Monitoring Shallow Wastewater Injection in Marathon

Rachel Housego, Miquela Ingalls, Lee Kump


GULF OF MEXICO
Marathon
The Great Florida Reef
ATLANTIC OCEAN
4 km
N
Image: NASA

- Marathon is part of the Florida Keys National Marine Sanctuary (FKNMS)
- Adjacent reefs are sensitive to eutrophication

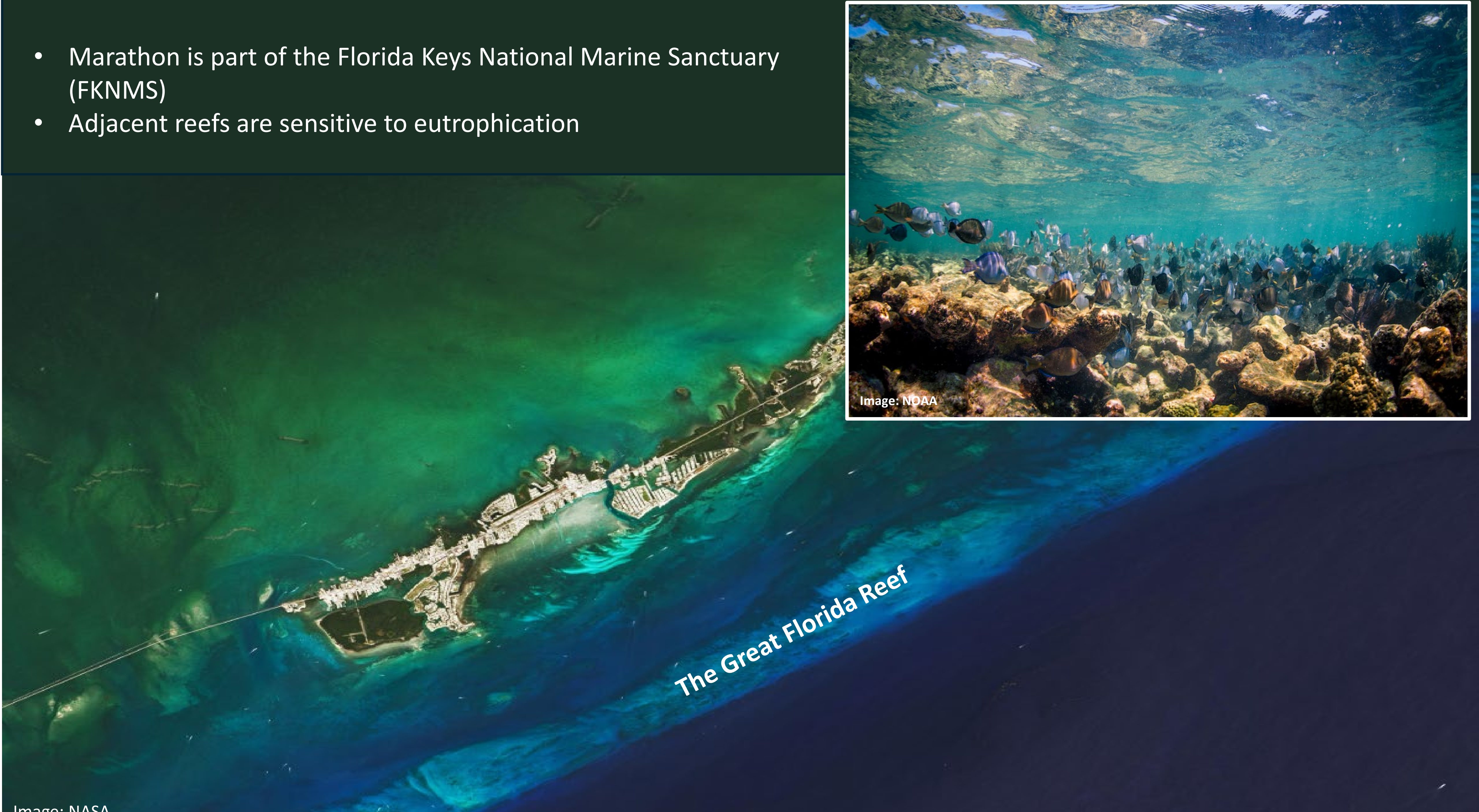


Image: NASA

- Marathon’s aquifer is key largo limestone (max. depth ~ 100 m)

Slower Flows through the karst matrix

Faster flows through interconnected pores

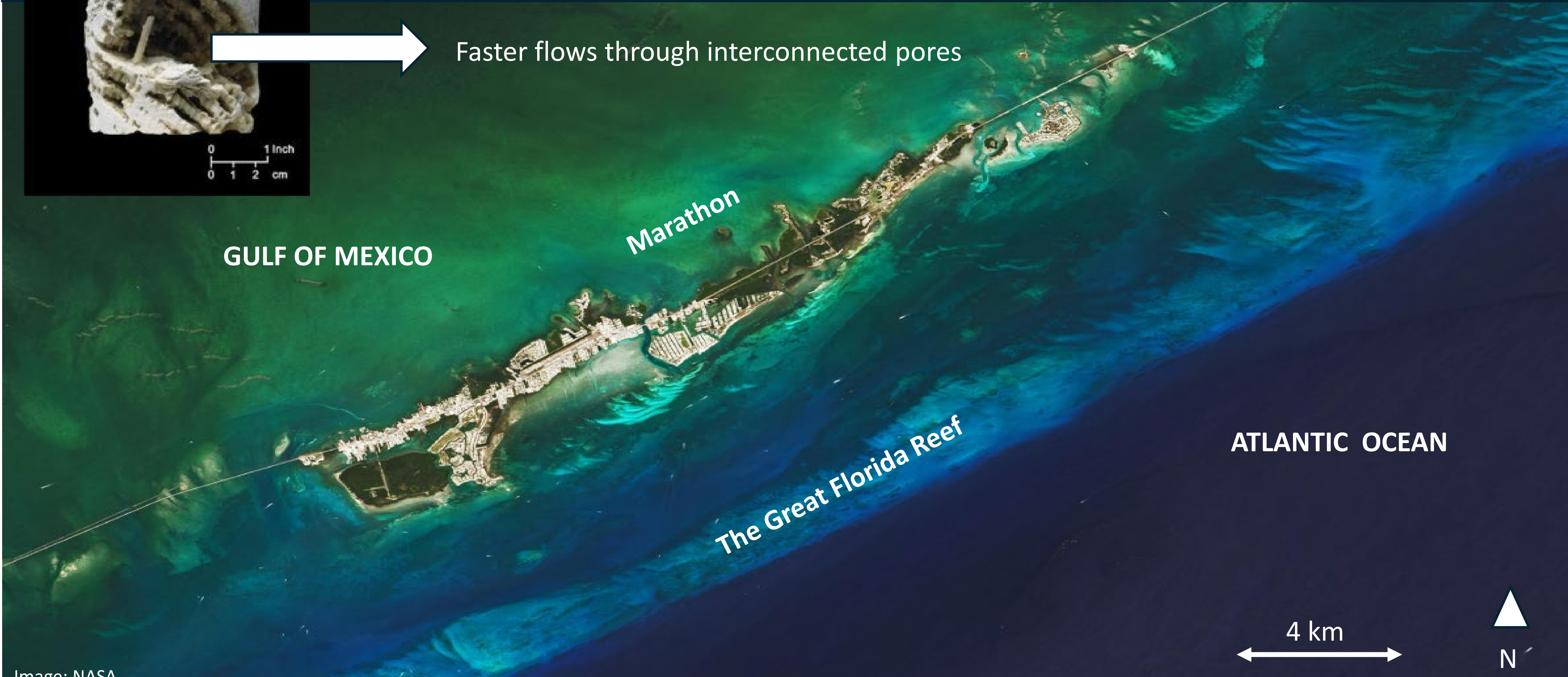
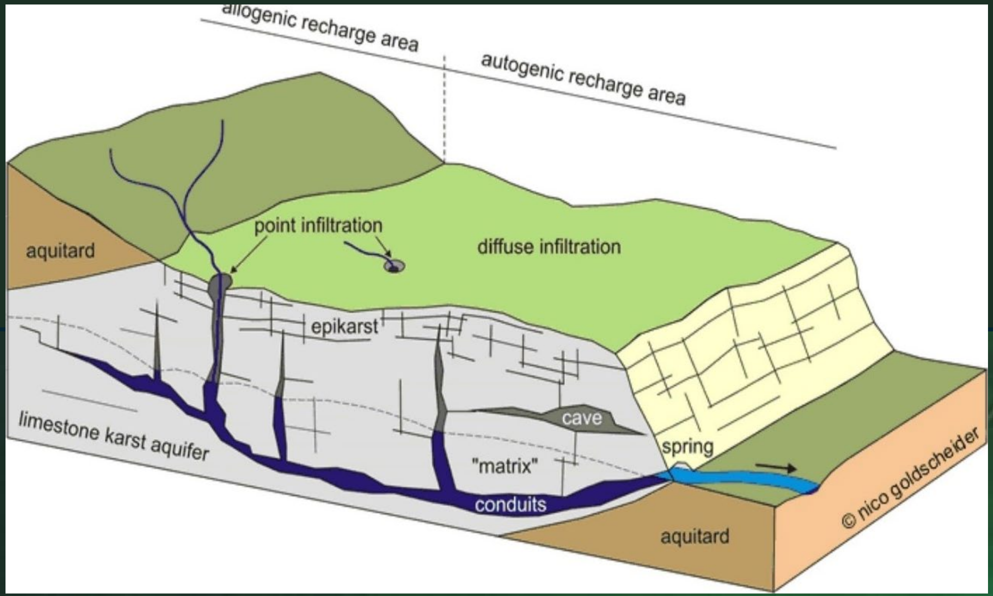


Image: NASA


allogenic recharge area
autogenic recharge area
aquitard
point infiltration
diffuse infiltration
epikarst
cave
limestone karst aquifer
"matrix"
spring
conduits
aquitard
© nico goldscheider

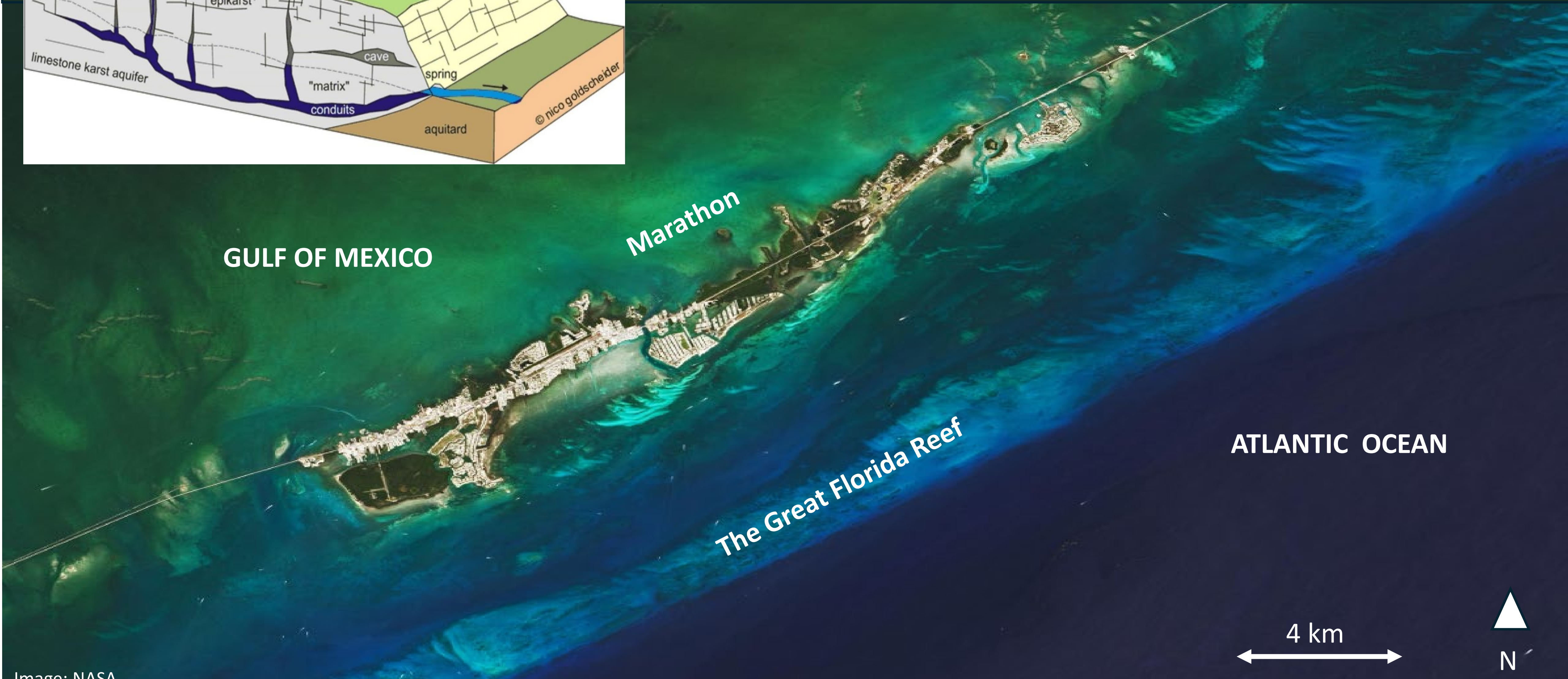
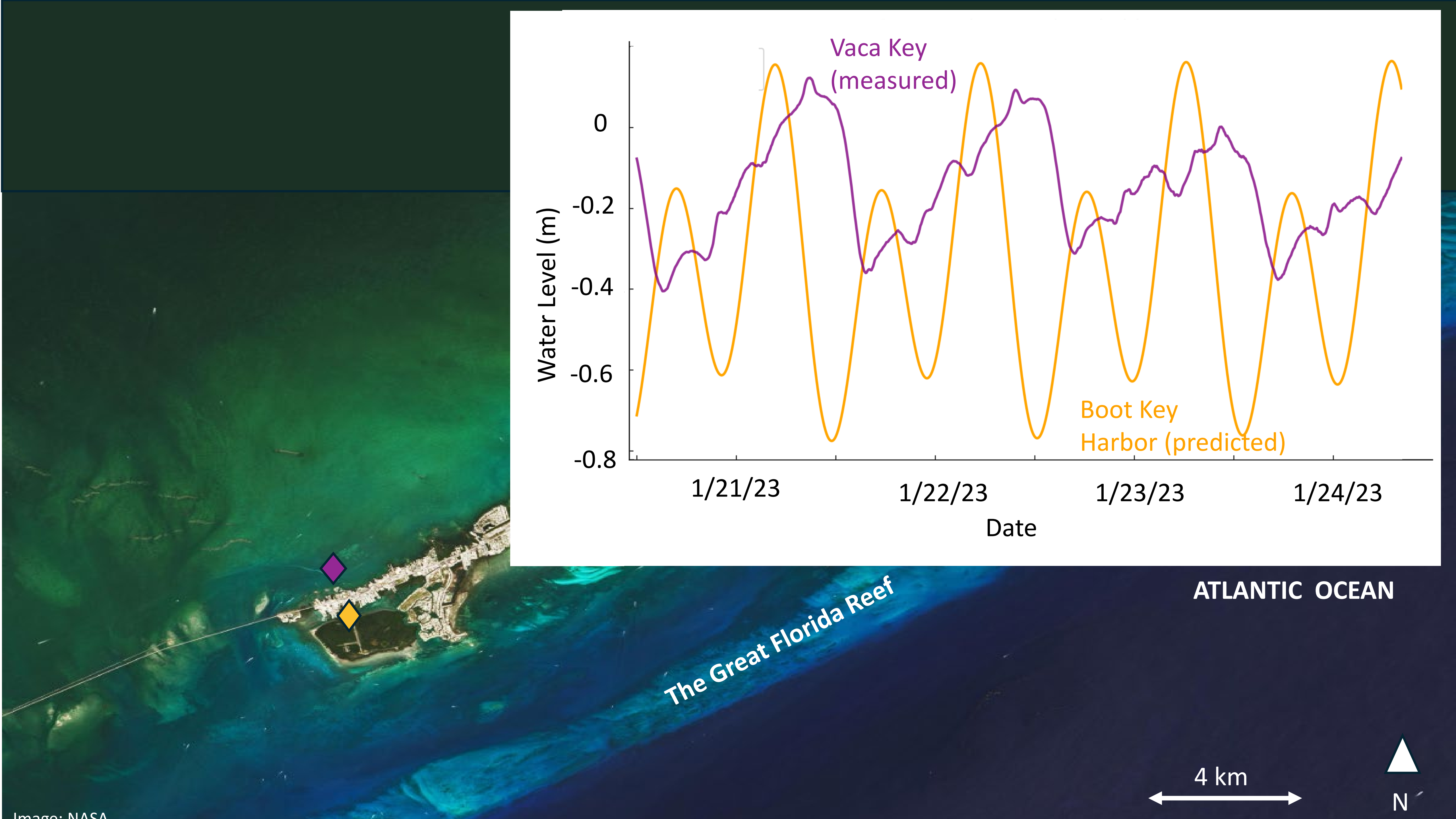
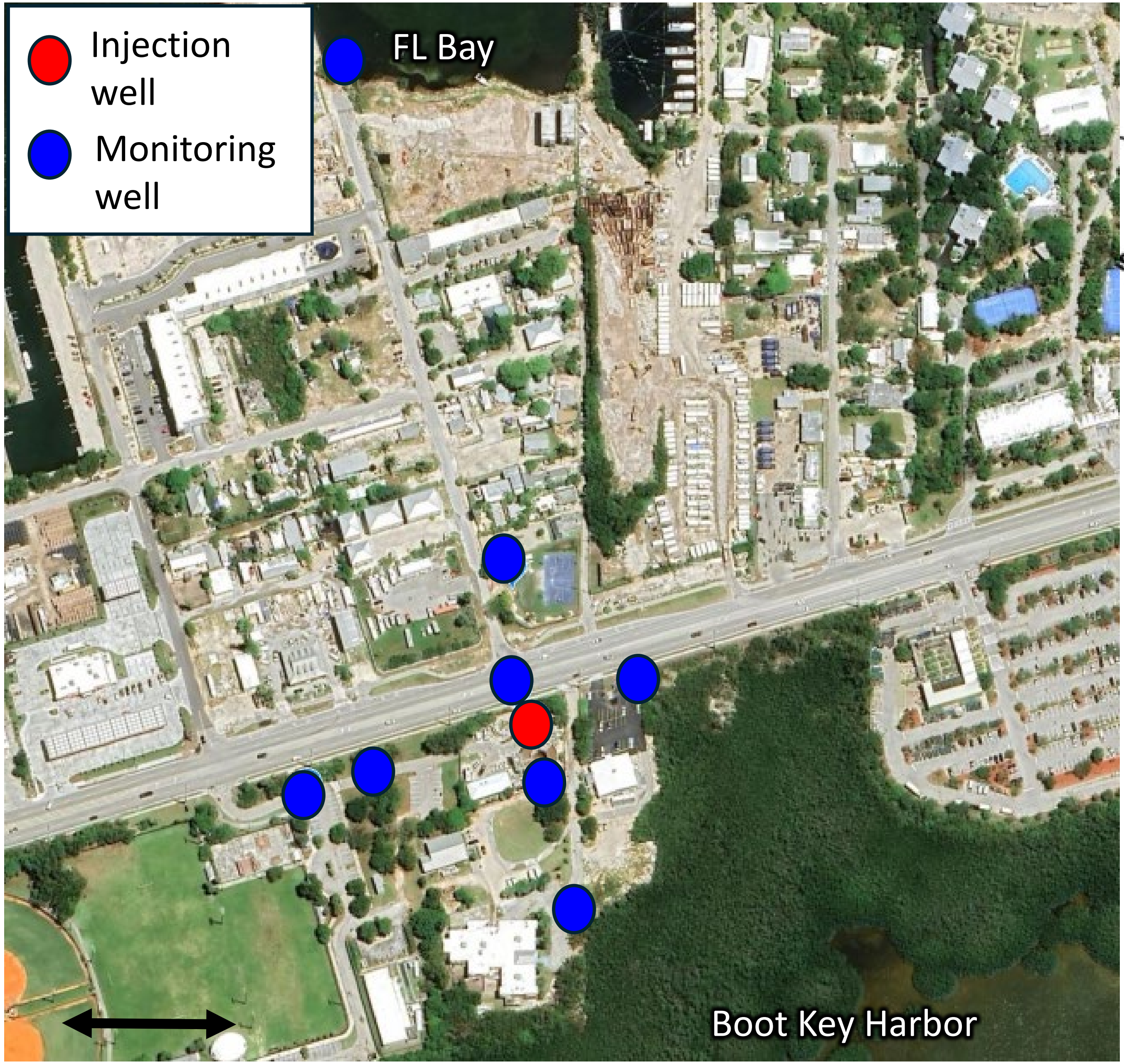
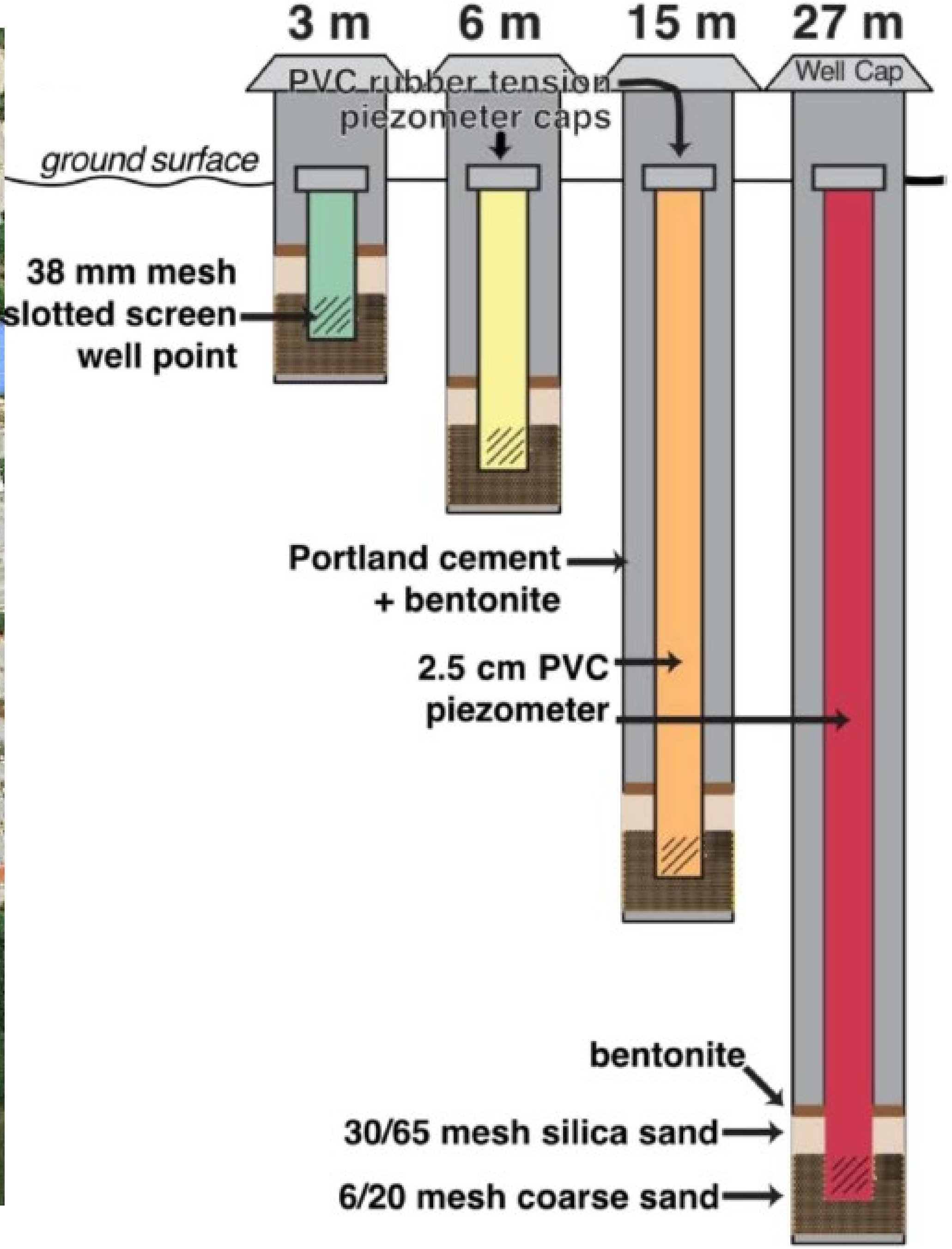

