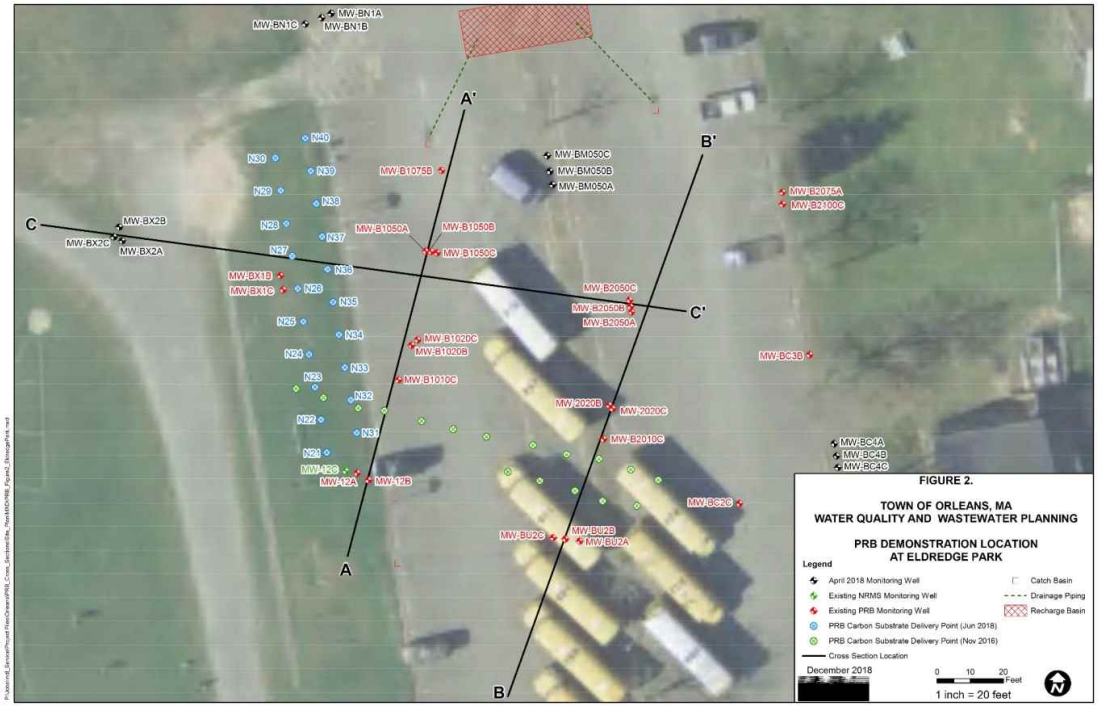
GWFR 0.2-0.3 ft/day

November 2016

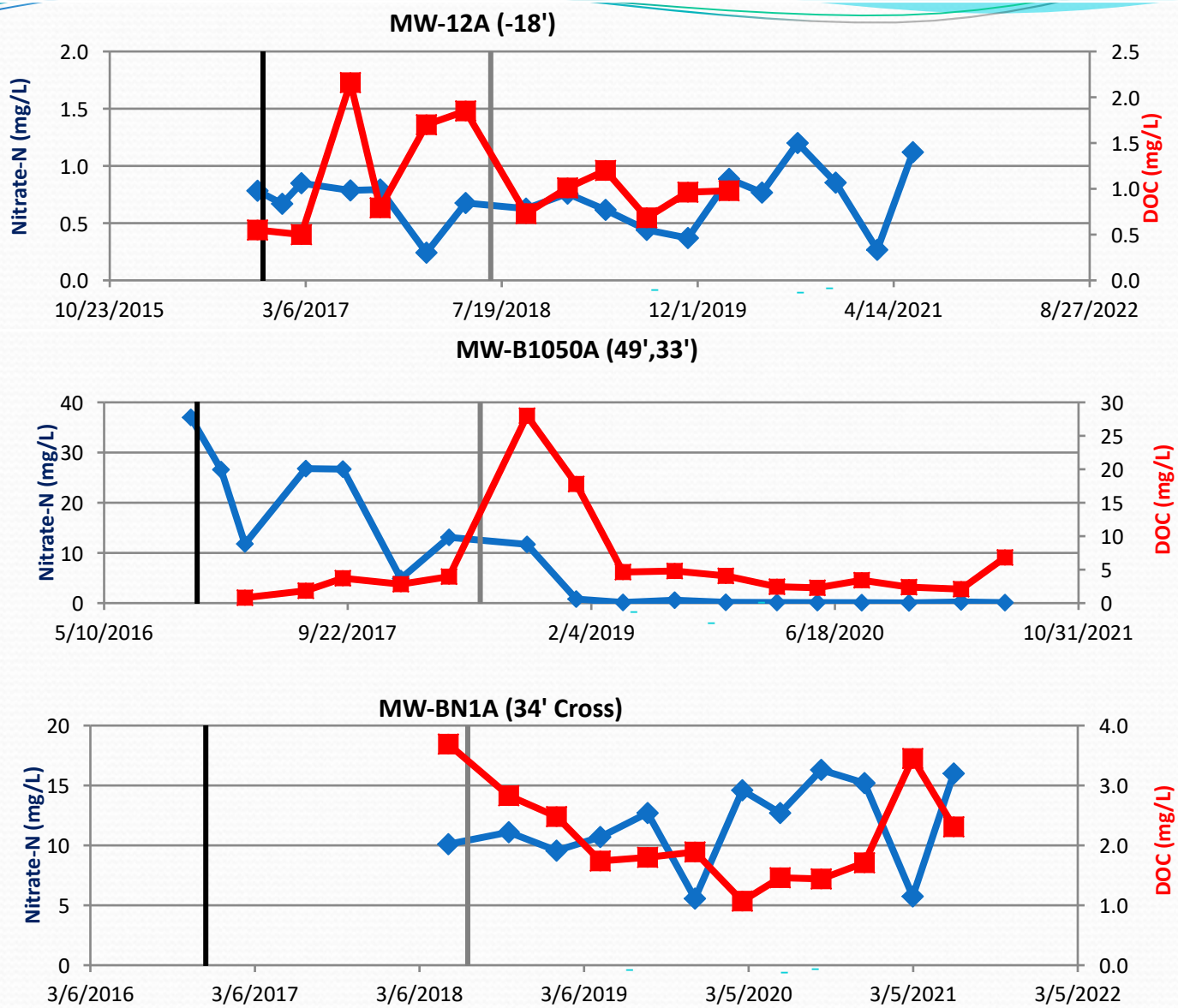
- **110 foot PRB**
- **17 Injection Points**
  - **1 and 2 rows of points**
  - **10 foot spacing**
  - **36 to 68 feet bgs**
- **2,600 gallons SRS®-NR (0.056-0.064 gal/ft³)**
- **350 pounds sodium bicarbonate (0.0064-0.0075 lb/ft³)**
- **10,800 gal total volume**