GULF OF MEXICO
Marathon
The Great Florida Reef
ATLANTIC OCEAN
4 km
N

Image: NASA

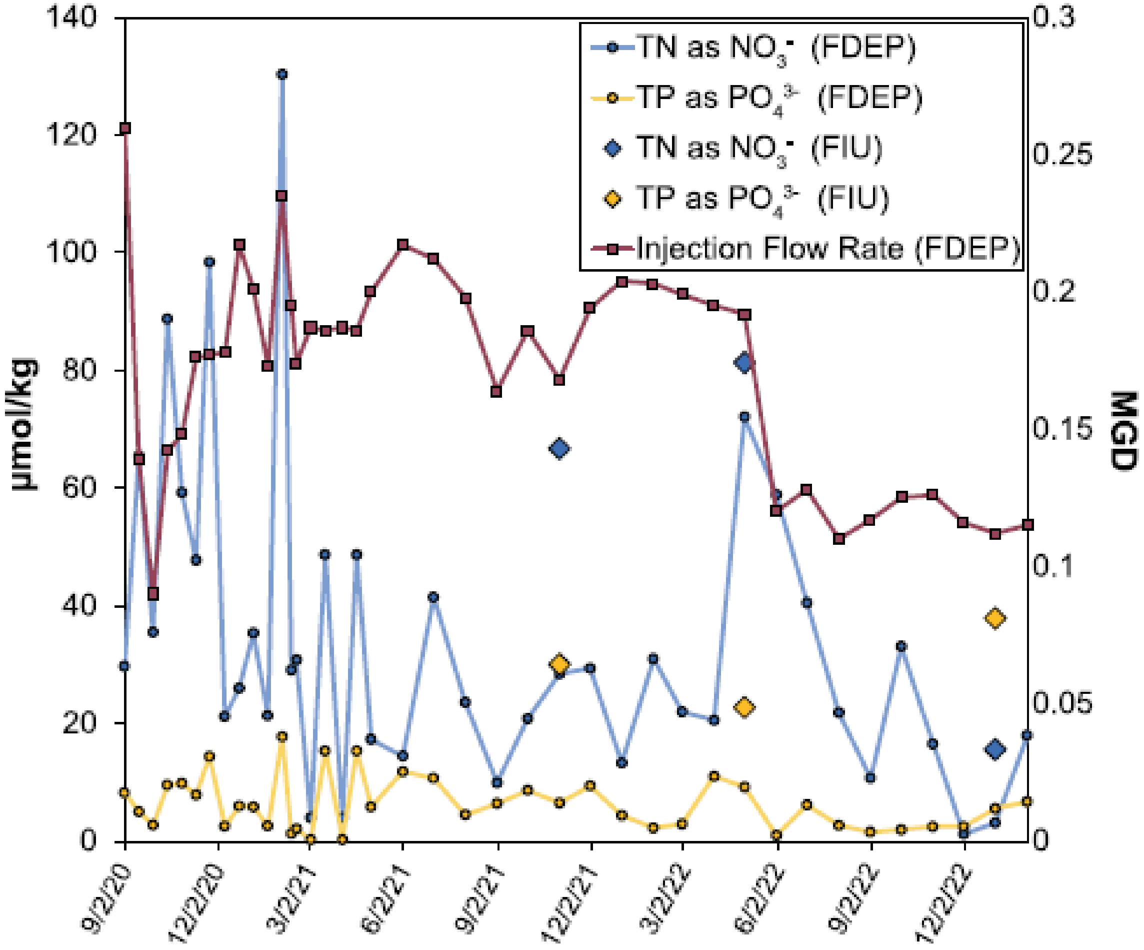

Vaca Key
(measured)
Water Level (m)
0
-0.2
-0.4
-0.6
-0.8
1/21/23
1/22/23
1/23/23
1/24/23
Date
Boot Key
Harbor (predicted)
ATLANTIC OCEAN
The Great Florida Reef
4 km
N
Image: NASA


Injection well
Monitoring well
FL Bay
Boot Key Harbor
N


Injection well
Monitoring well
FL Bay
Boot Key Harbor


3 m
6 m
15 m
27 m
Well Cap
PVC rubber tension piezometer caps
ground surface
38 mm mesh slotted screen well point
Portland cement + bentonite
2.5 cm PVC piezometer
bentonite
30/65 mesh silica sand
6/20 mesh coarse sand

- City of Marathon injects ~ 642,000 to 720,000 m^3/day at depths of 18-27 m below NAVD88
- Treated effluent ~2-3 PSU, aquifer 35 PSU at injection depth
- Effluent contains significant concentrations of both nitrogen and phosphorous

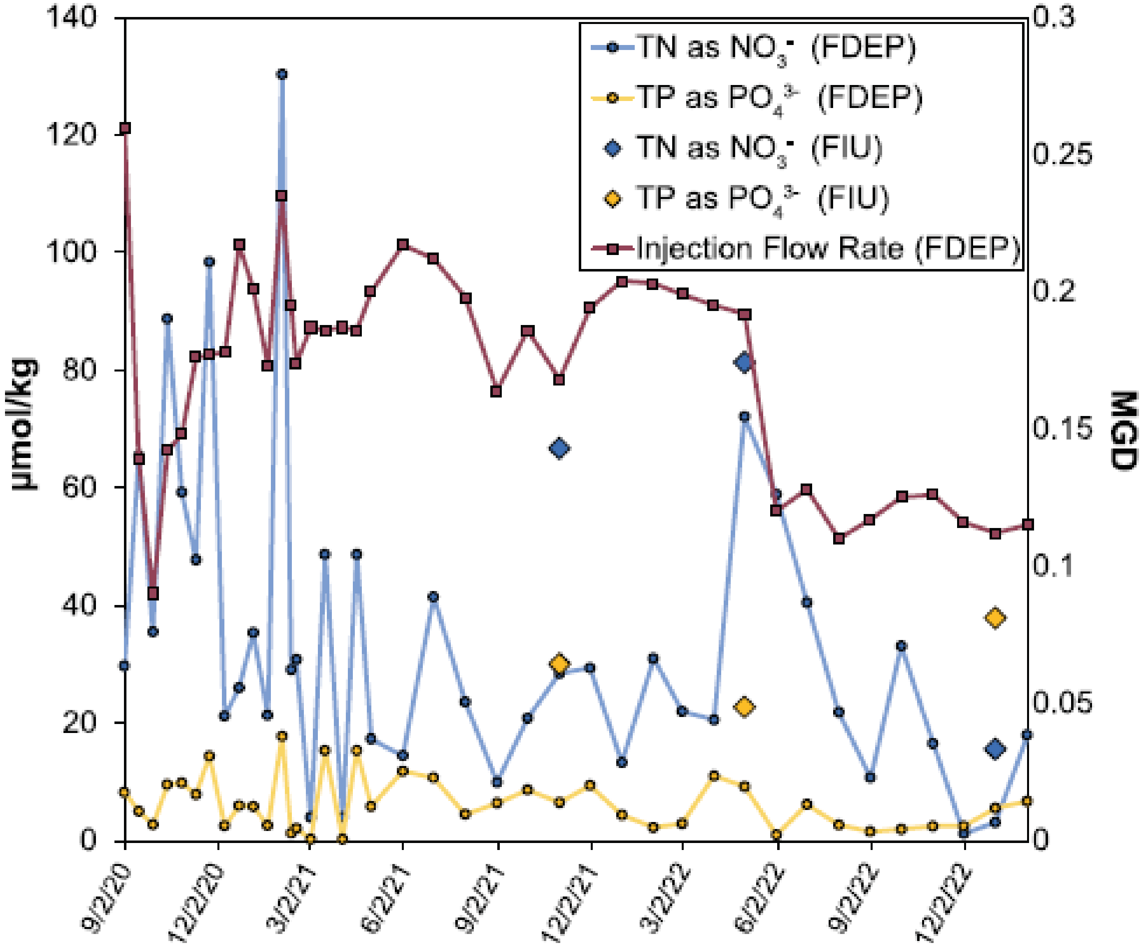


Where is the wastewater going?

How is it being transformed along the flow path?

Physical Hydrology

Geochemistry



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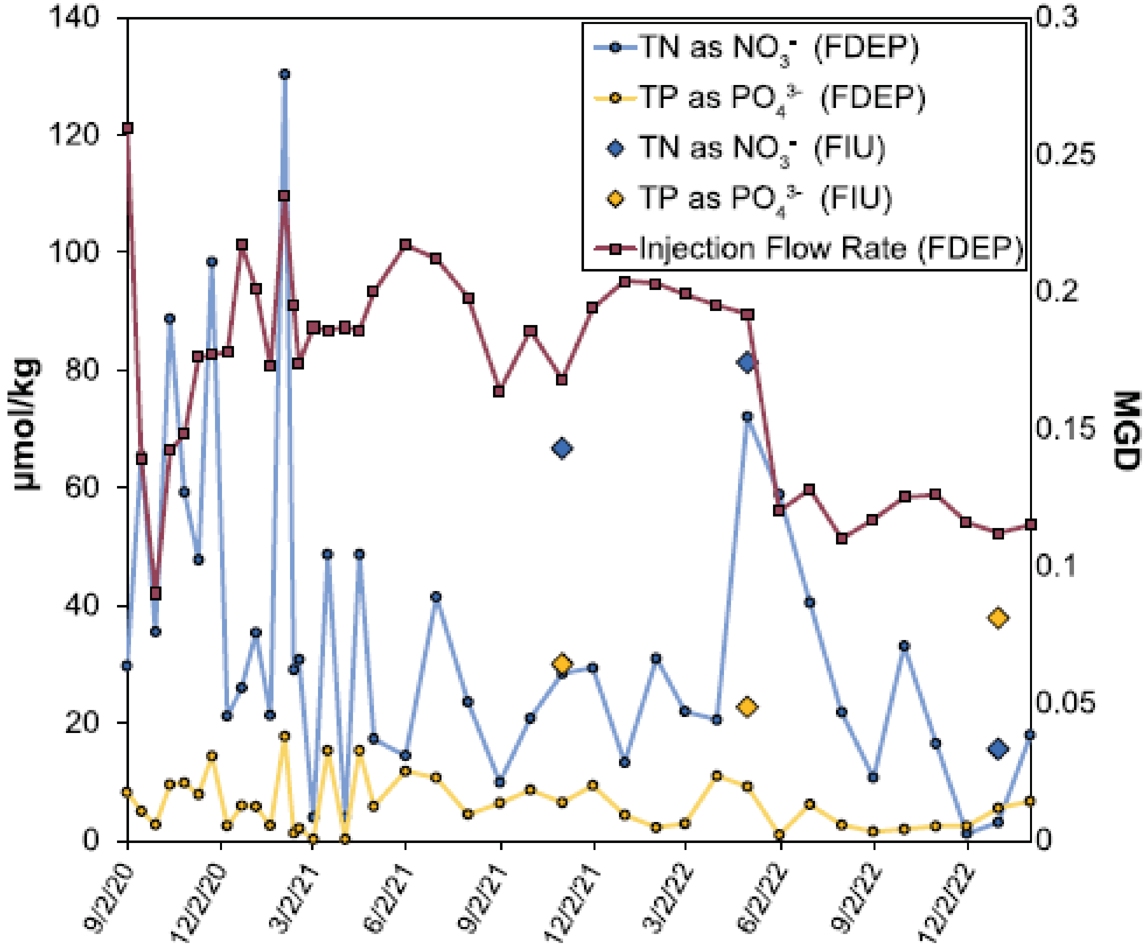
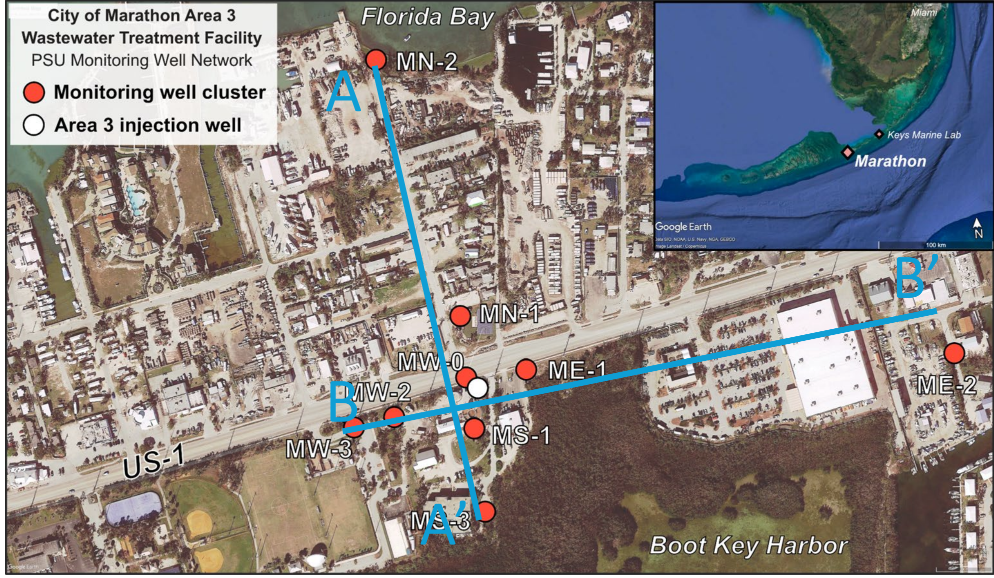
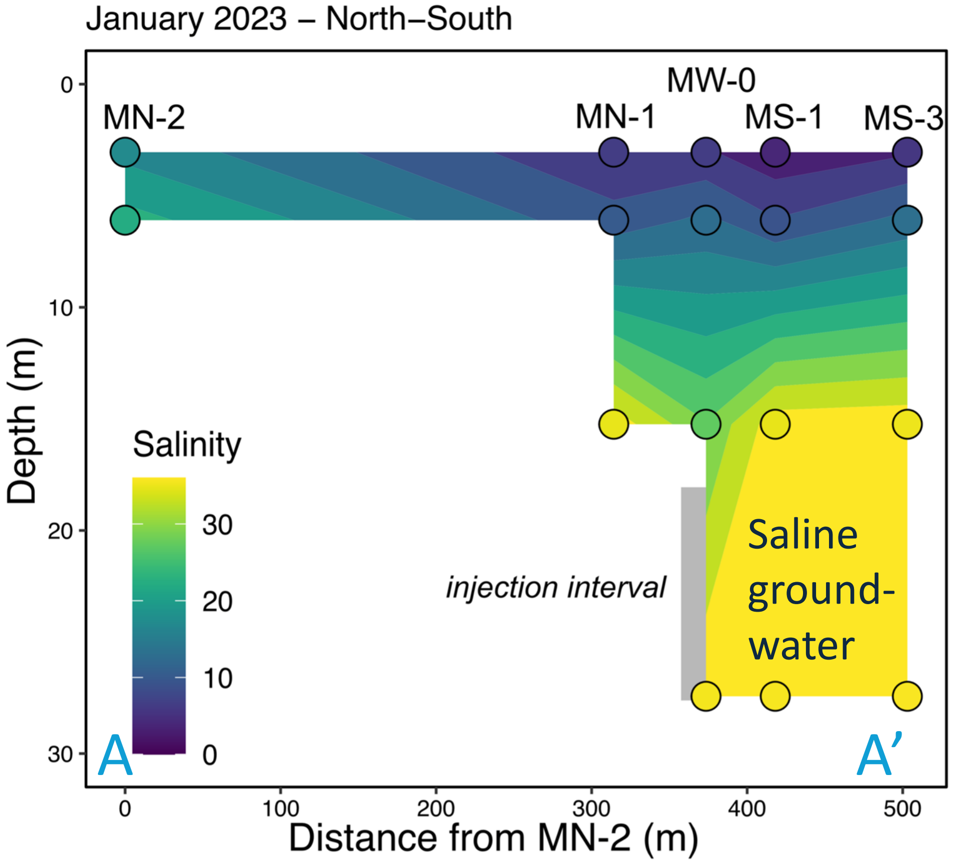
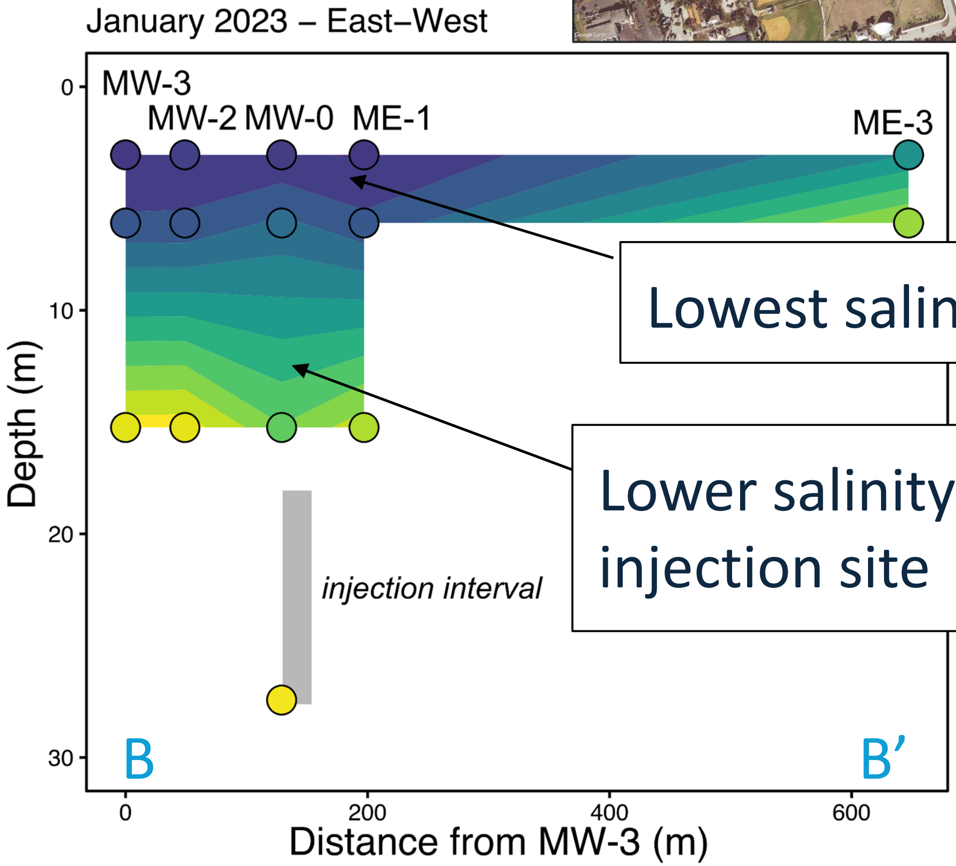