June 2018 Extended PRB to North

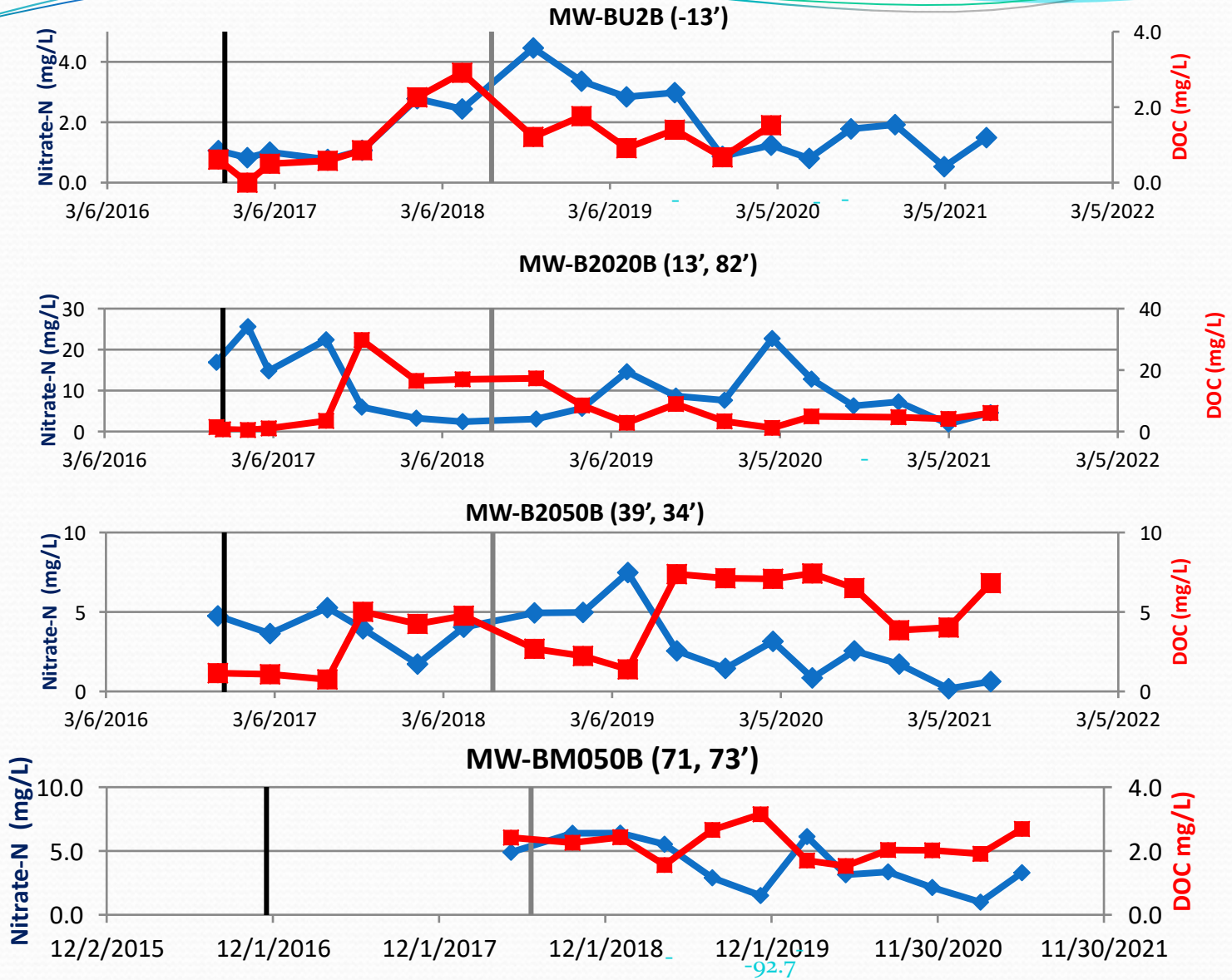
- **110 feet PRB 38 feet thick**
- **20 injection points, 10 feet spacing, 2 rows**
- **3,700 gal SRS®-NR (0.040 gallons/ft³)**
- **225 gallons sodium lactate**
- **950 pounds sodium bicarbonate (0.0125 lb/ft³)**
- **14,800 gal total volume**



Transect A A Zone

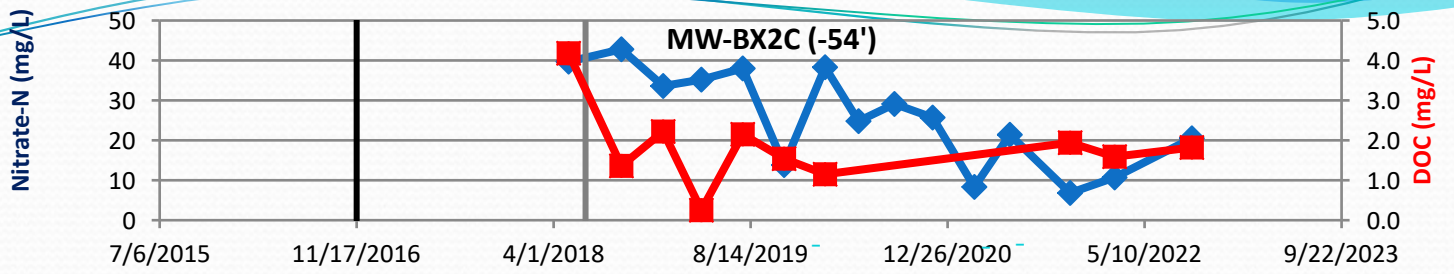


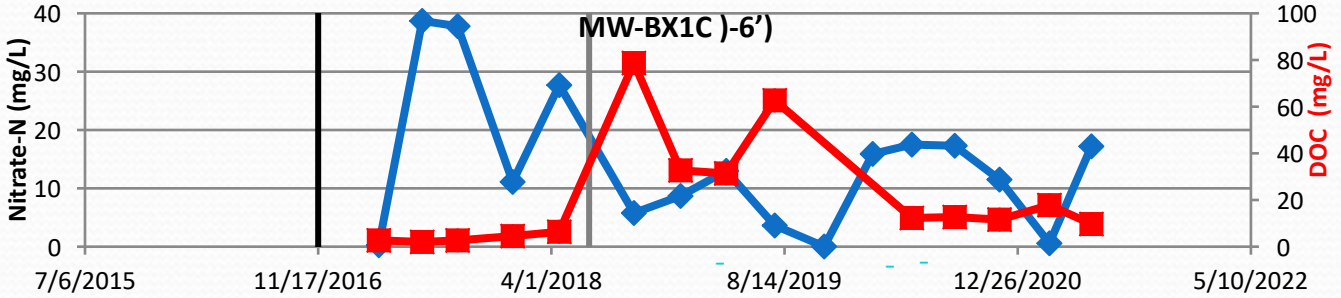
Transect B B Zone

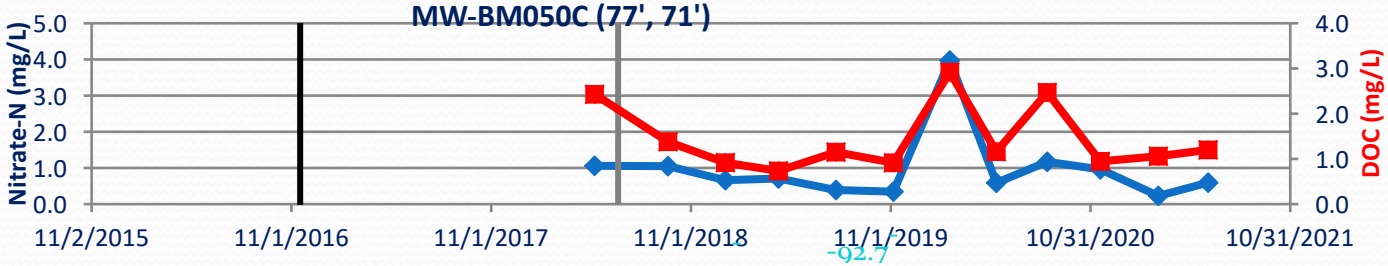


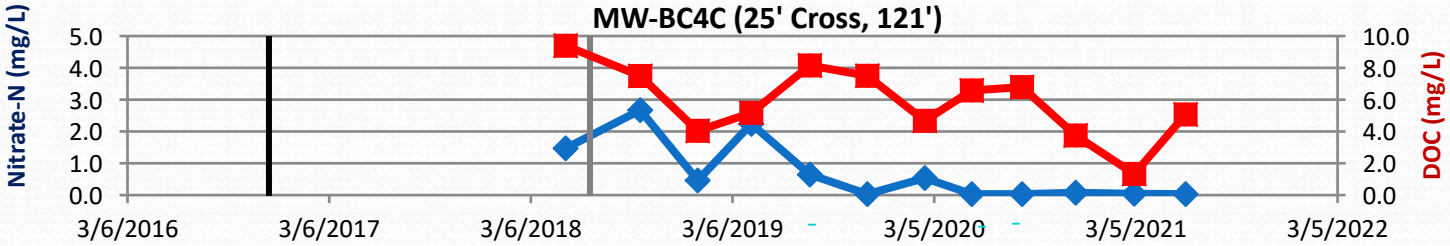
-92.7

Transect C C Zone









Eldredge Park, Orleans Conclusions

1. Where DOC sustained >4 mg/L, average of 94.5% removals of nitrate-N
2. DOC persisted for more than 4.7 years
3. The water table sloshes around due to rainfall and septic tank discharge, but groundwater flow is predominantly to east at 0.2 to 0.3 ft/day
4. DOC retained within about 50 feet from injection wells
5. Consumption of DO and sulfate with production of up to 157 mg/L dissolved iron, 11 mg/L manganese, 17 mg/L methane, and 0.043 mg/L arsenic

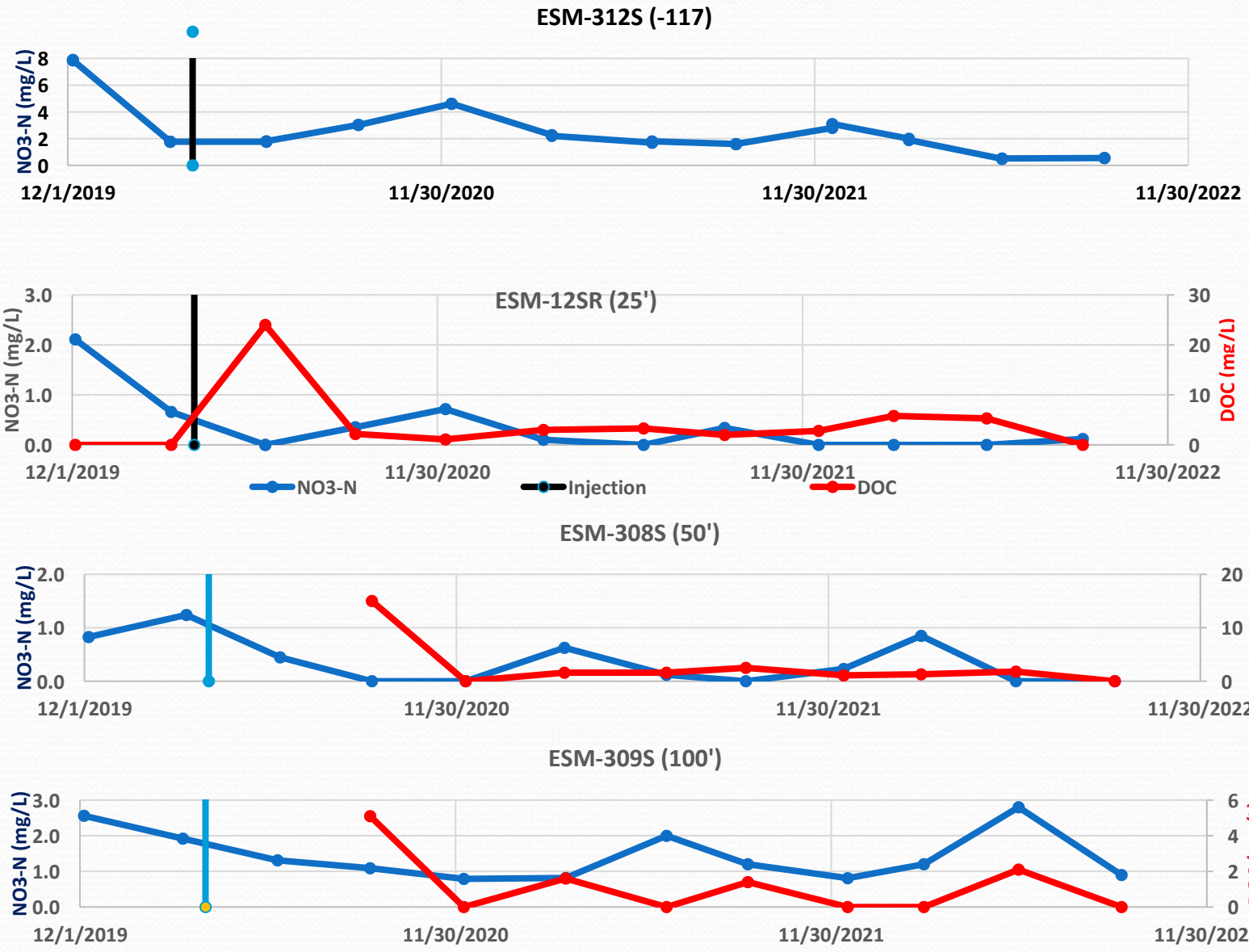
Verdantas and MT Environmental Eastham Pilot Test Design