Characterizing plume geometry: salinity

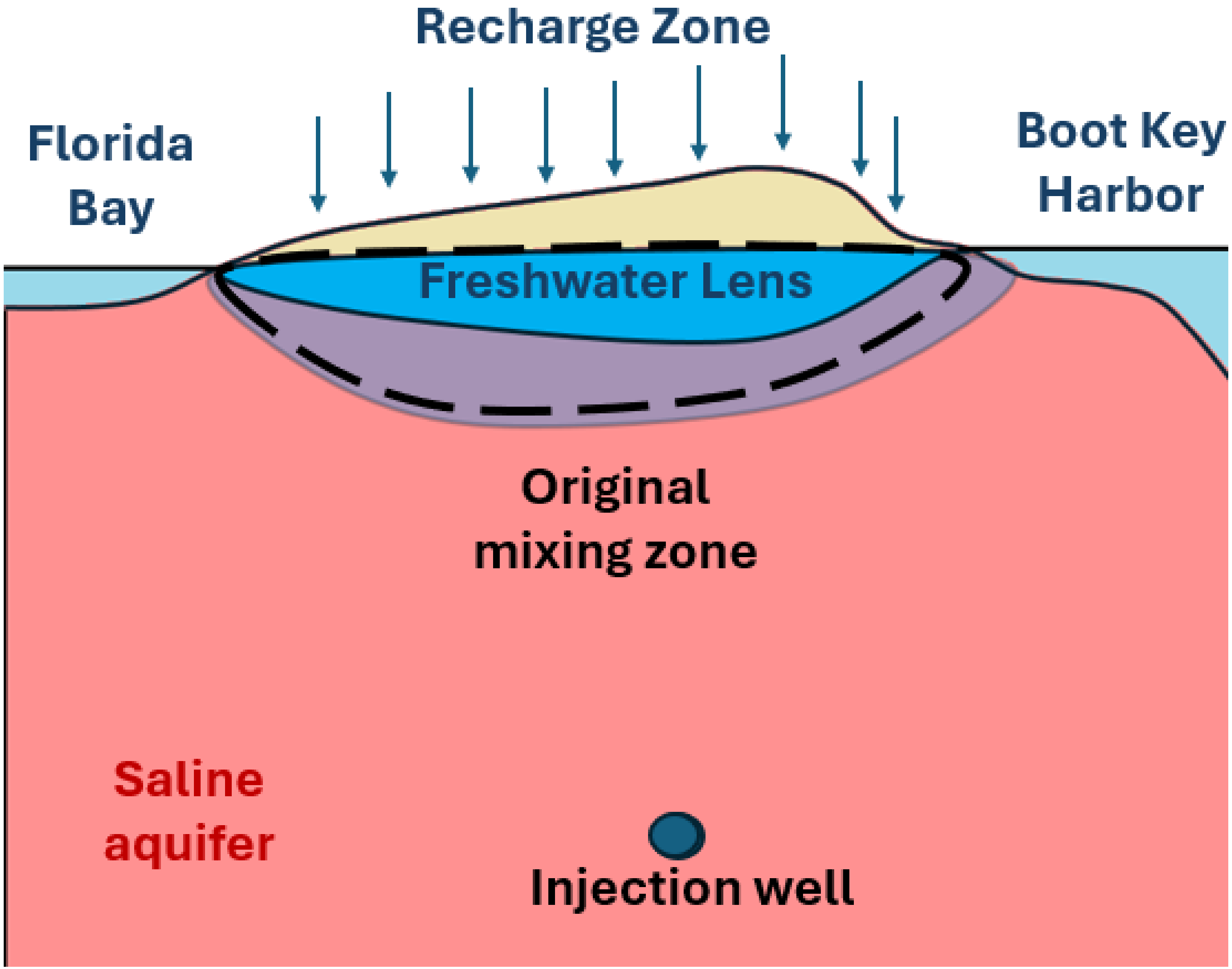




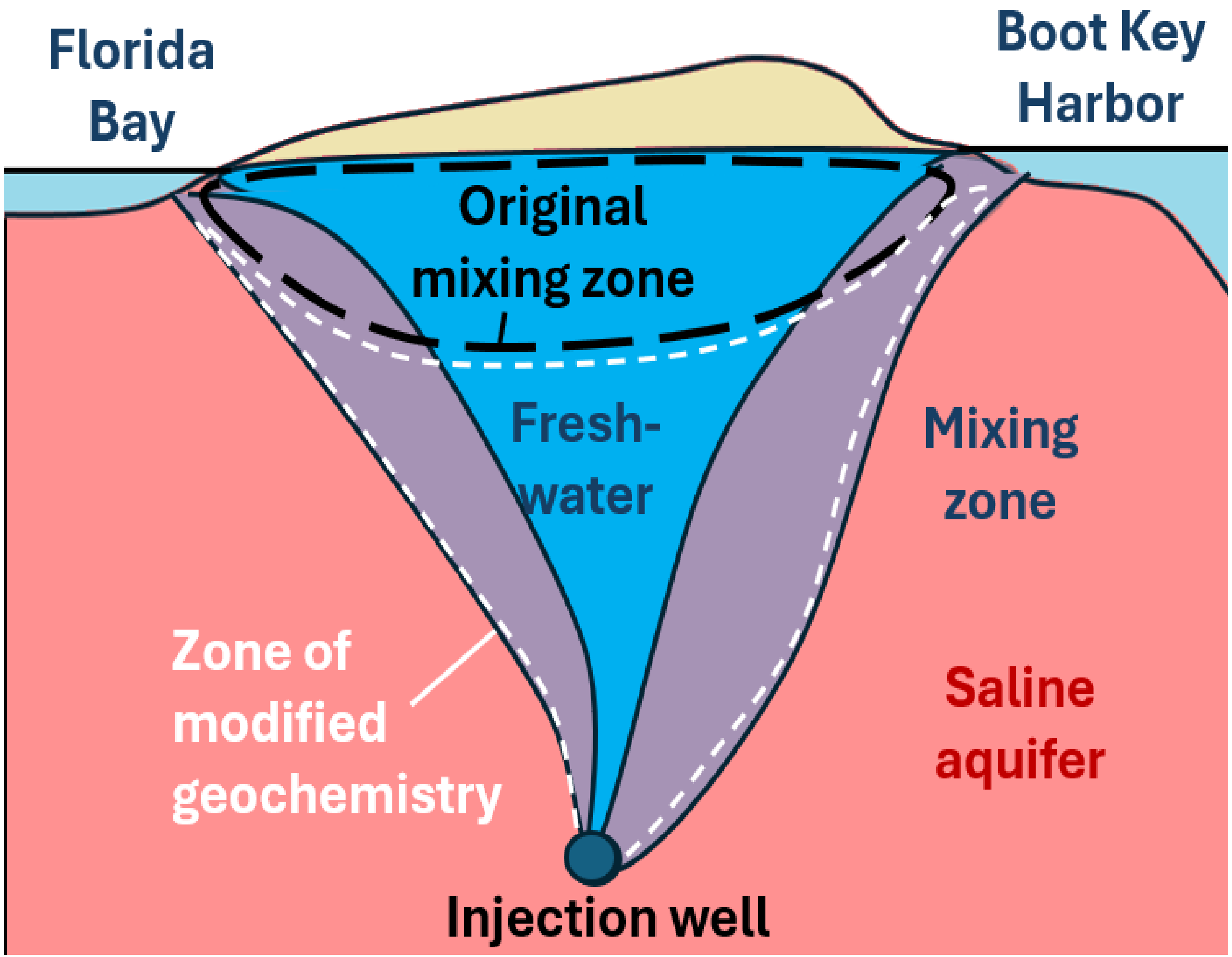


Lowest salinity at the surface

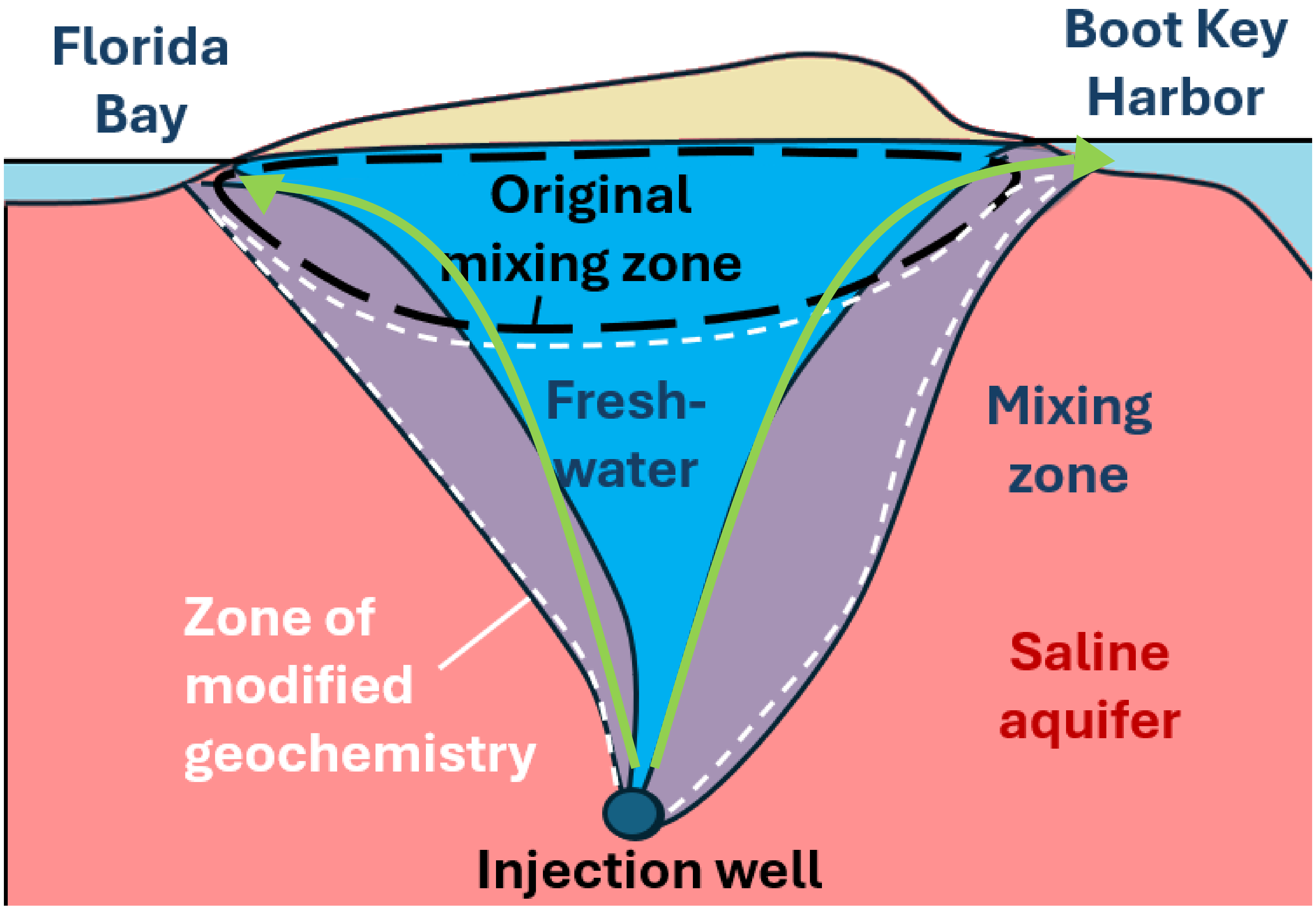
Lower salinity plume at injection site

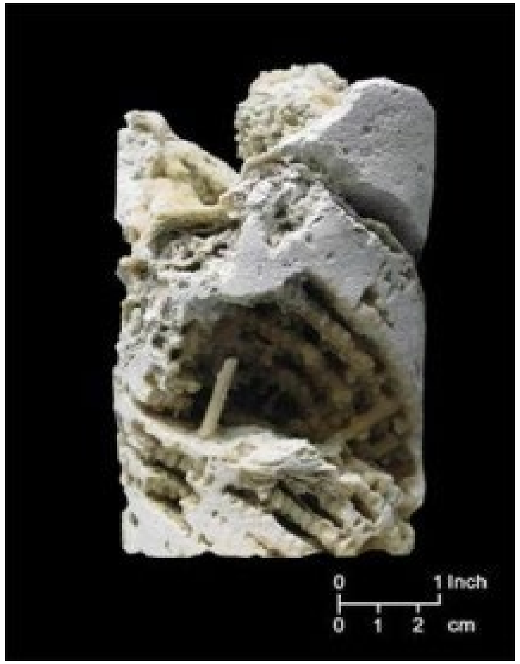


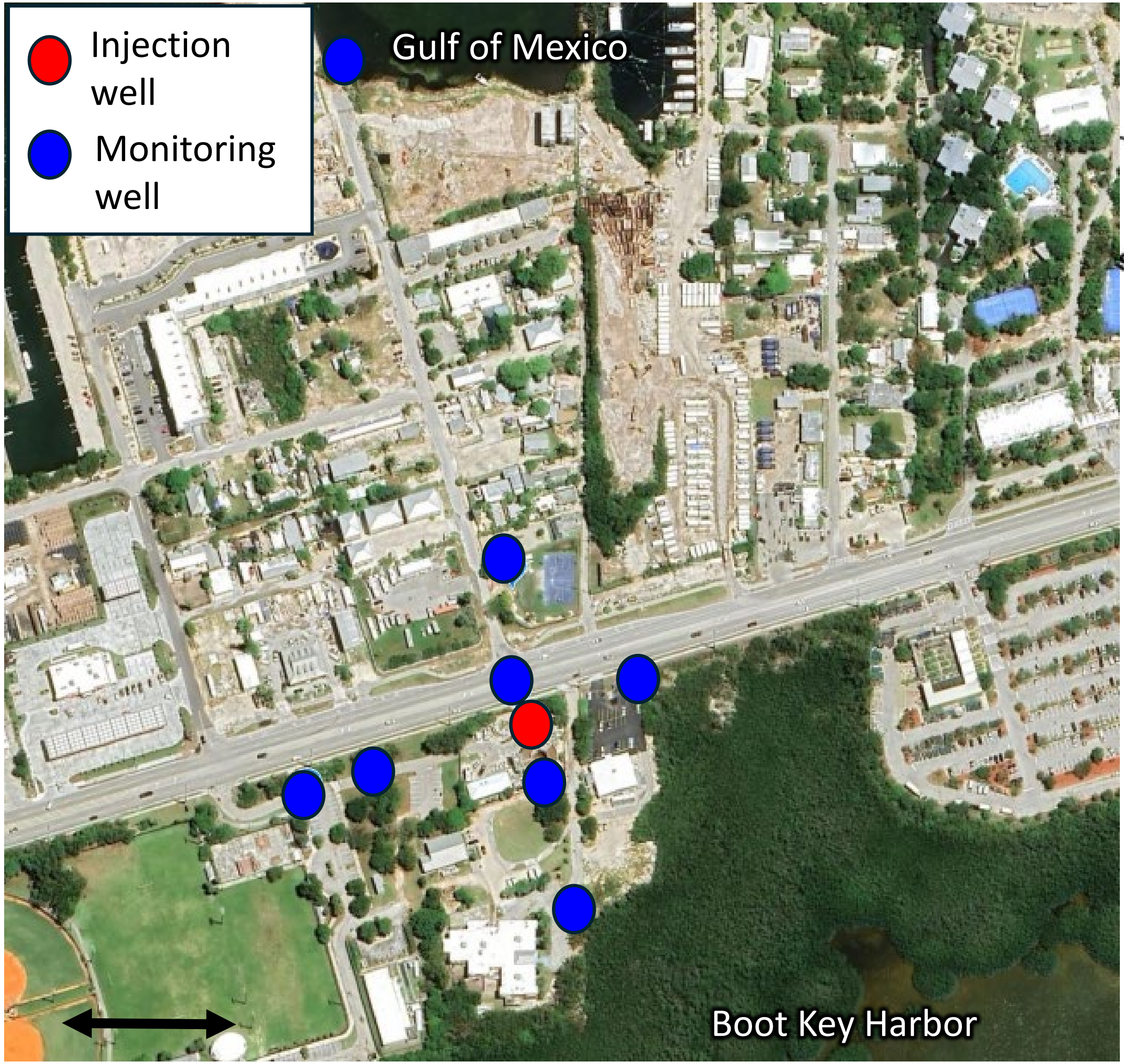
Recharge Zone
Florida Bay
Boot Key Harbor
Freshwater Lens
Original mixing zone
Saline aquifer
Injection well


Florida Bay
Boot Key Harbor
Original mixing zone
Fresh-water
Mixing zone
Zone of modified geochemistry
Saline aquifer
Injection well

What are the flow paths and travel times?