0.5 ft/day GWFR

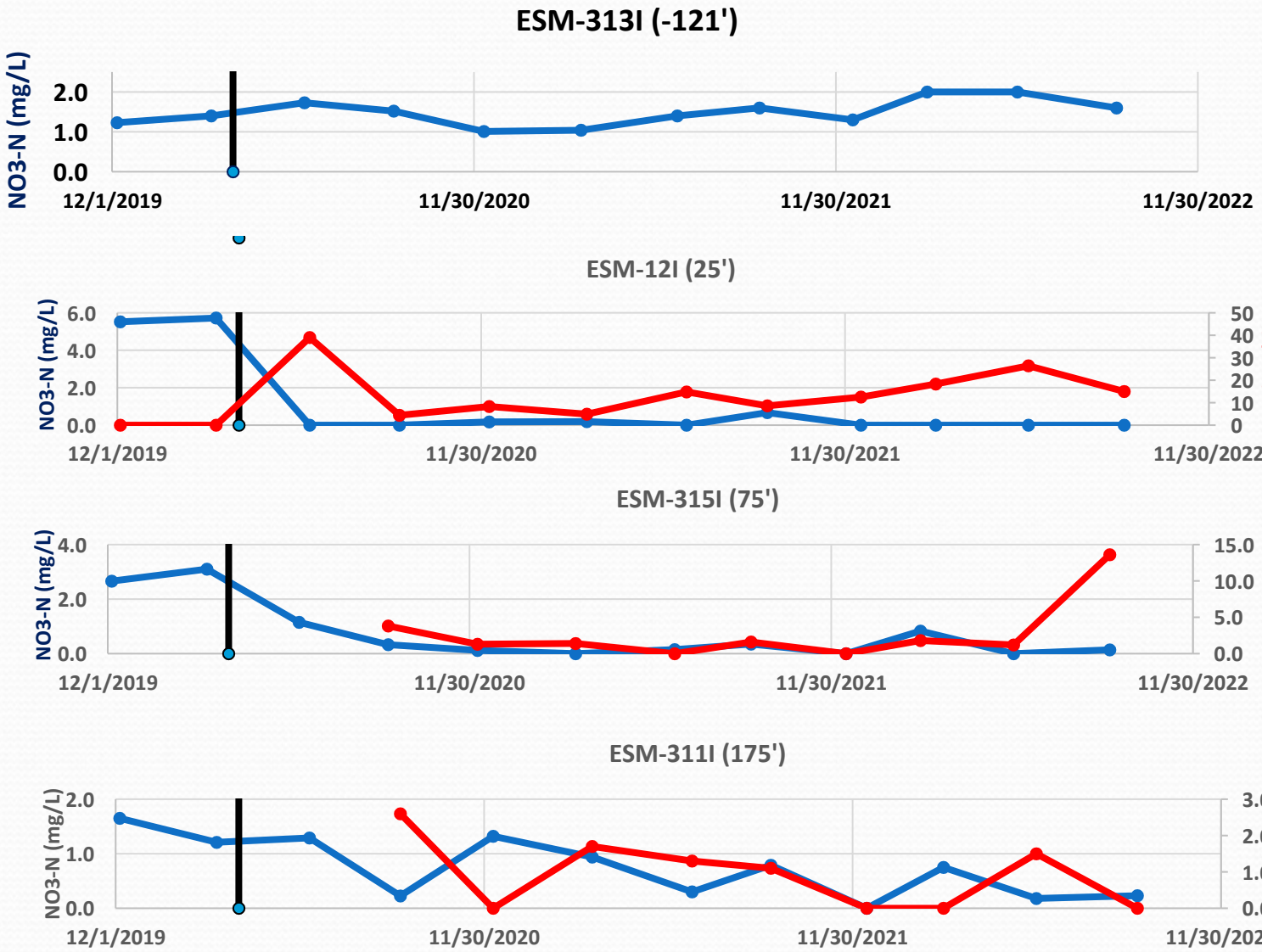
April 2020 Injections

- **200 foot long PRB**
- **21 Injection Points**
  - **1 row of points**
  - **10 foot spacing**
  - **21 to 64 feet bgs**
- **6,600 gallons SRS®-NR (0.064 gal/ft³)**
- **264 gallons sodium lactate**
- **550 pounds sodium bicarbonate (0.0053 lb/ft³) and 550 pounds of calcium carbonate (0.0053 lb/ft³)**
- **31,000 gallons**

Eastham Pilot Test Shallow



Eastham Pilot Test Intermediate



Eastham Conclusions

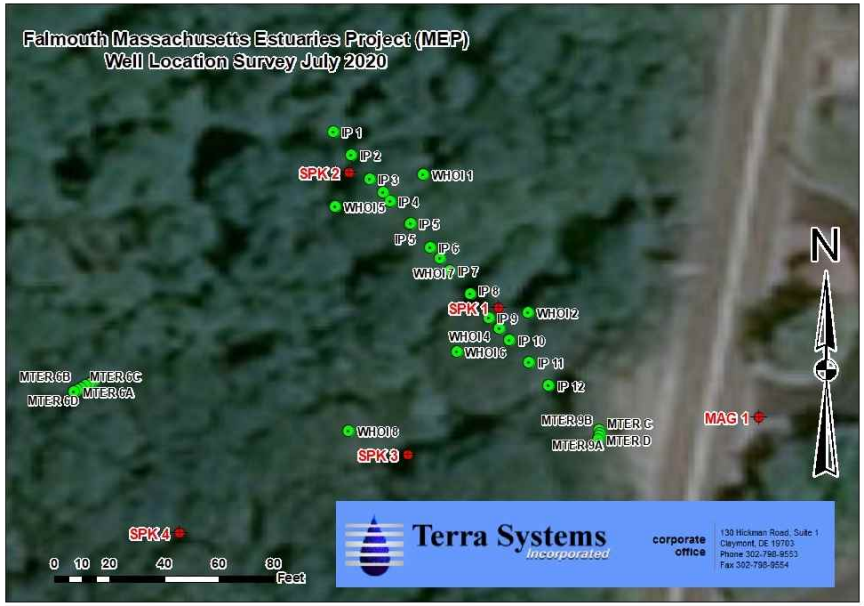
1. DOC sustained >5 mg/L for over 2.4 years
2. Average of 91.9% removals of nitrate-N in shallow zone up to 50 feet from PRB (excluding ESM-310S).
3. Average of 95.0% removals of nitrate-N in intermediate zone up to 75 feet from PRB (excluding ESM-308I)
4. Buffer increased pH up to 25 feet downgradient in shallow zone and 100 feet in intermediate zone
5. Consumption of DO and sulfate with production of up to 263 mg/L dissolved iron, 18 mg/L manganese, 19 mg/L methane, and 0.050 mg/L arsenic.

WHOI Falmouth Pilot Test Design

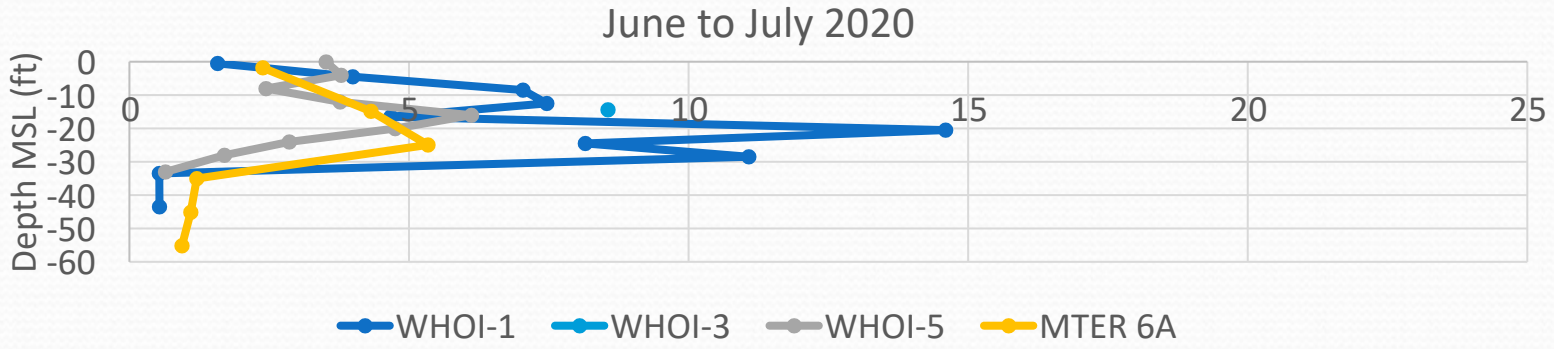
0.13 ft/day GWFR

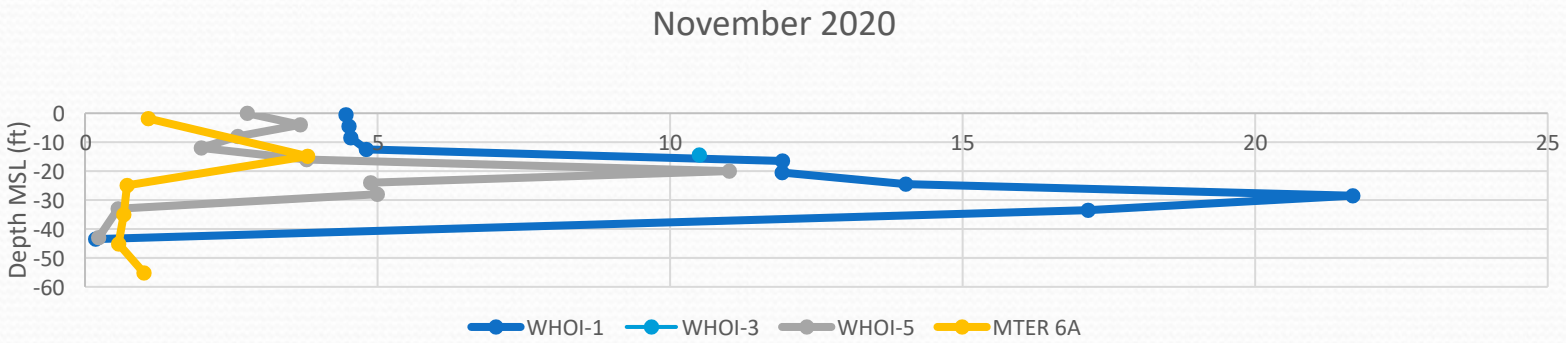
April 2020 Injections

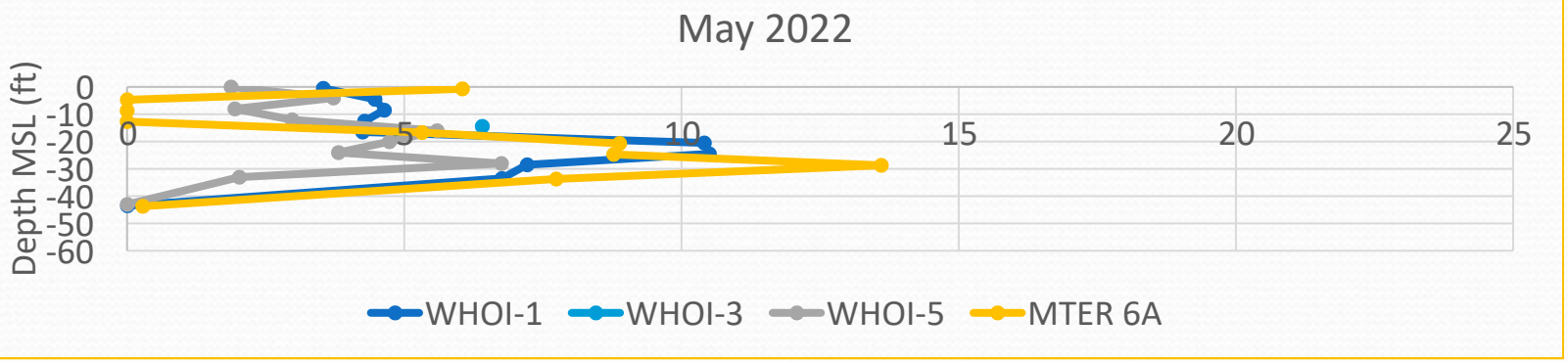
- **120 foot PRB**
- **12 Injection Points**
  - **1 row of points**
  - **10 foot spacing**
  - **21 to 64 feet bgs**
- **1 Yr Demand 6 Injection Points**
  - **1,001 gallons SRS®-NR (0.070 gal/ft^3)**
  - **164 pounds calcium carbonate (0.014 lb/ft^3)**
  - **6,290 gallons Injection**
  - **Multilevel MW WHOI-1 (-14'), WHOI-3 (0'), WHOI-5 (15'), and MTER-6A (125')**
- **2 Yr Demand 6 Injection Points**
  - **1,751 gallons SRS®-NR (0.122 gal/ft^3)**
  - **156 pounds calcium carbonate (0.014 lb/ft^3)**
  - **5,915 gallons.**
  - **Multilevel MW WHOI-2 (-12'), WHOI-4 (0'), WHOI-6 (17'), and WHOI-8 (64')**