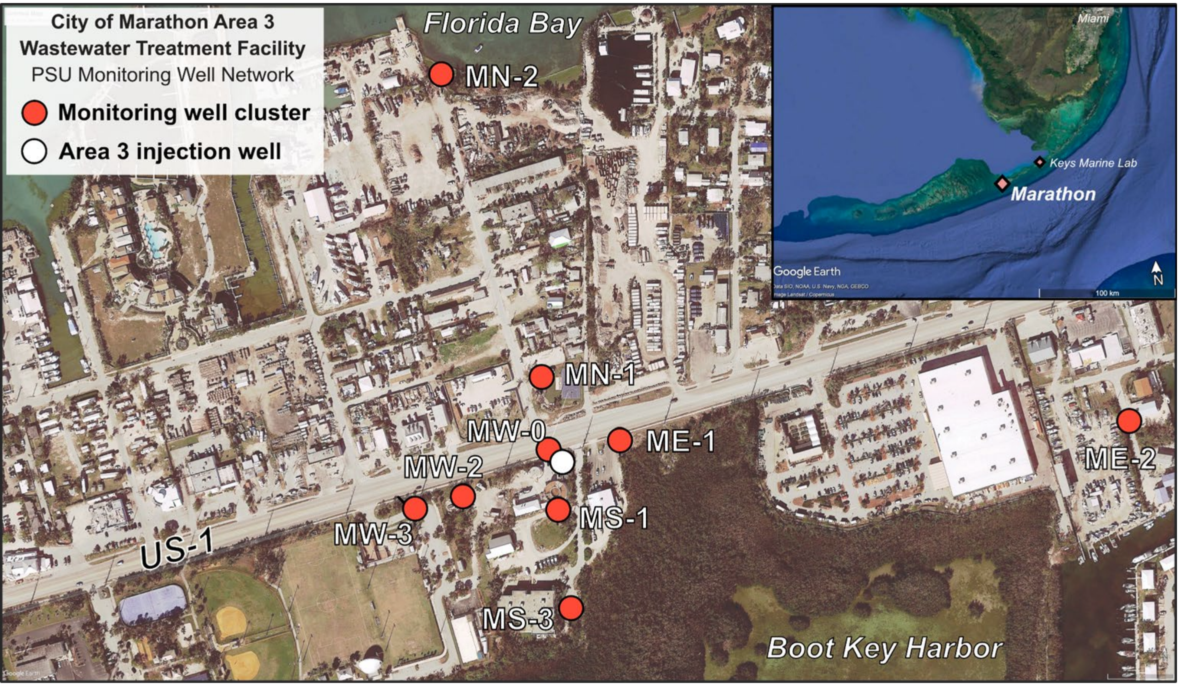


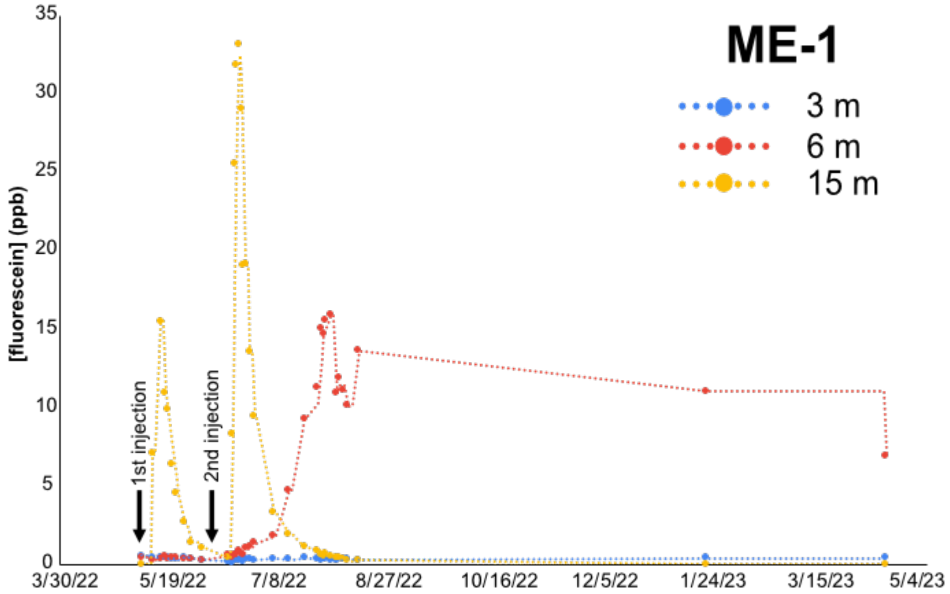

Injection well
Monitoring well
Gulf of Mexico
Boot Key Harbor

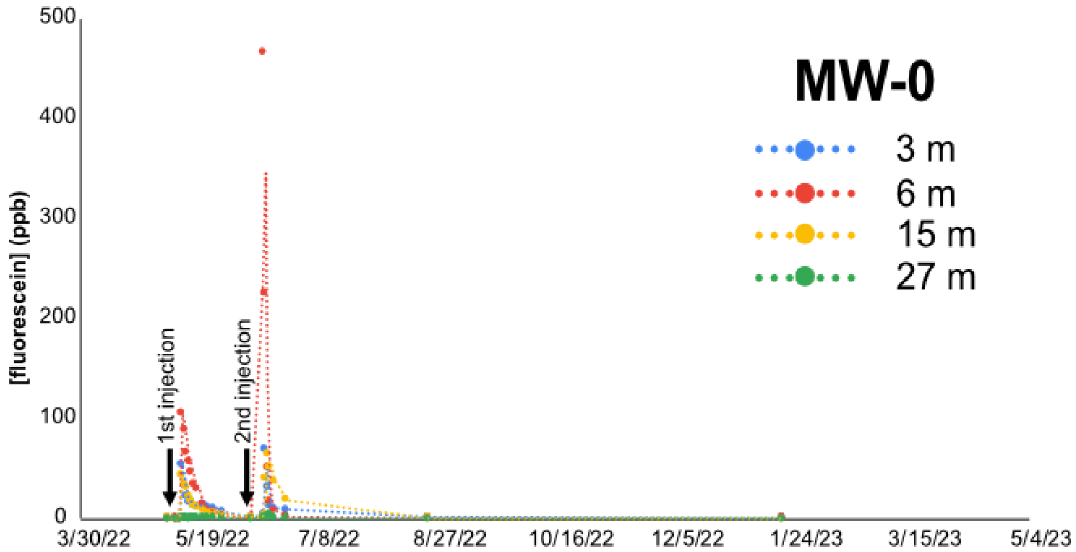

Miquela Ingalls
Kate Meyers

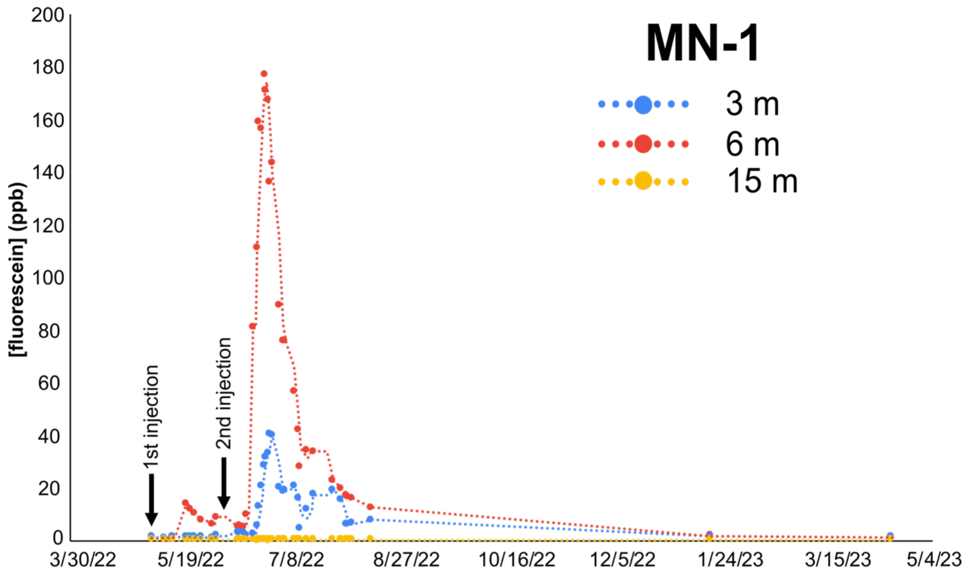
Dye tracer study

Dye introduced to Area 3 injection well May and June 2022









Dye tracer study

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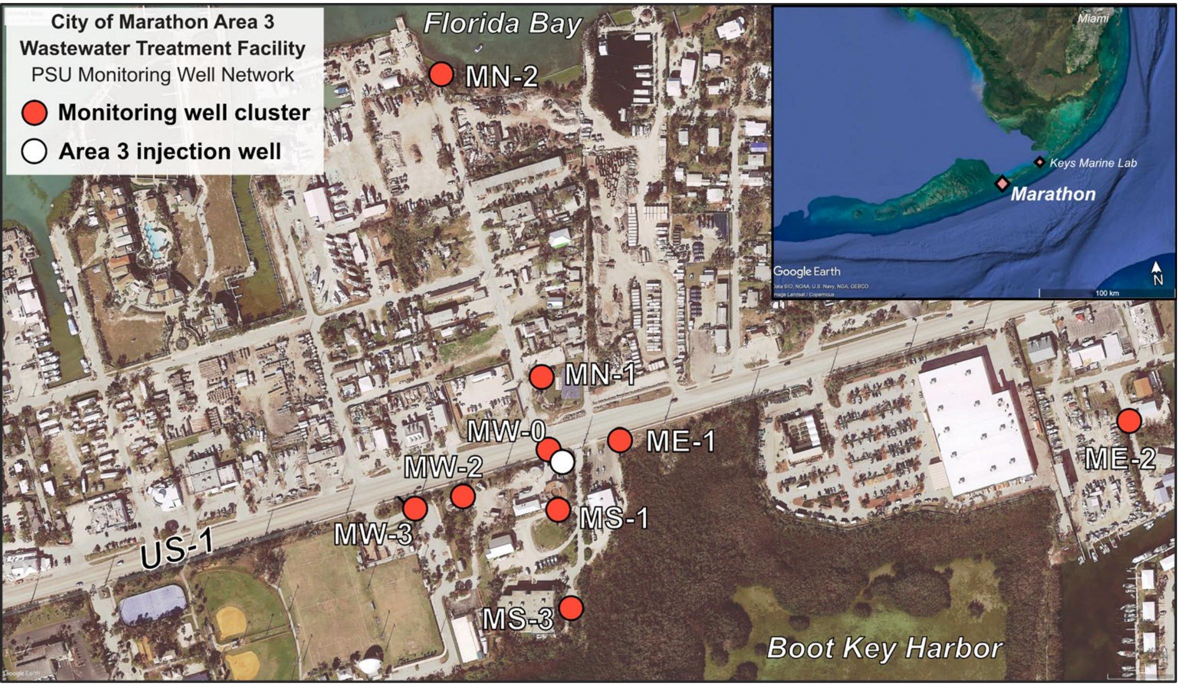
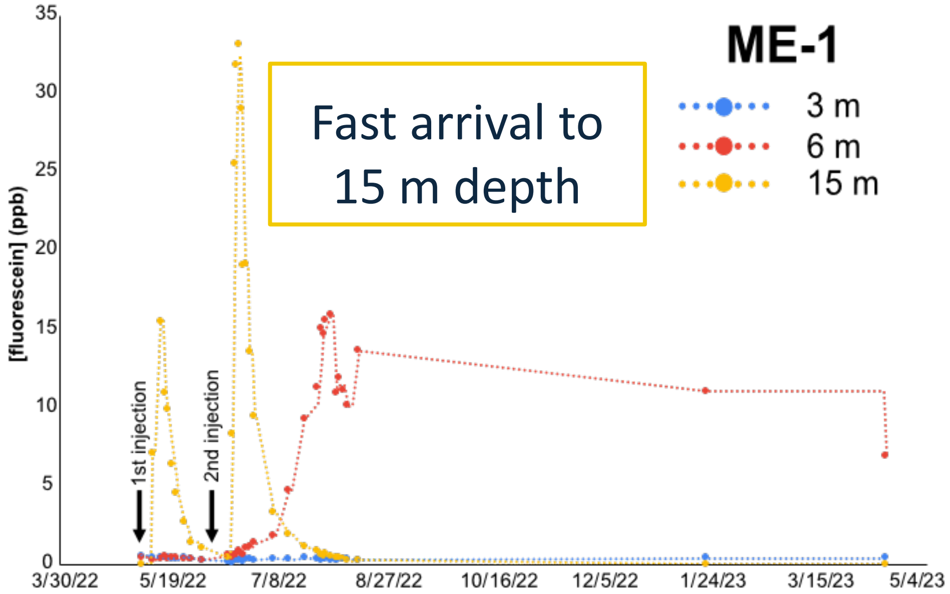
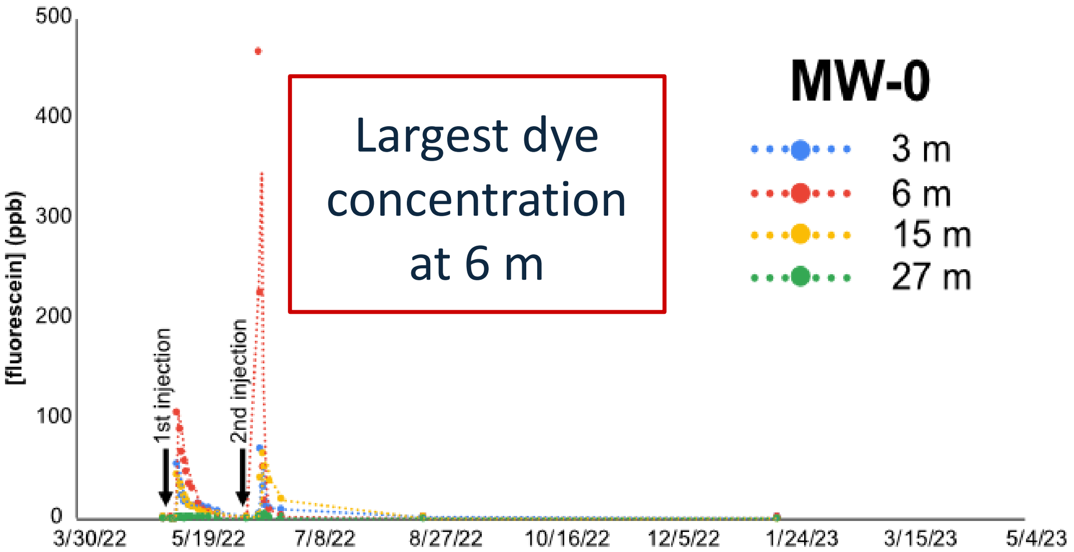
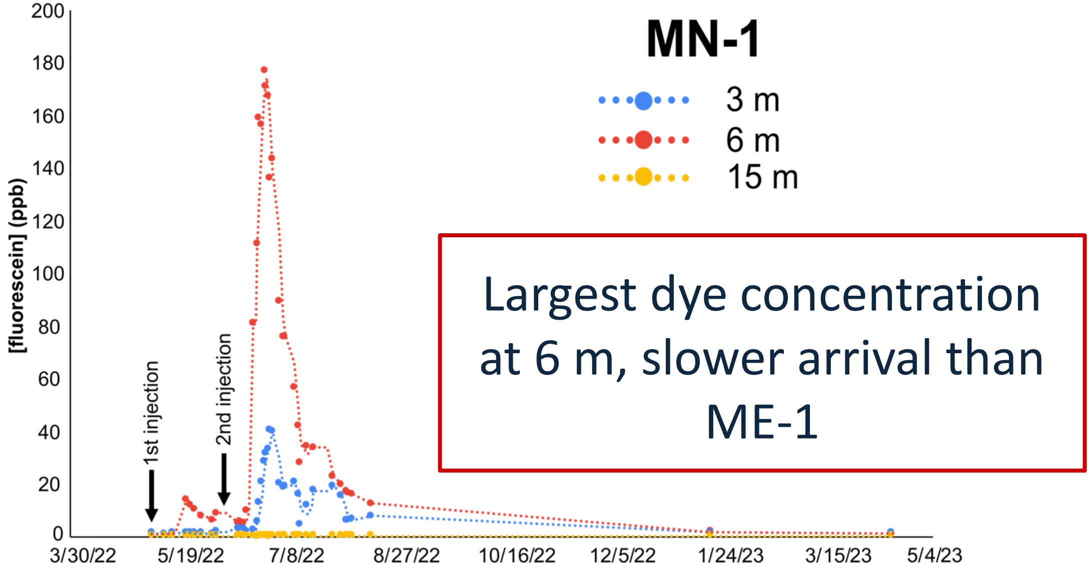
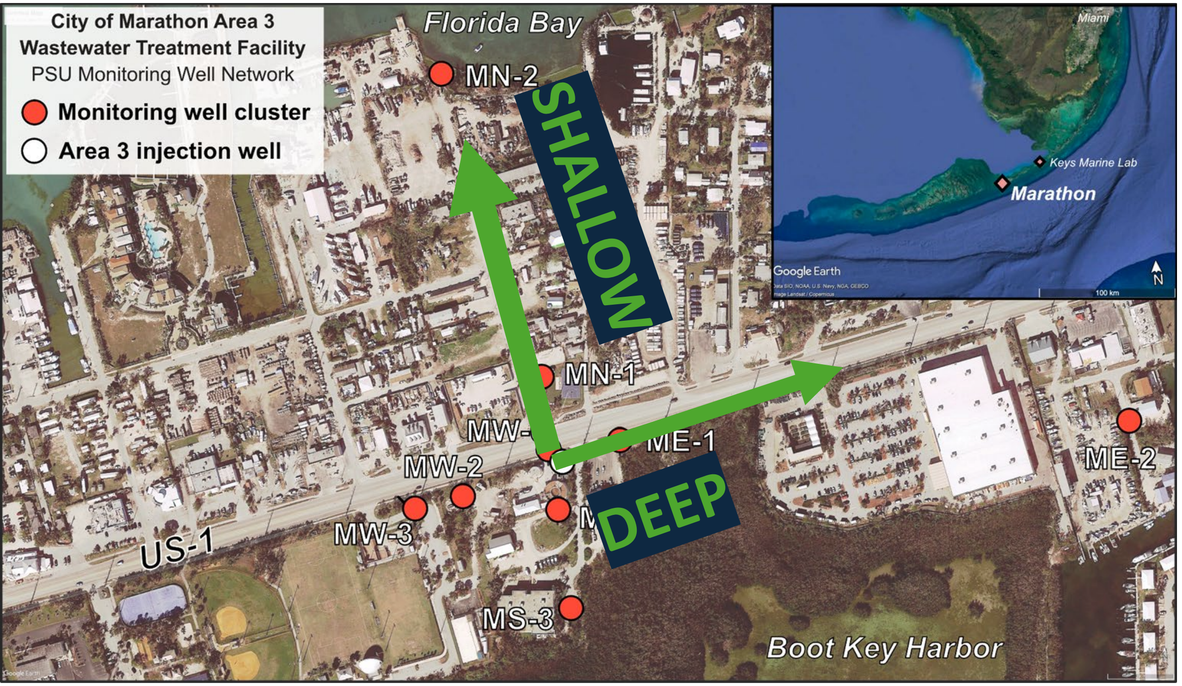