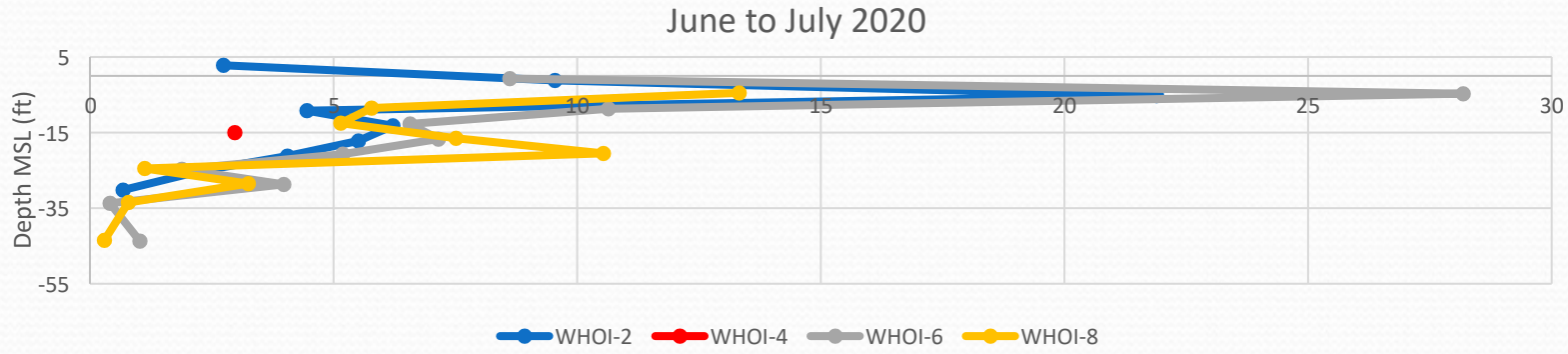
WHOI Falmouth 1 Yr Pilot Test

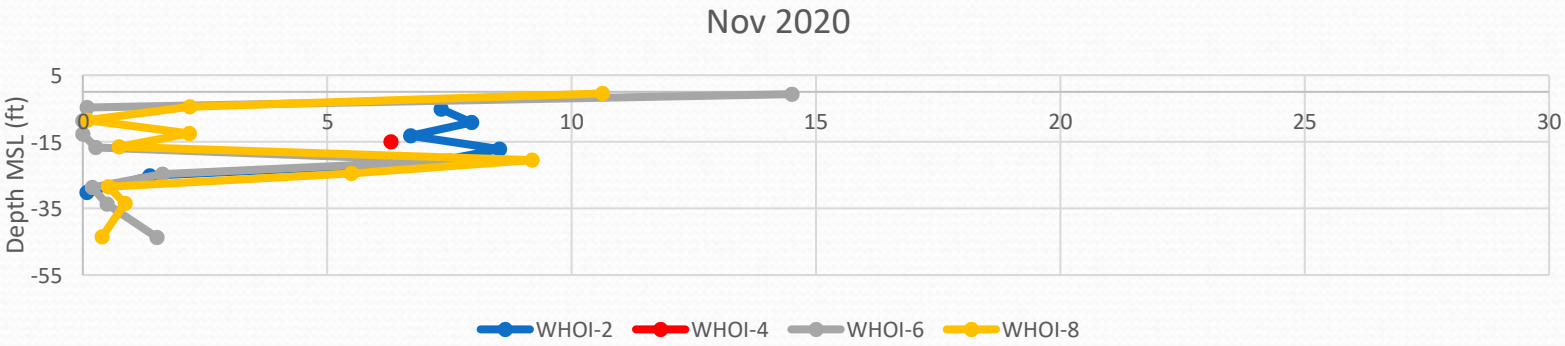


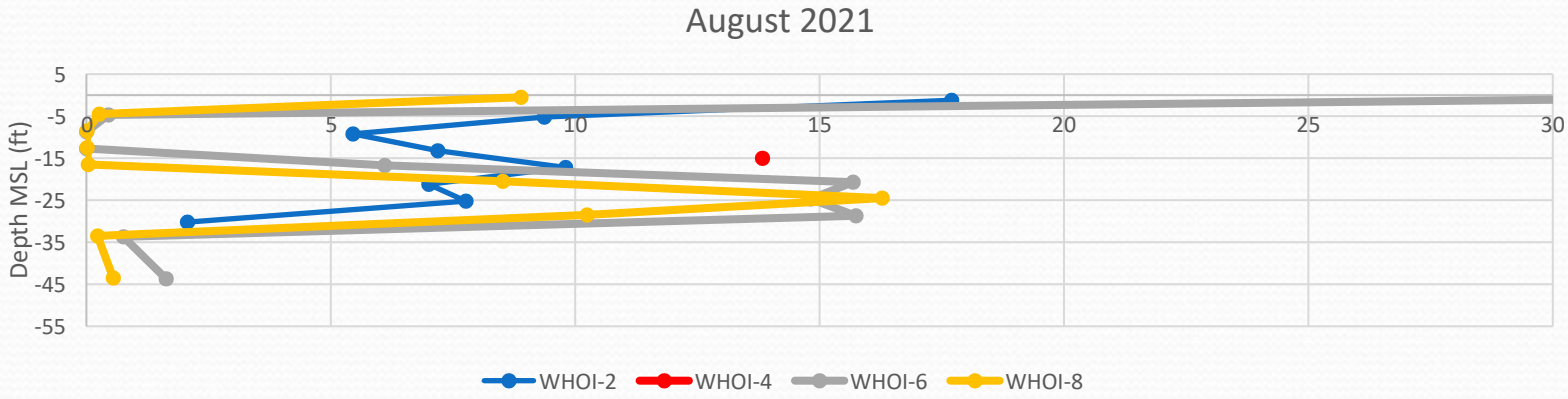




WHOI Falmouth 2 Yr Pilot Test







WHOI Falmouth Conclusions

1. 1 Yr PRB not much denitrification observed in WHOI-5 (16 feet downgradient). Sustained denitrification in MTER-6 (125 feet downgradient) at depths of -14.8', -24.9', -36', and -45' for over 1.8 years
2. 2 Yr PRB denitrification observed in WHOI-6 (17 feet downgradient) at depths of -4.7 to -12.7' and WHOI-8 (64 feet downgradient) at depths of -4.5 to -16.5 for over 1.8 years
3. Buffer increased pH up to 125 feet downgradient in MTER-6 of 1 Yr PRB and 64 feet downgradient in WHOI-8 at 64 feet downgradient
4. Consumption of DO and sulfate with production of up to 71 mg/L dissolved iron, 30 mg/L manganese, and 0.020 mg/L arsenic.

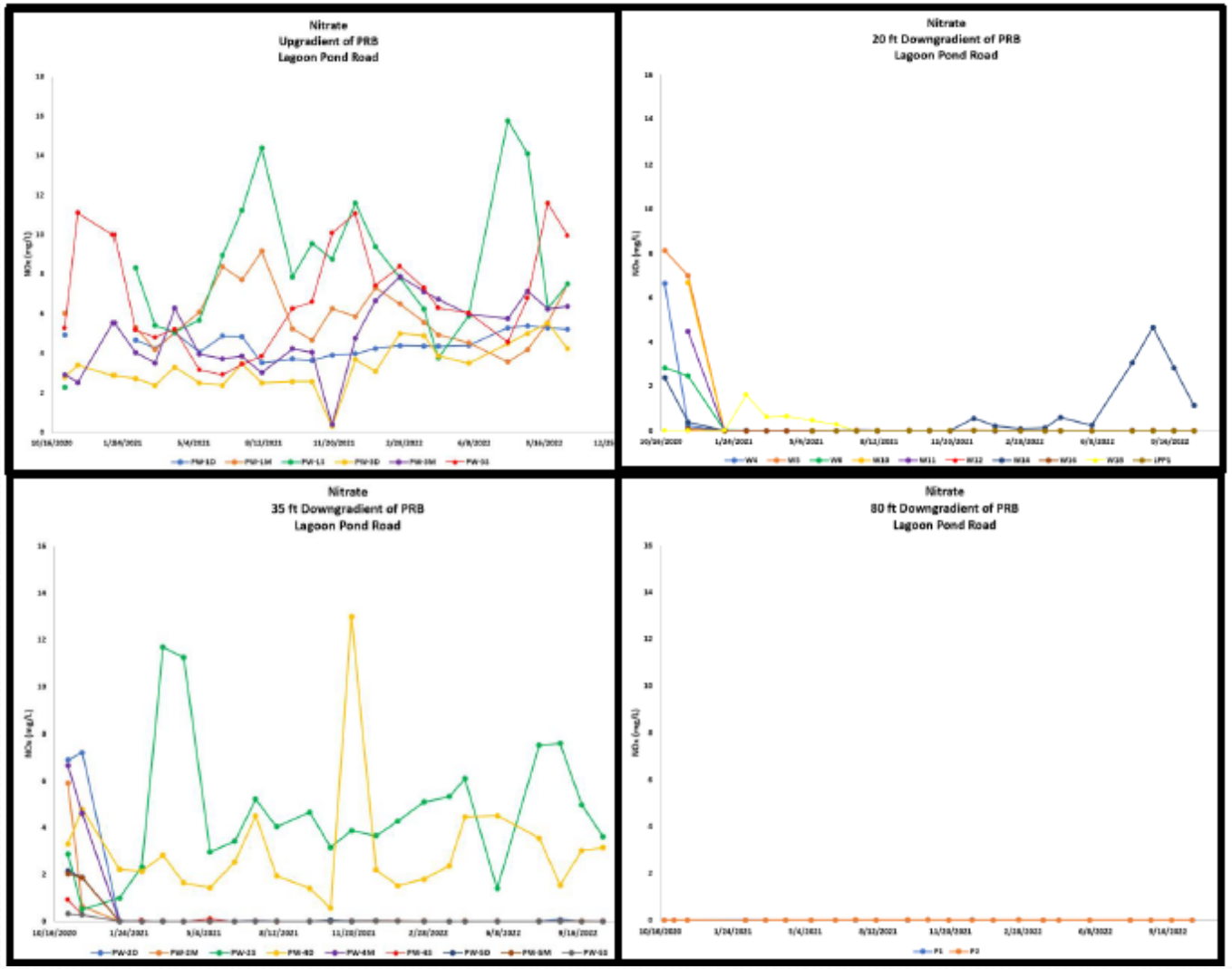
SMAST Martha's Vineyard Lagoon pond Pilot Test Design

0.6 ft/day GWFR

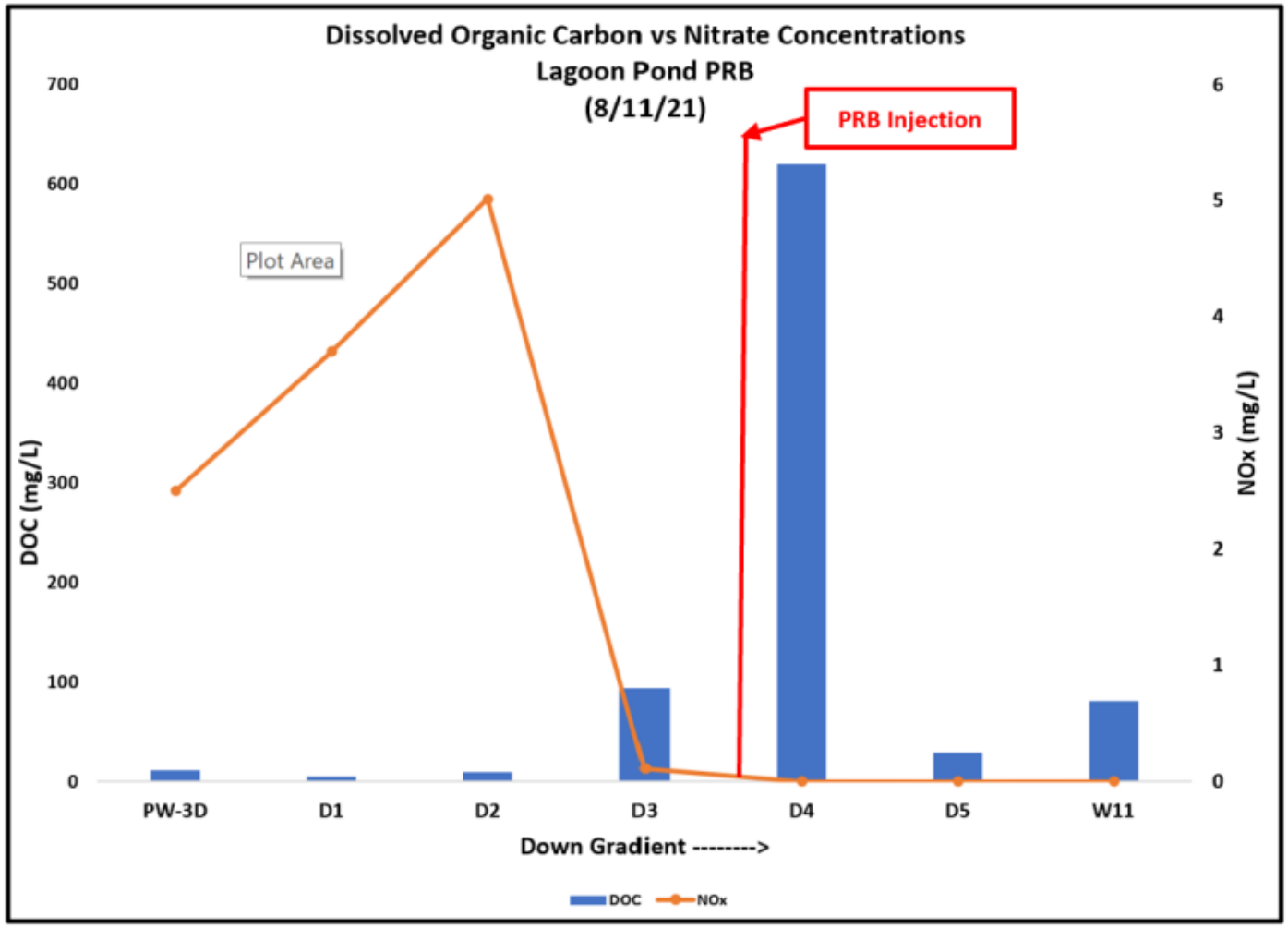
November 2020 Injections

- **150 foot PRB**
- **12 Injection Points**
  - **1 row of points**
  - **10-15 foot spacing**
  - **4 to 22 feet bgs**
  - **Water body 80 feet away**
- **3,432 gallons SRS®-NR (0.102 gal/ft³)**
- **1,600 pounds calcium carbonate (0.049 lb/ft³)**
- **17,155 gallons**