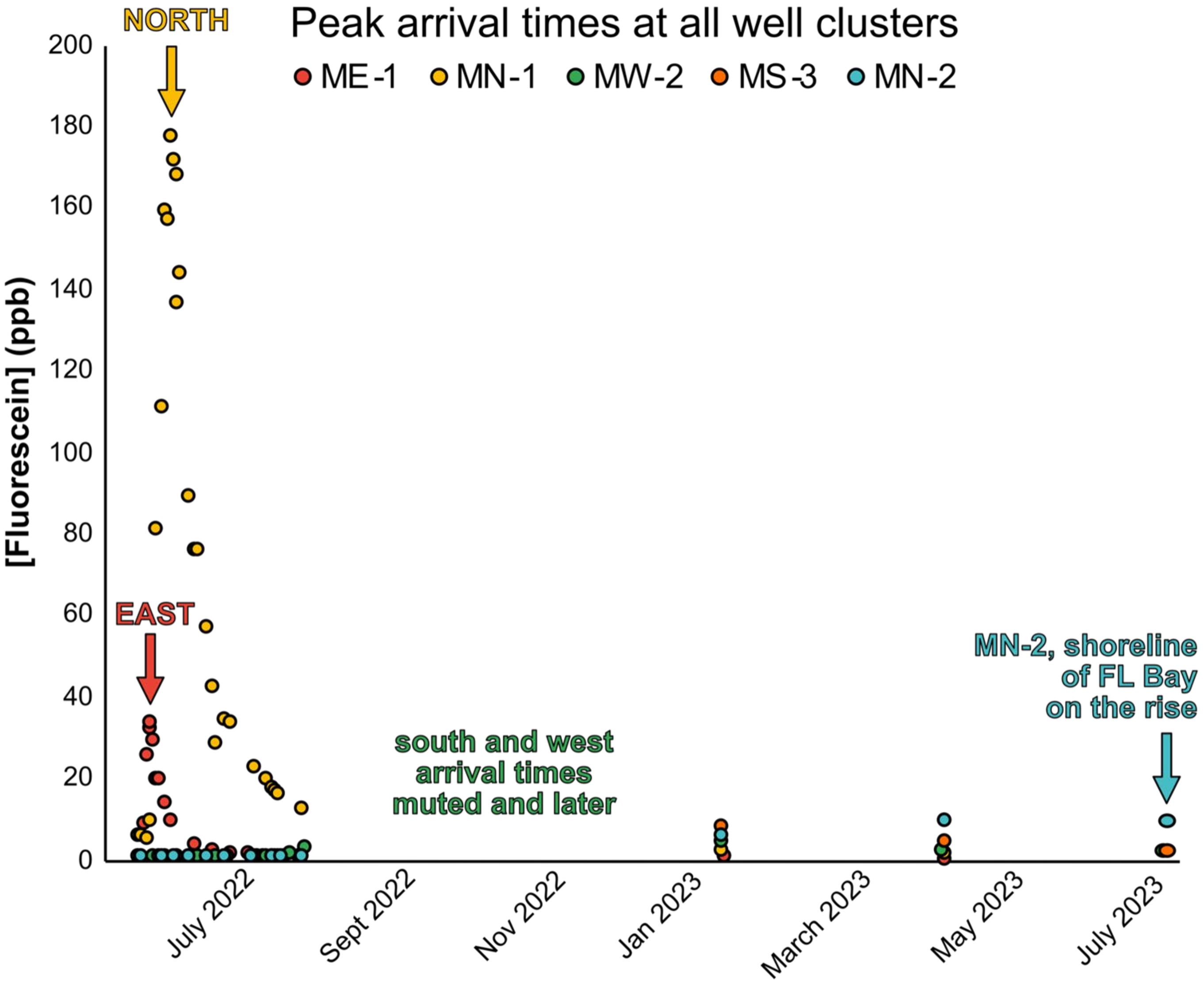




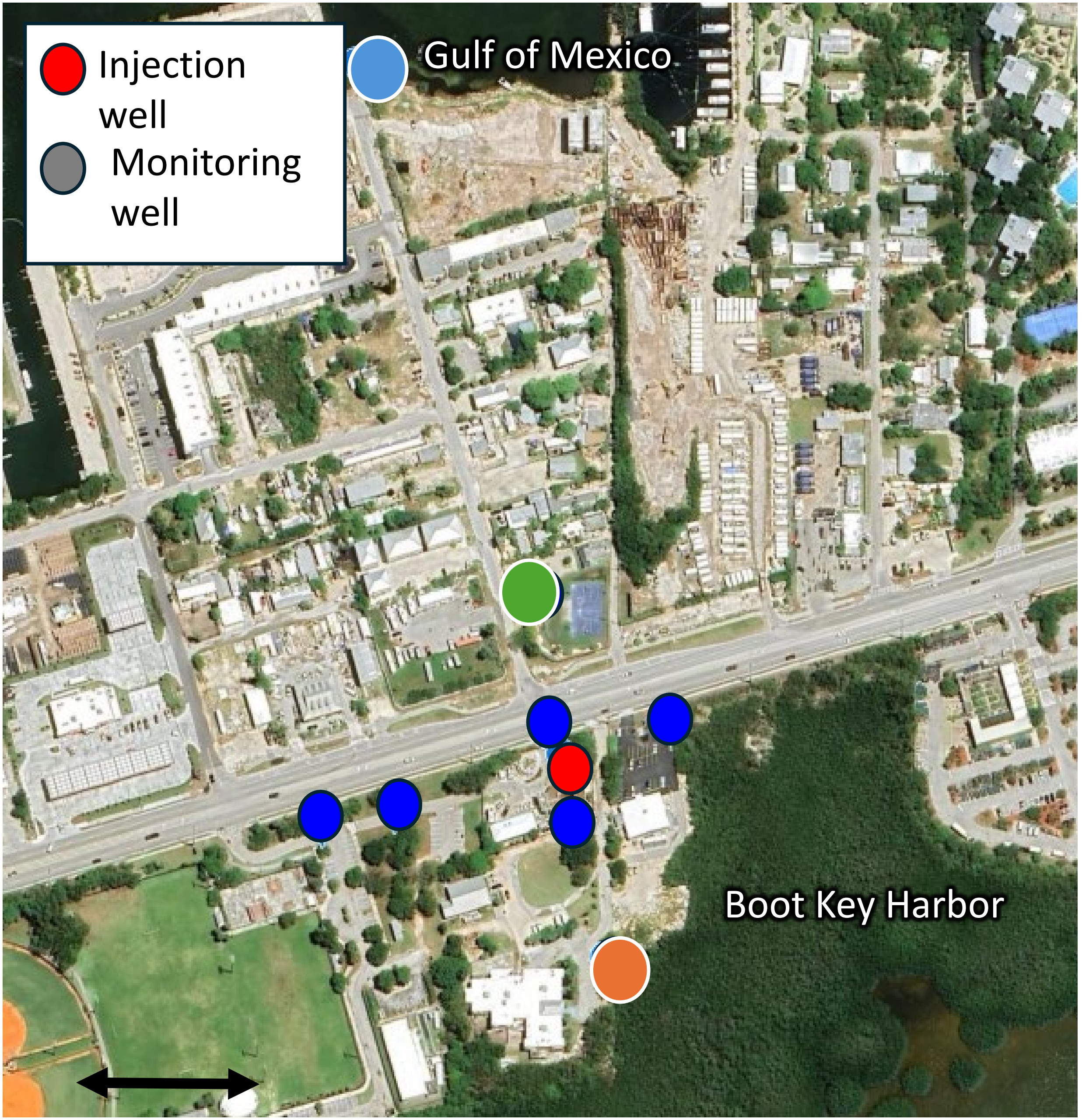


Dye tracer study confirms dominant flow paths to the north and east

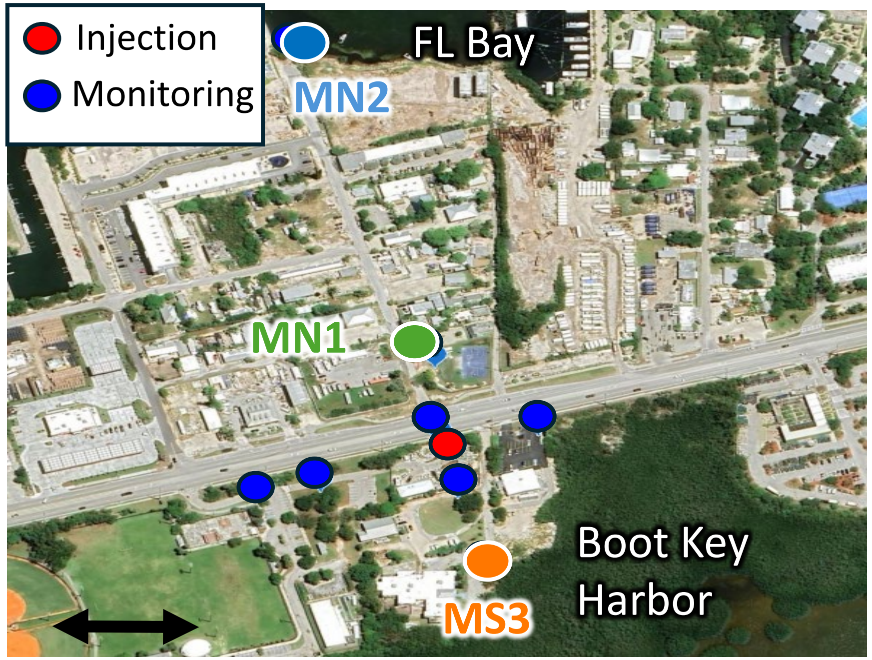




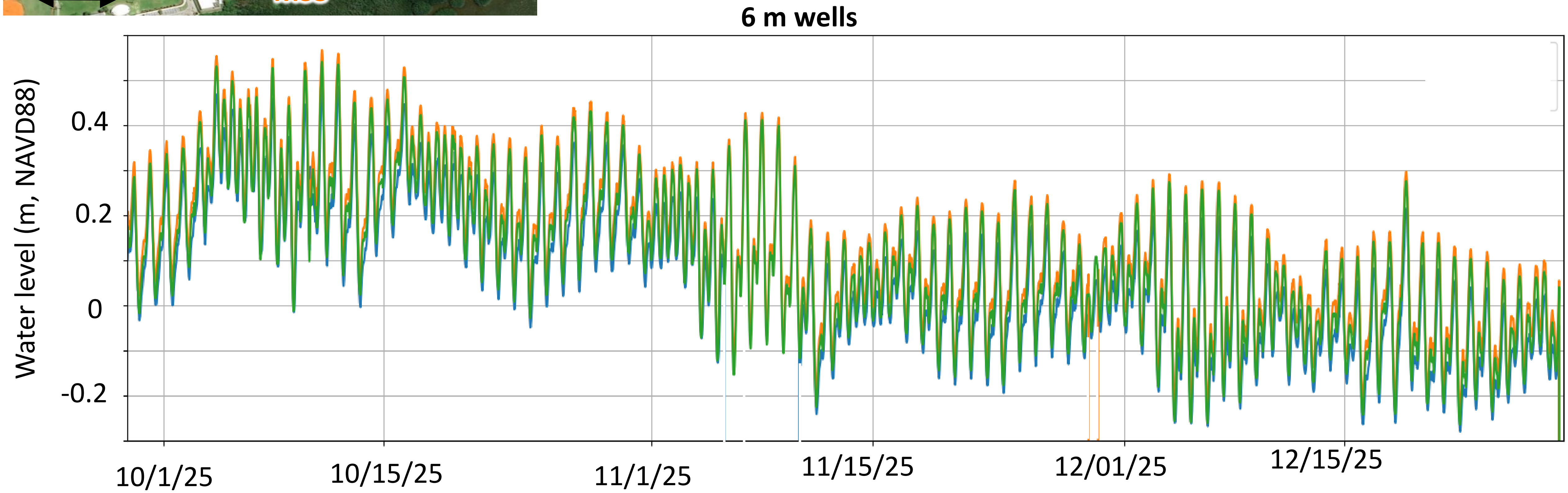
How is plume morphology varying with time?

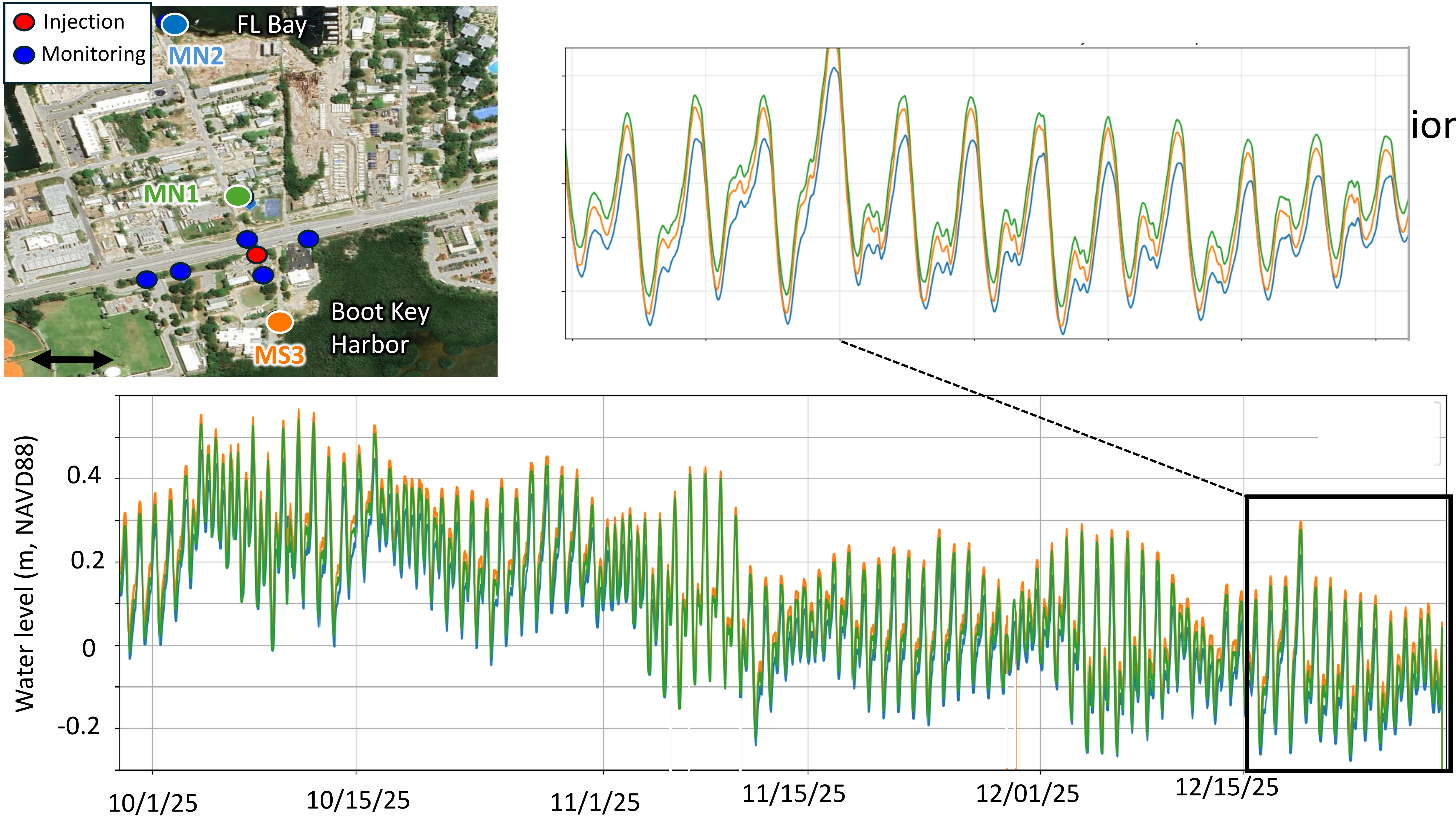


- Installed CTDs in 3 monitoring clusters in September 2025
- Collected data every 15 minutes for 3 months

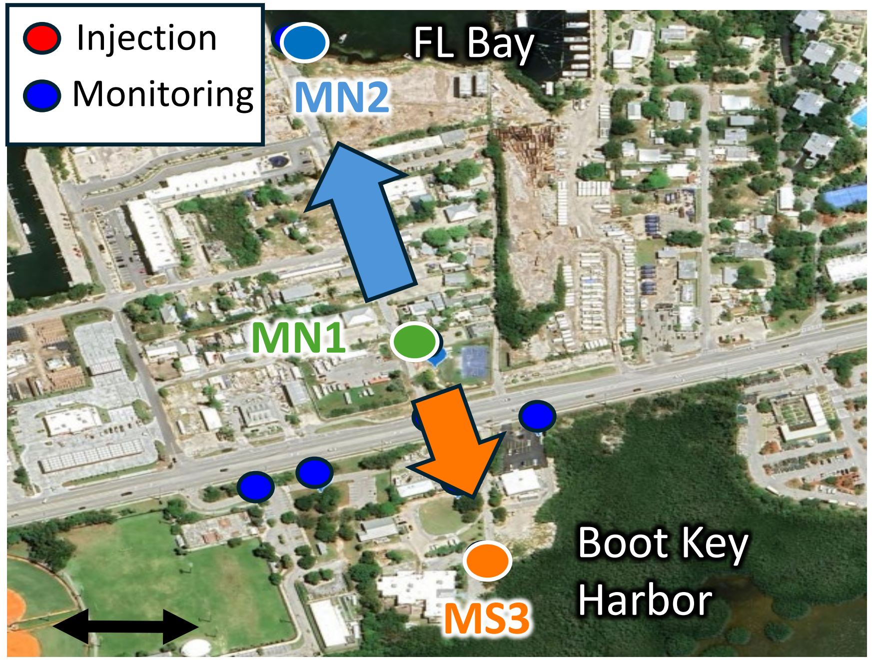


- Water levels dropped ~ 50 cm over observation period
- Magnitude and timing of tidal fluctuations nearly identical at all sites

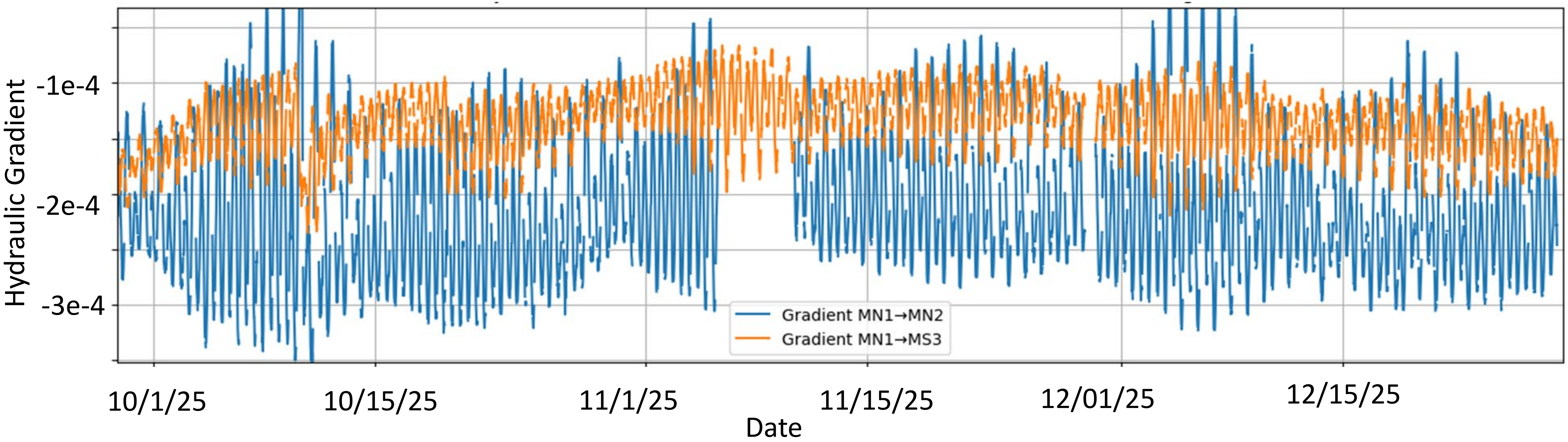


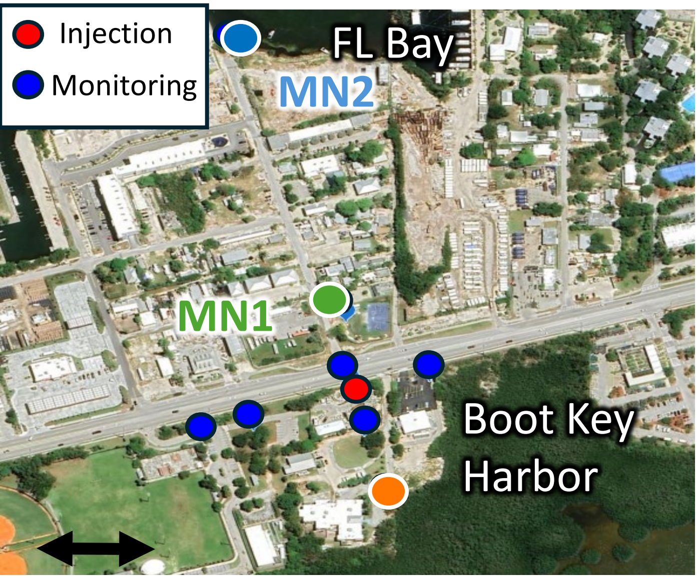


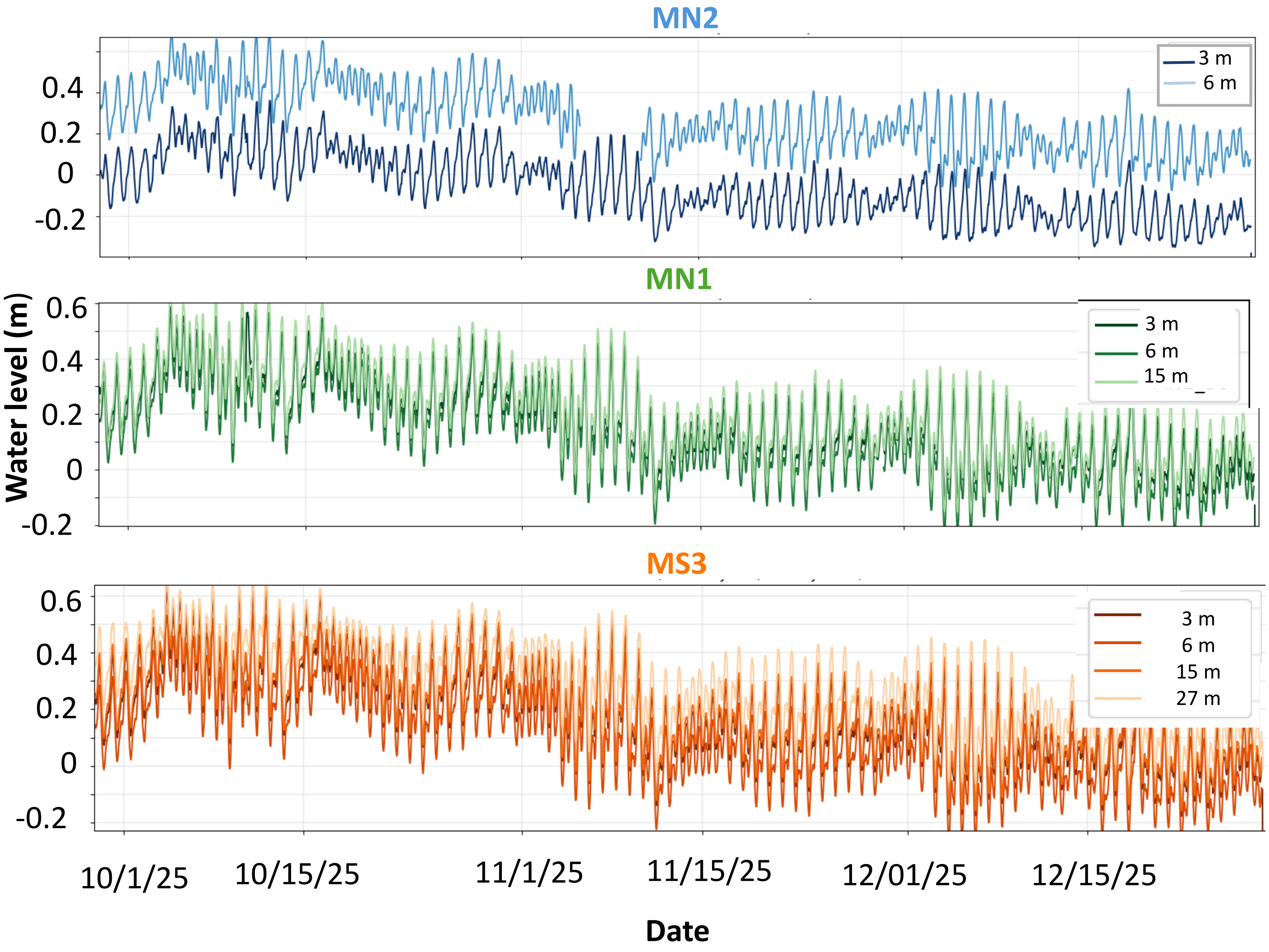
Injection
Monitoring
FL Bay
MN2
MN1
Boot Key
Harbor
MS3
ion
Water level (m, NAVD88)
0.4
0.2
0
-0.2
10/1/25
10/15/25
11/1/25
11/15/25
12/01/25
12/15/25