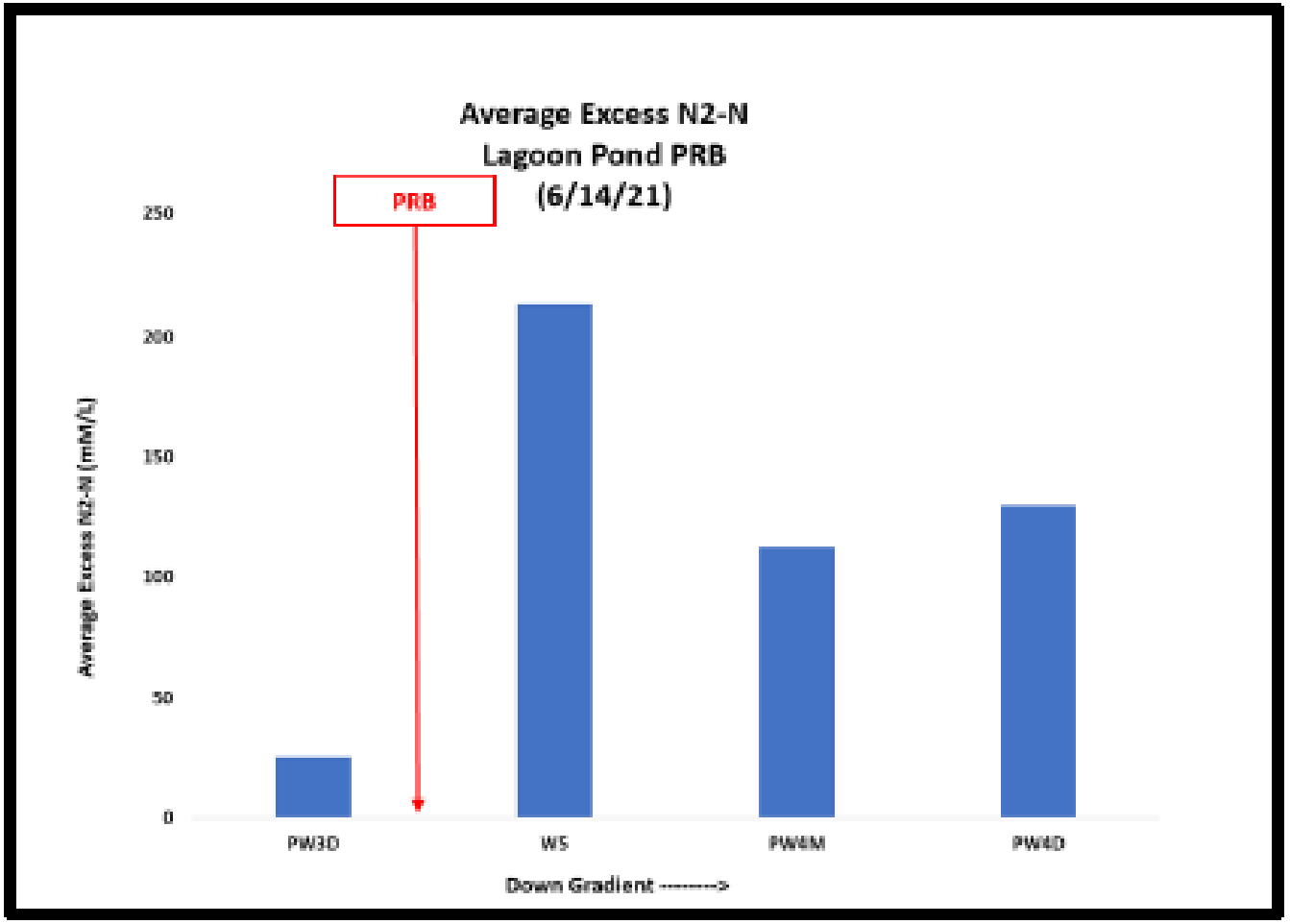
SMAST Martha's Vineyard Lagoon Pond PRB



SMAST Martha's Vineyard Lagoon Pond PRB



SMAST Martha's Vineyard Lagoon Pond PRB



N2/Ar measurements by High Precision Membrane Inlet Mass Spectrometry, where N2 excess was measured using membrane-inlet mass spectrometry (MIMS).

SMAST Martha's Vineyard Conclusions

1. **The PRB was situated as close as 80 feet from the water body.**
2. **The PRB had minimal impact on wells closest to the water body.**
3. **Alkalinity, manganese, iron, and arsenic increased up to 35 feet downgradient. Little impact in wells 80 feet away near Lagoon Pond.**
4. **The PRB was estimated to remove 91% of the nitrogen or about 1.3 pounds per foot of PRB per year.**

Conclusions

1. SRS®-NR loadings 0.040 to 0.102 gallons per cubic foot of aquifer with an average of 0.072 gal/ft^3.
2. Understanding the groundwater flow rate and direction is important for a proper design.
3. No impact on surface water bodies were noted with the PRBs installed as close as 80 and 130 feet upgradient of the water bodies.
4. The PRBs were effective in promoting denitrification for up to 4.7 years.
5. Buffer additions of 0.0053 to 0.0492 pounds per cubic foot of the PRB increased the groundwater pH by 0.9 to 1.8 SU for up to 4.7 years.
6. Iron, manganese, and carbon dioxide reductions to ferrous iron, manganese(II), and methane exert significant electron donor demands.

WHOI PRB Design Manual

SNEP Funded

PERMEABLE REACTIVE BARRIERS FOR REMOVAL OF NITRATE FROM GROUNDWATER THROUGH INJECTION OF EMULSIFIED VEGETABLE OIL

Engineering Design Manual

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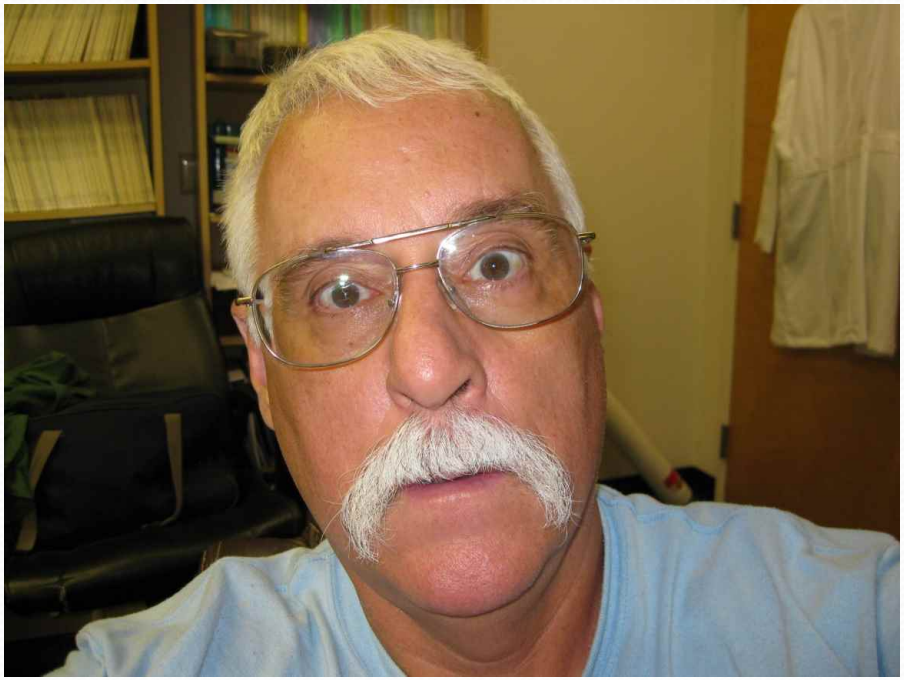
Questions?



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