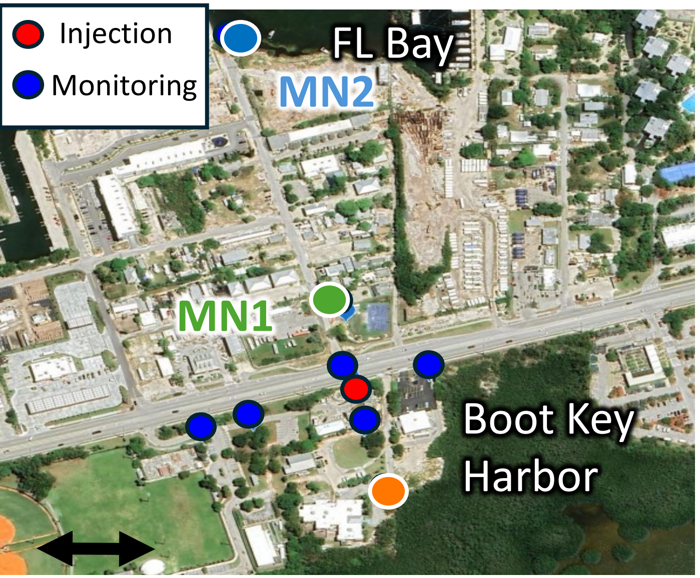
- Magnitude of the hydraulic gradient varies with tide
- Average gradient factor of two larger towards MN-2



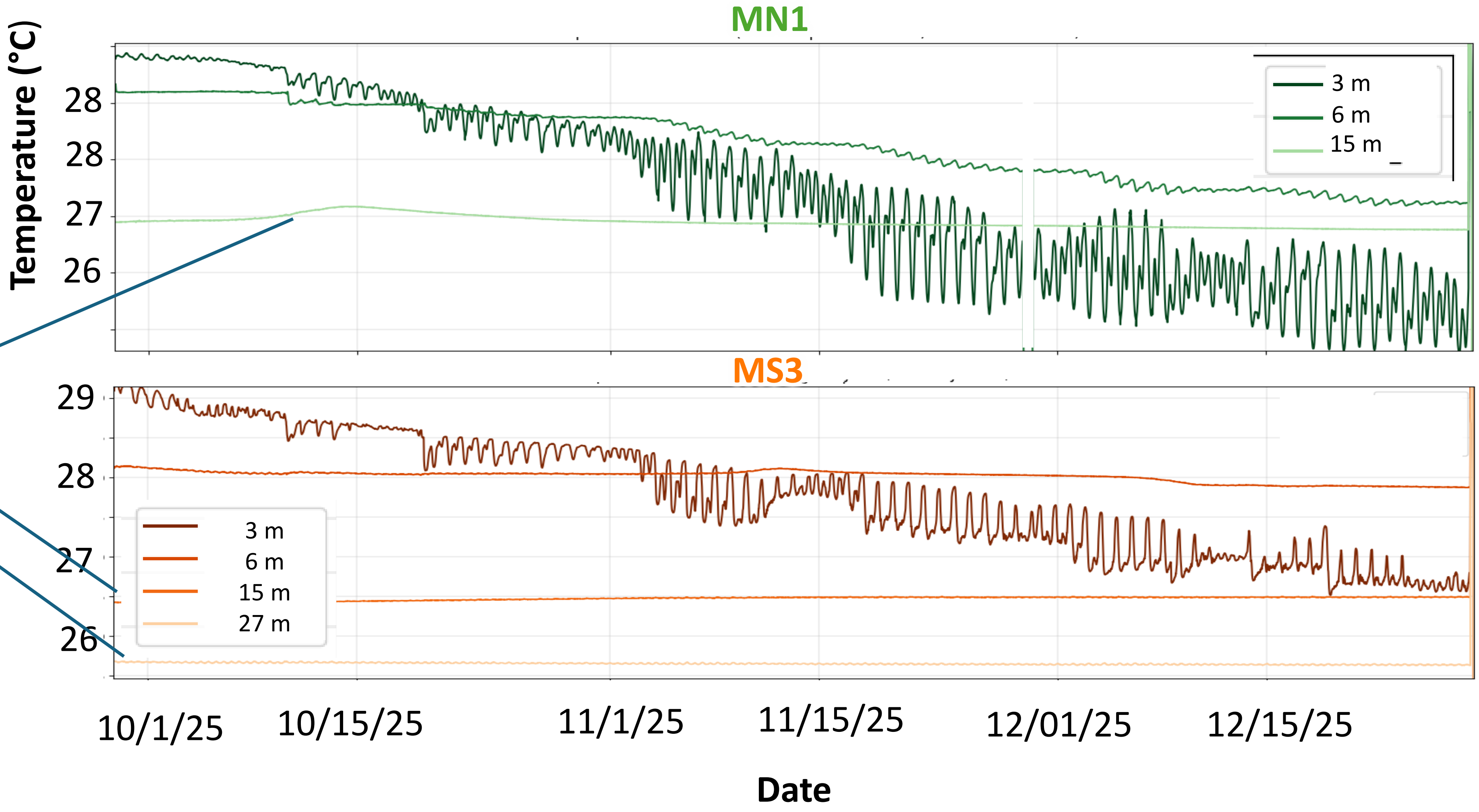


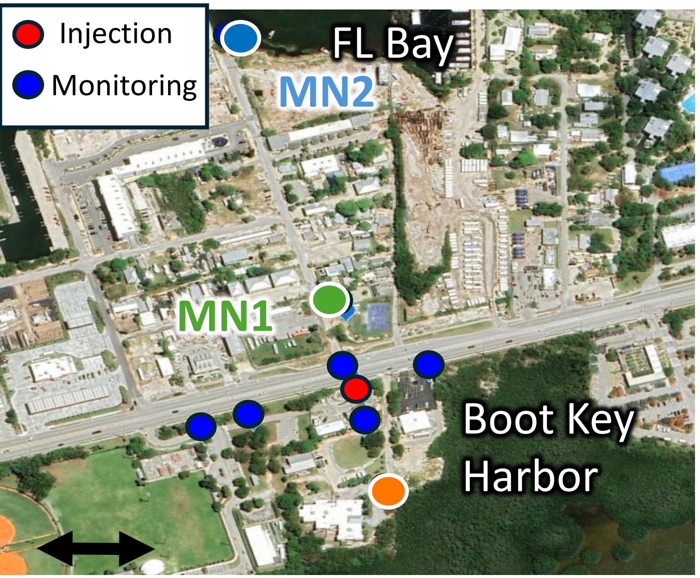


Magnitude and timing of the tidal fluctuations also don't vary with depth

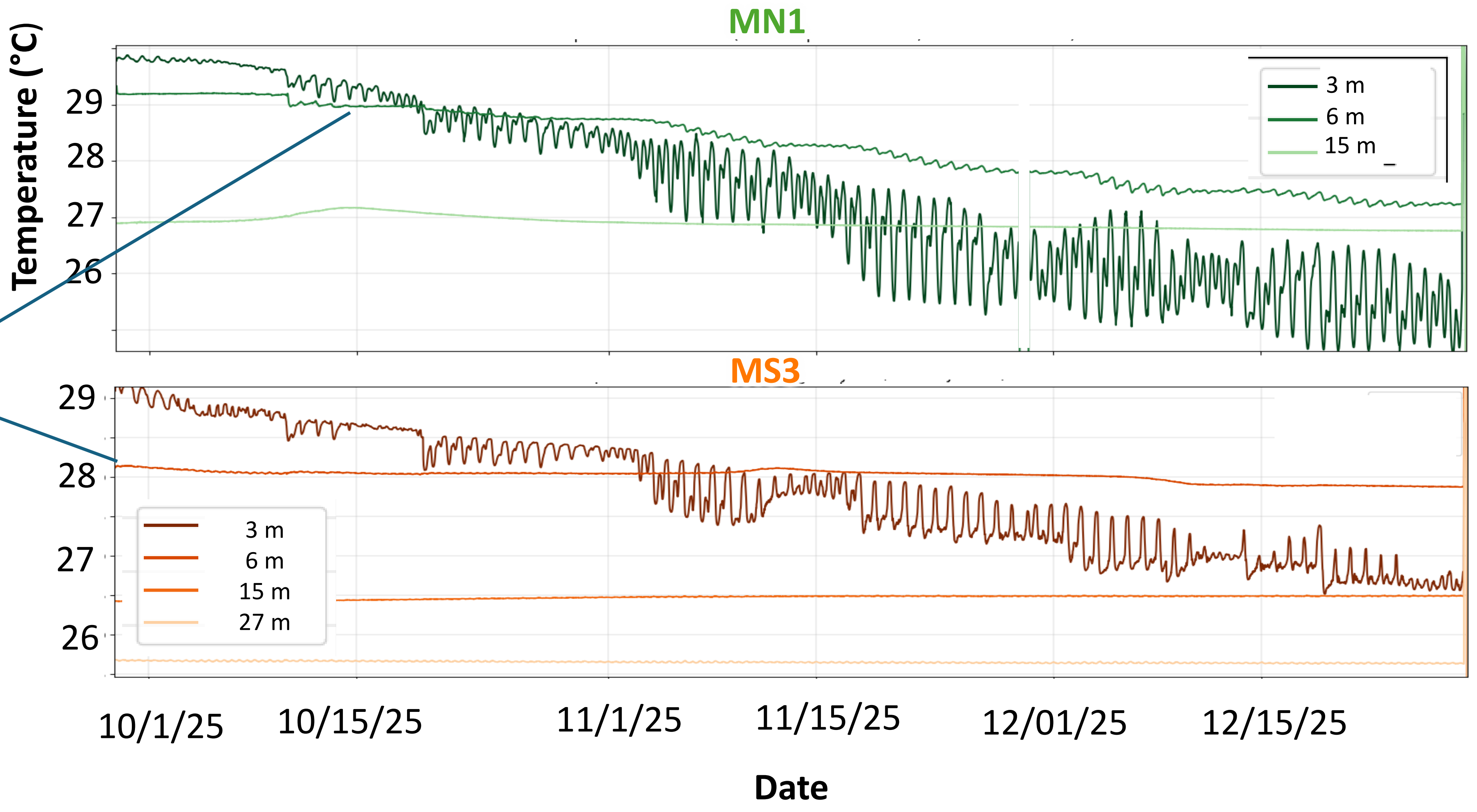


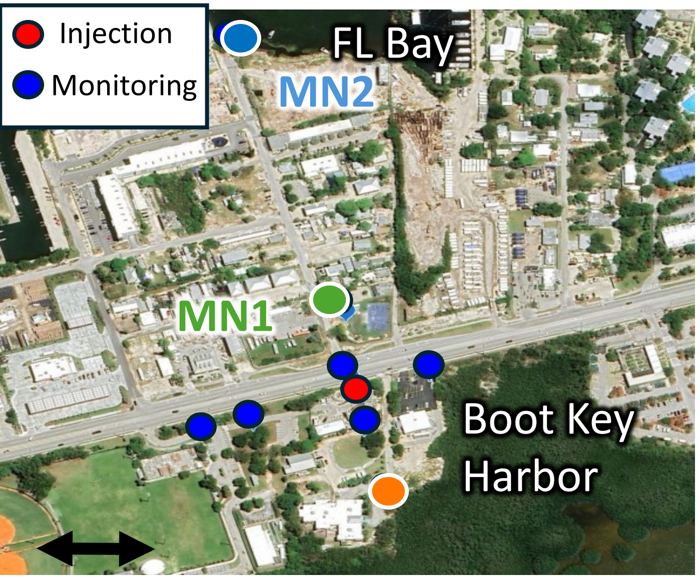
Deep wells (>15 m) show constant temperature



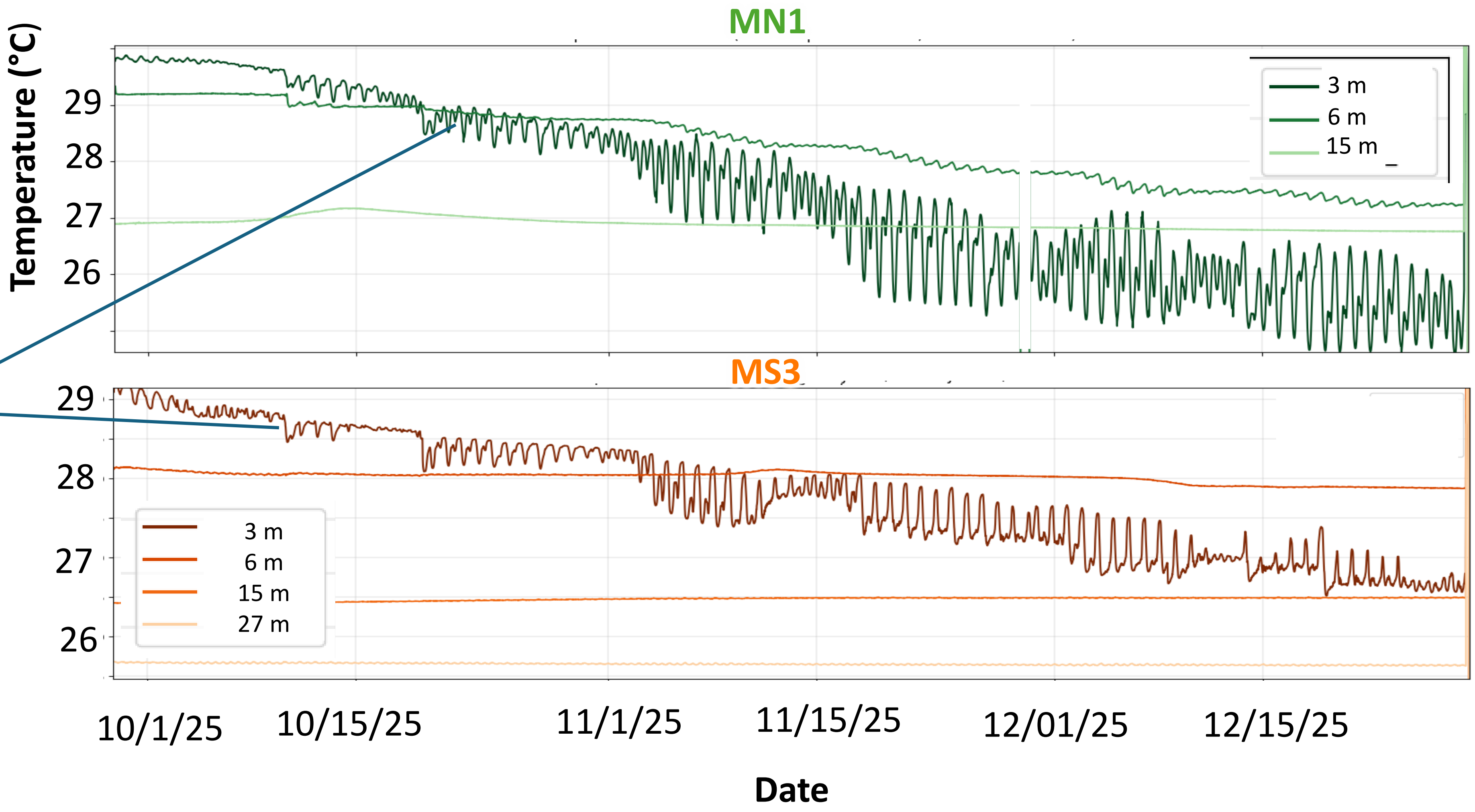


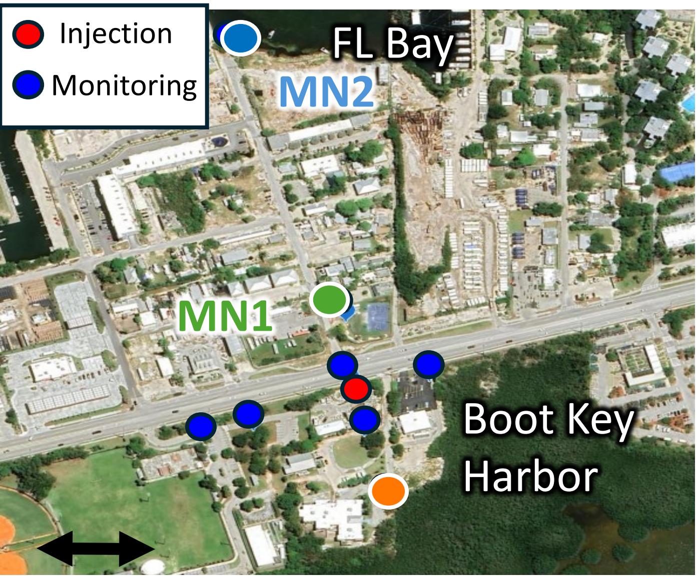
At 6 m MN1 has 1 degree of seasonal cooling, MS3 stays constant



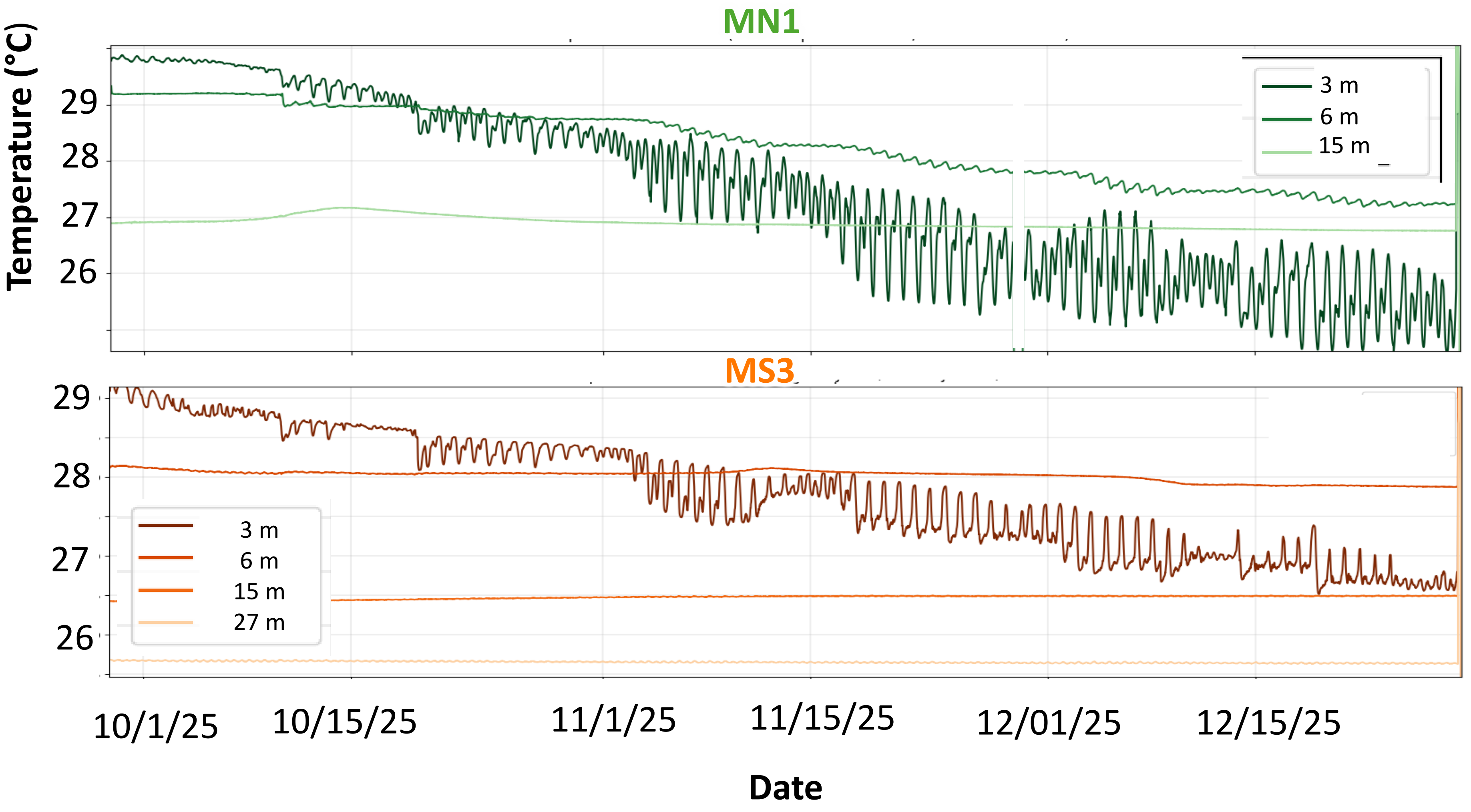


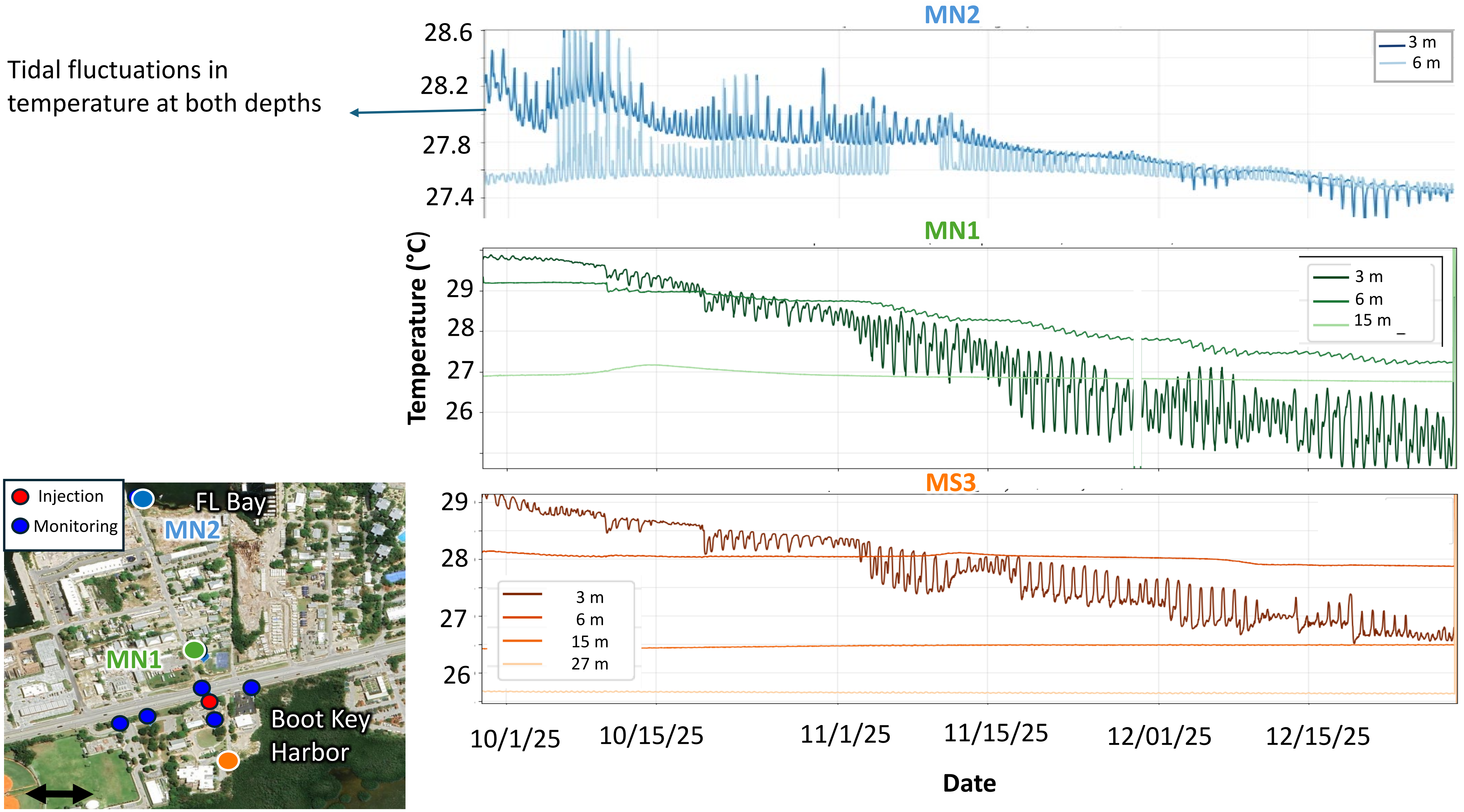
At 3m, seasonal cooling and temperature fluctuations at tidal frequencies

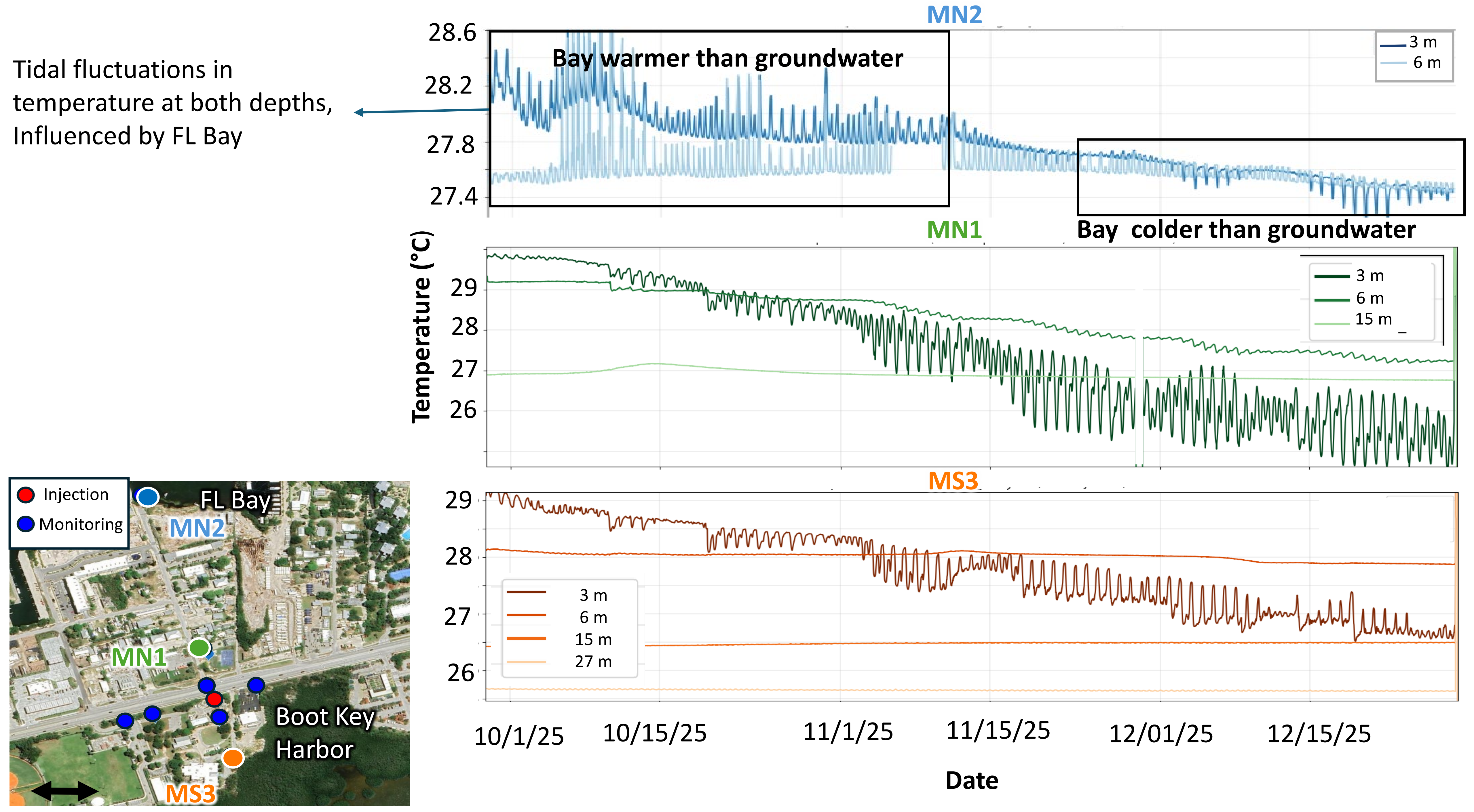




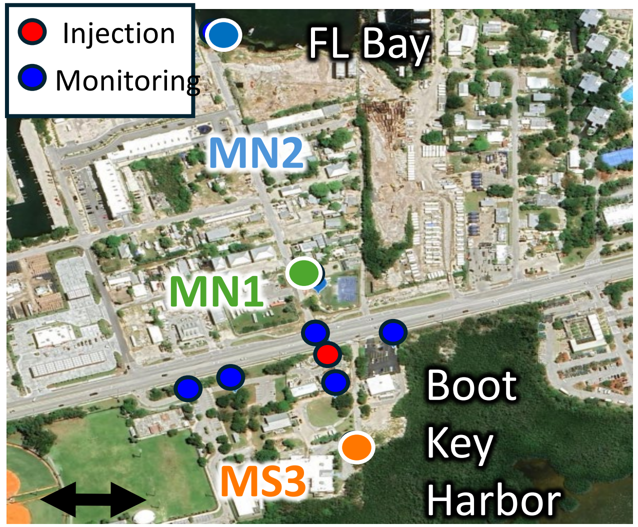
No clear temperature signal associated with the injectate

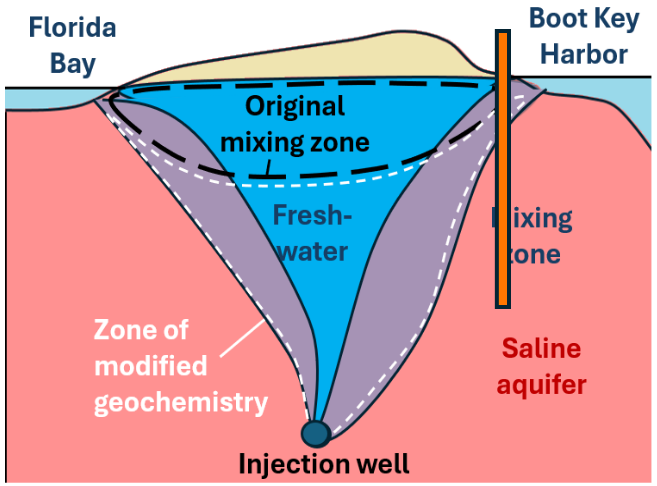


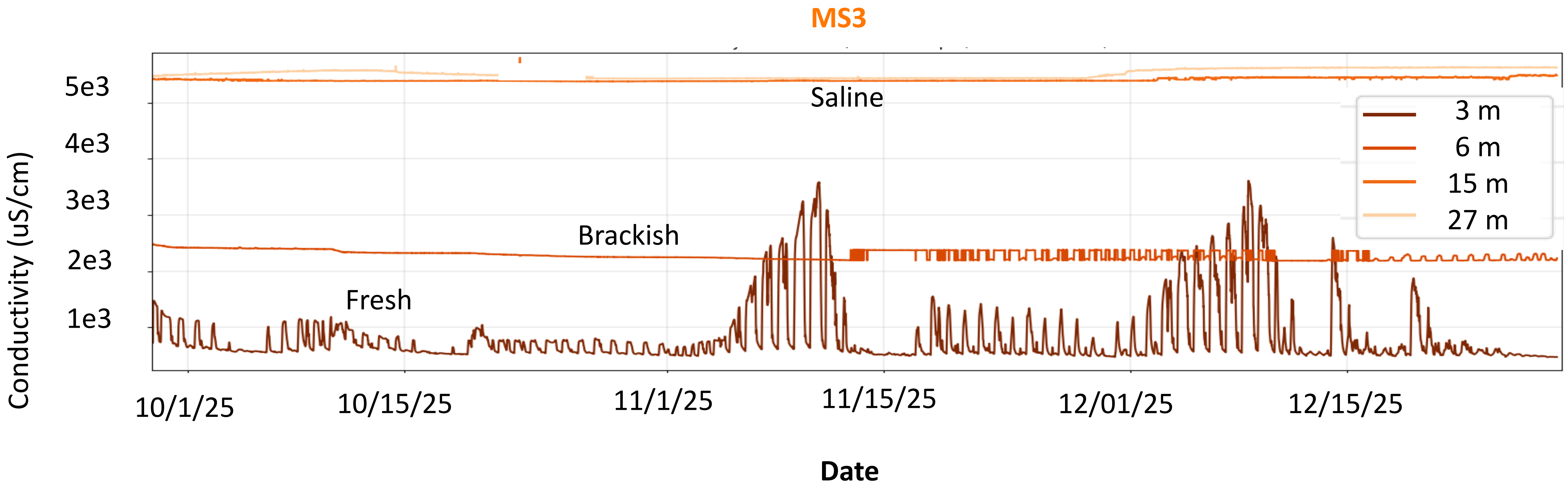

Tidal fluctuations in temperature at both depths
MN2
28.6
28.2
27.8
27.4
3 m
6 m
MN1
Temperature (°C)
29
28
27
26
3 m
6 m
15 m
MS3
29
28
27
26
3 m
6 m
15 m
27 m
10/1/25
10/15/25
11/1/25
11/15/25
12/01/25
12/15/25
Date
Injection
Monitoring
FL Bay
MN2
MN1
Boot Key
Harbor

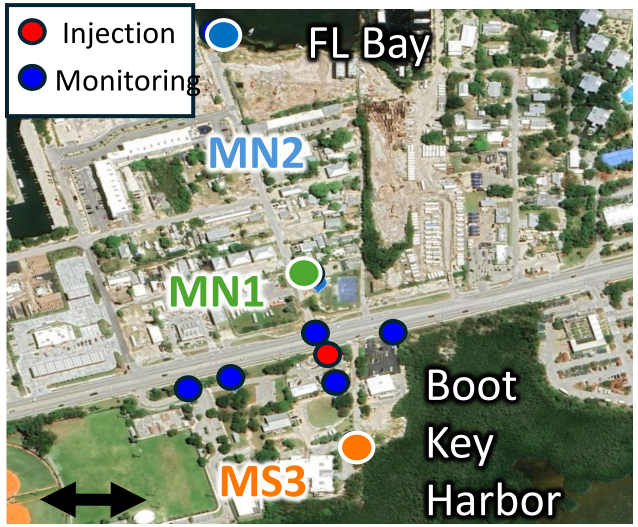


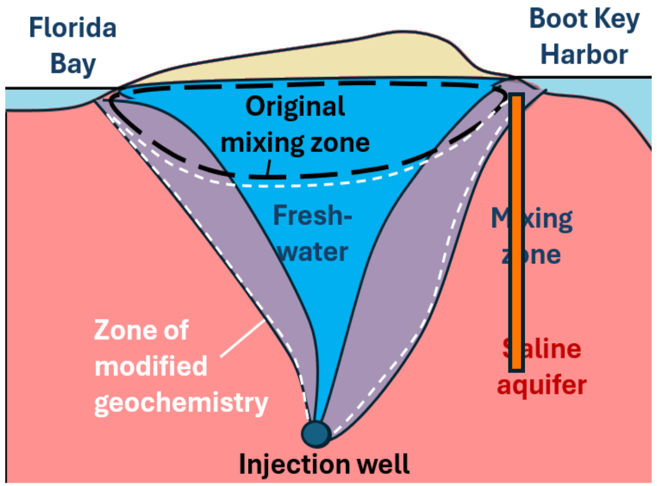
Tidal fluctuations in temperature at both depths, Influenced by FL Bay
MN2
Bay warmer than groundwater
Bay colder than groundwater
3 m
6 m
28.6
28.2
27.8
27.4
MN1
3 m
6 m
15 m
29
28
27
26
Temperature (°C)
MS3
3 m
6 m
15 m
27 m
29
28
27
26
10/1/25
10/15/25
11/1/25
11/15/25
12/01/25
12/15/25
Date
Injection
Monitoring
FL Bay
MN2
MN1
Boot Key Harbor
MS3


Injection
Monitoring
FL Bay
MN2
MN1
Boot
Key
Harbor
MS3

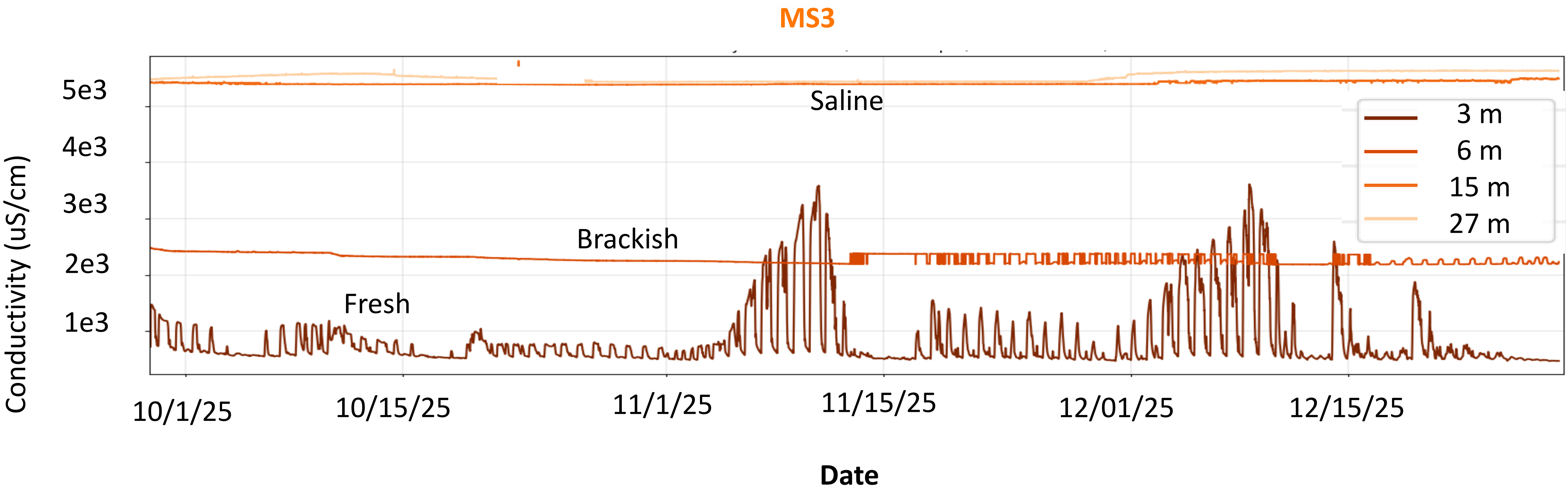

Florida
Bay
Boot Key
Harbor
Original
mixing zone
Fresh-
water
Zone of
modified
geochemistry
Saline
aquifer
Injection well

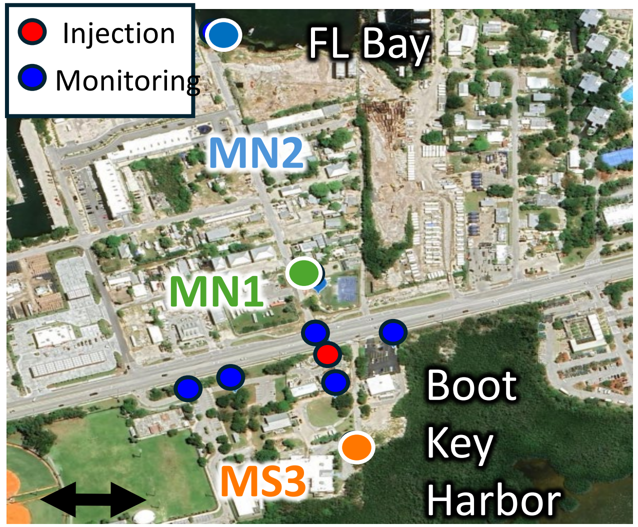

MS3
Conductivity (uS/cm)
5e3
4e3
3e3
2e3
1e3
Saline
Brackish
Fresh
3 m
6 m
15 m
27 m
10/1/25
10/15/25
11/1/25
11/15/25
12/01/25
12/15/25
Date

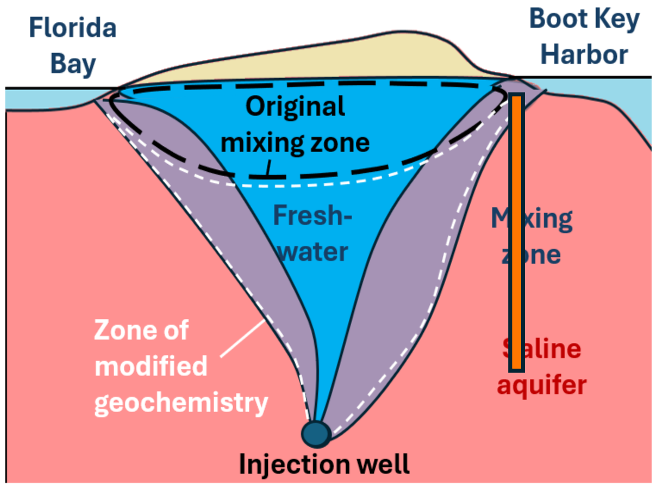




- Deep wells have constant salinities
- At the shallowest well salinity modulated by tide

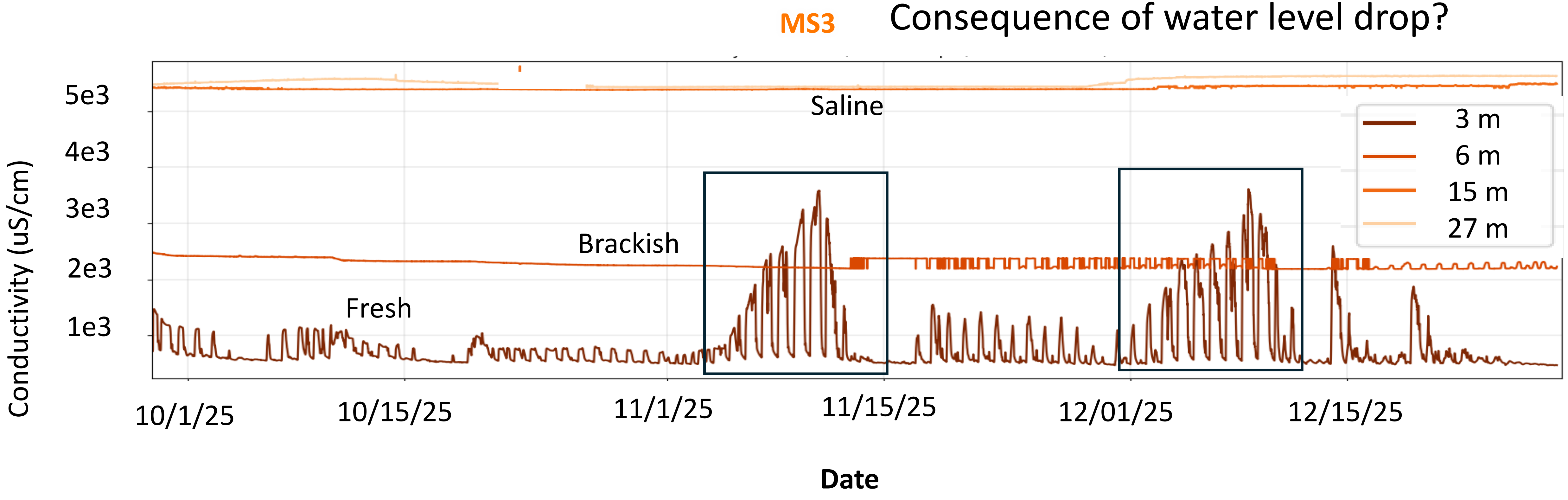


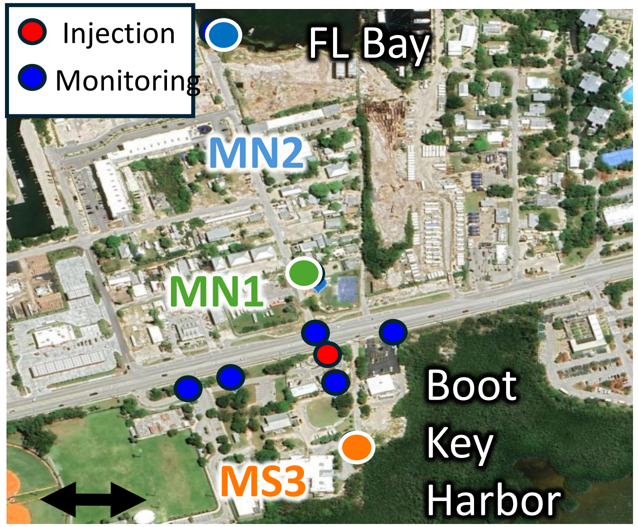


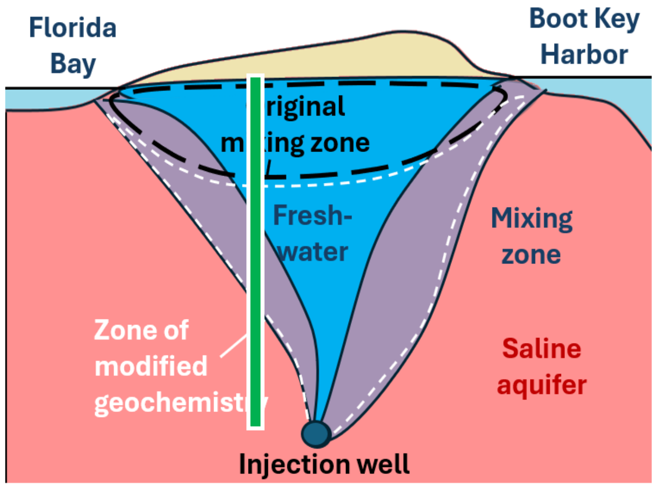


- Deep wells have constant salinities
- At the shallowest well salinity modulated by tide
- Magnitude of tidal fluctuations changes through time

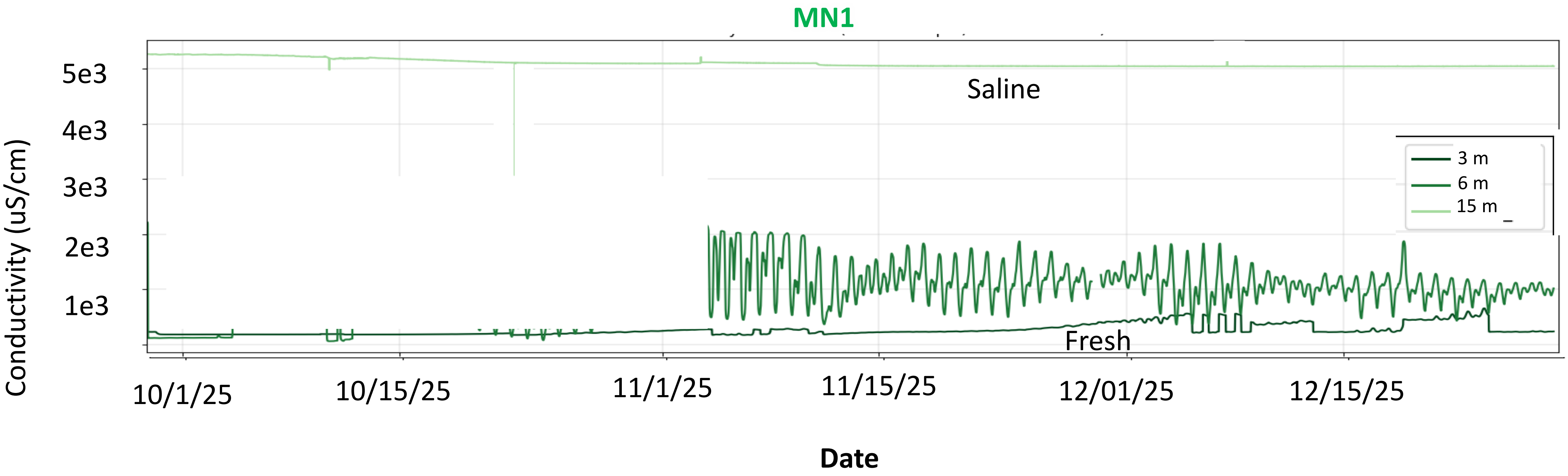
Different injection schedule?
Consequence of water level drop?

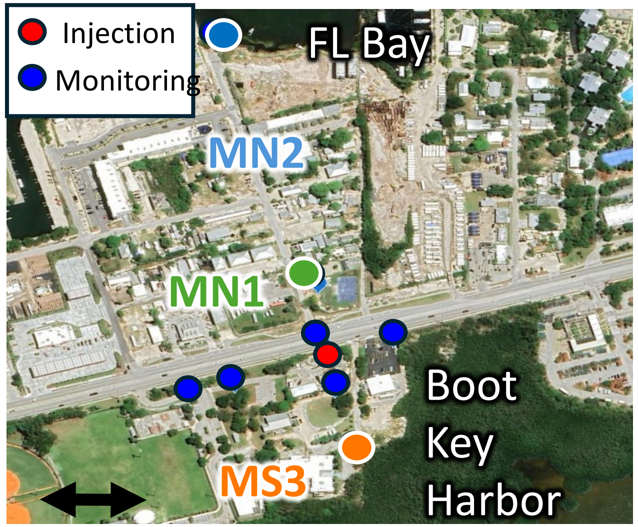


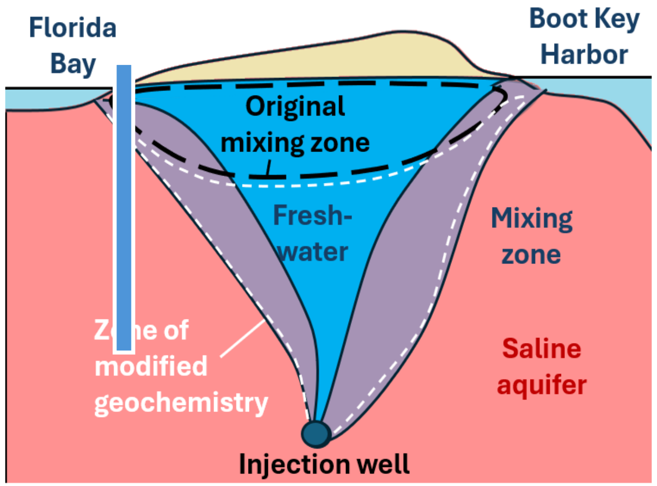




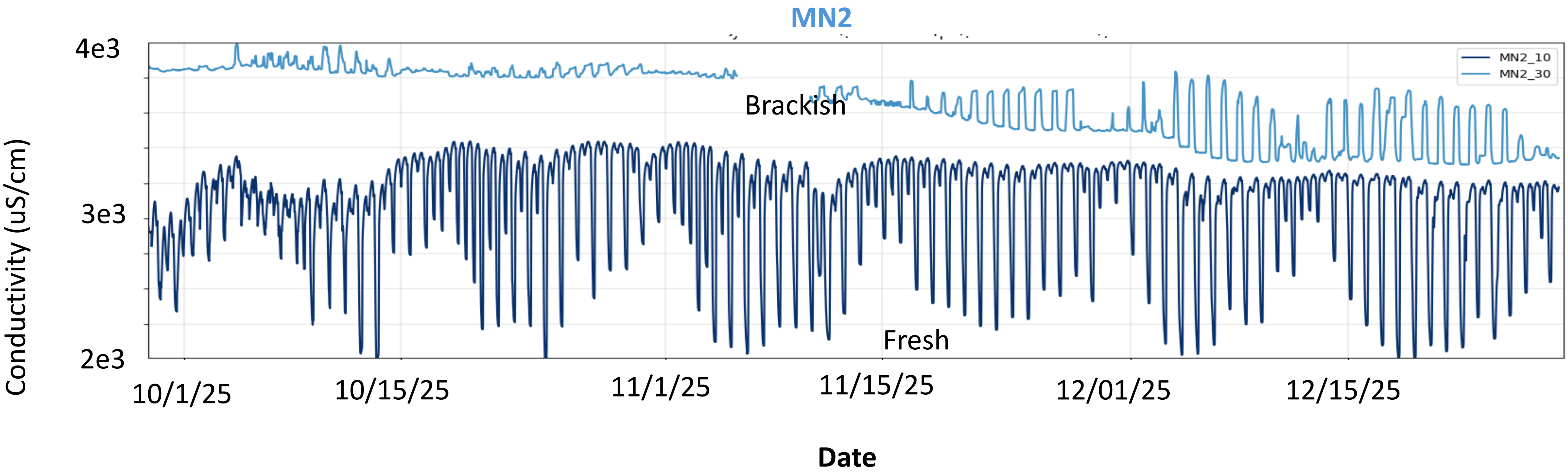
- Deep wells has constant salinity (unaffected by plume)
- Shallowest well consistently fresh
- Tidal fluctuations in salinity at 6m as plume interface is affected by the tide





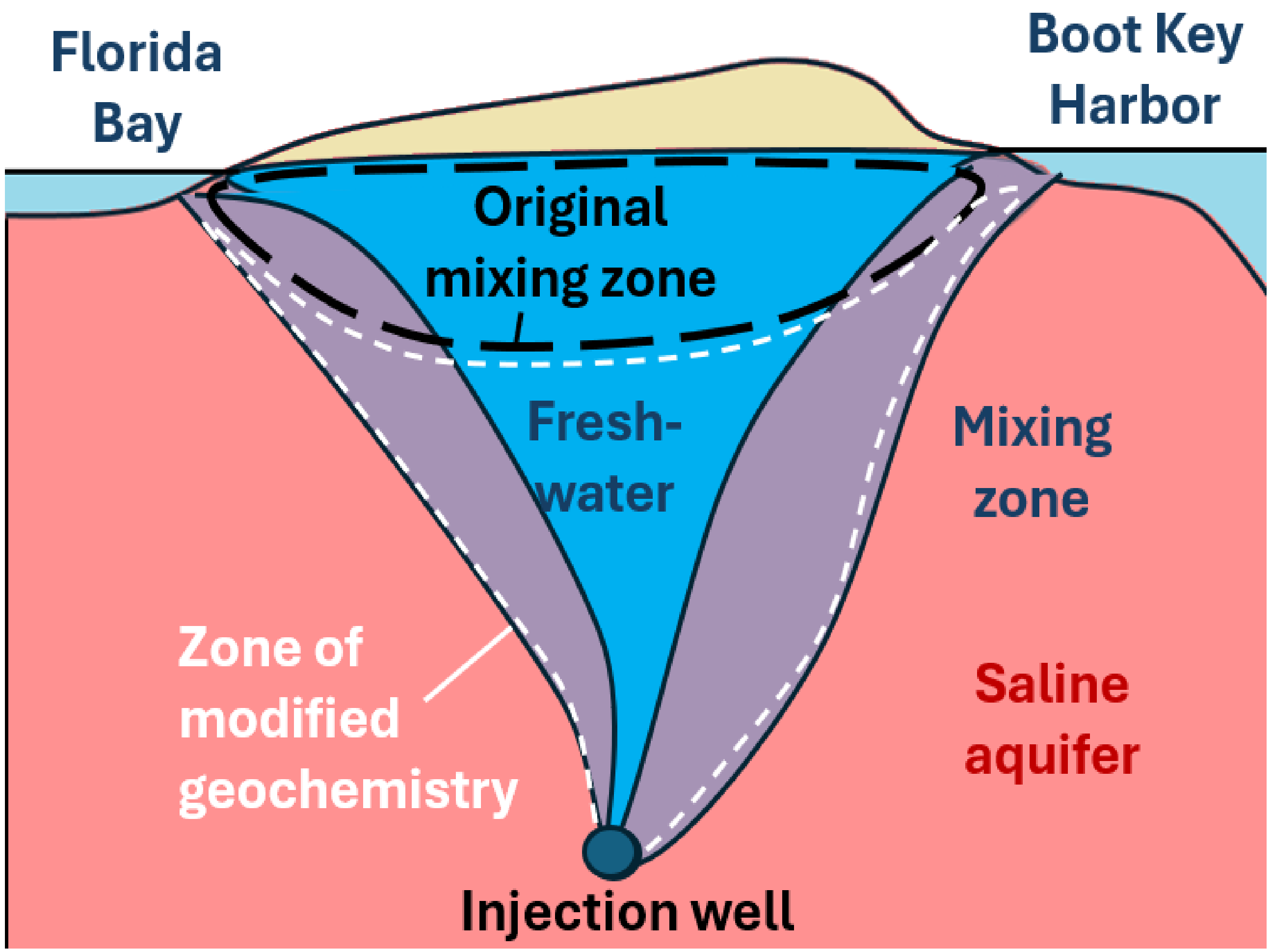


- Salinity at shallow well switches from fresh to more brackish at tidal frequencies



Hydrologic controls and plume morphology

- Morphology of the plume consistent through time, but interface positions affected by tidal fluctuations
- Hydraulic gradients have consistent directionality, but magnitude is modulated by the tide
- Evidence of fast break through preferential flow paths from dye tracer test



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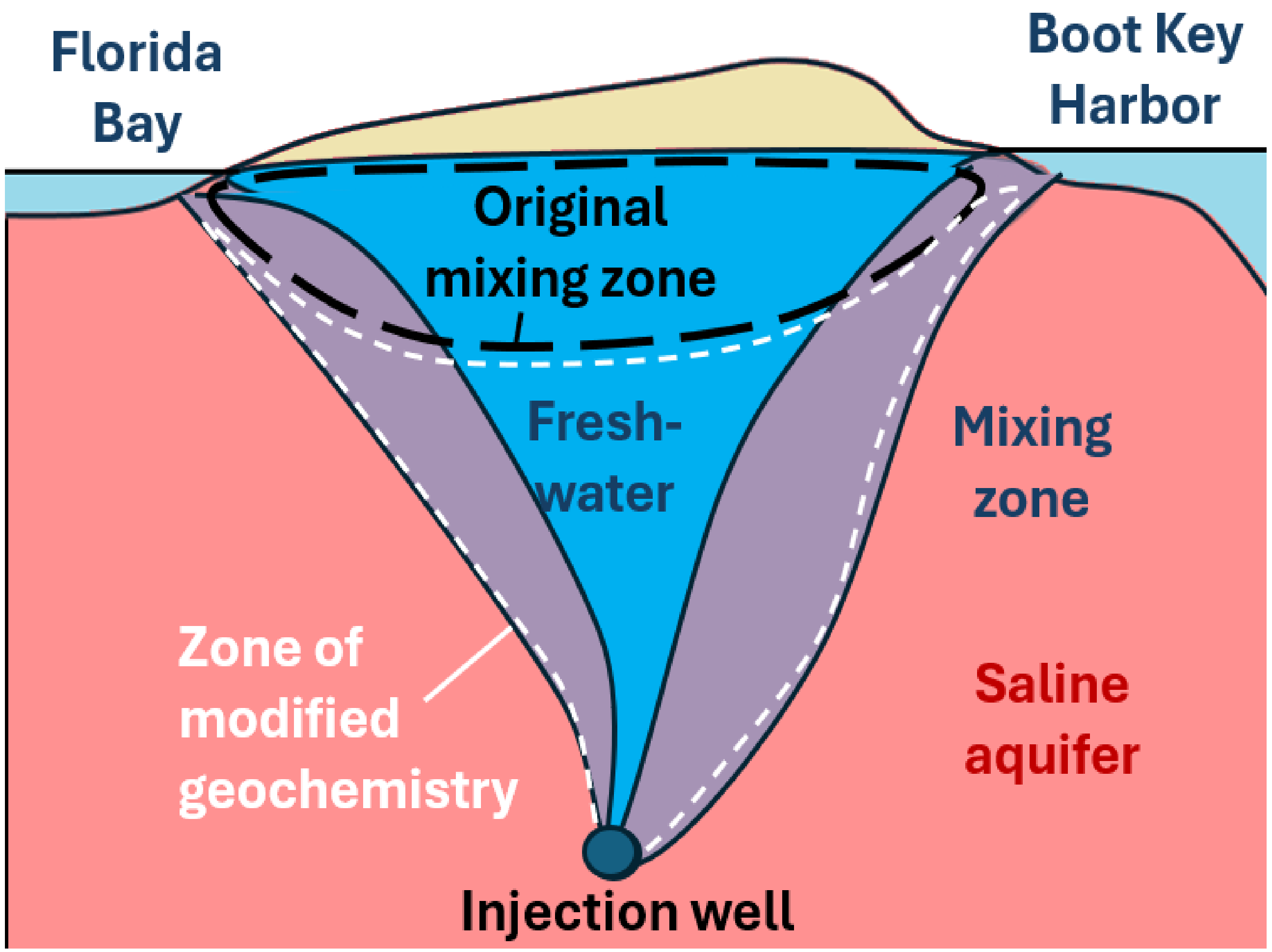
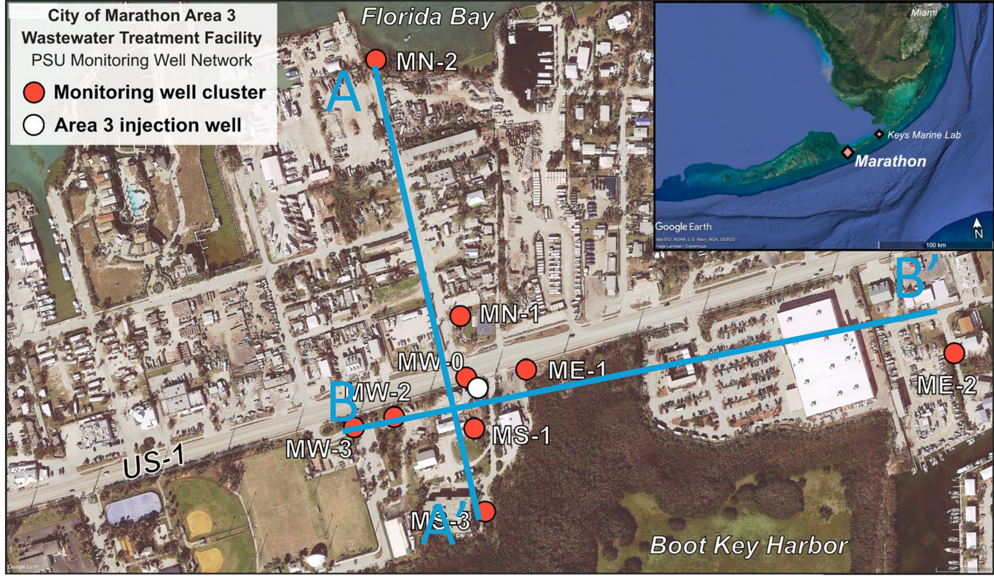


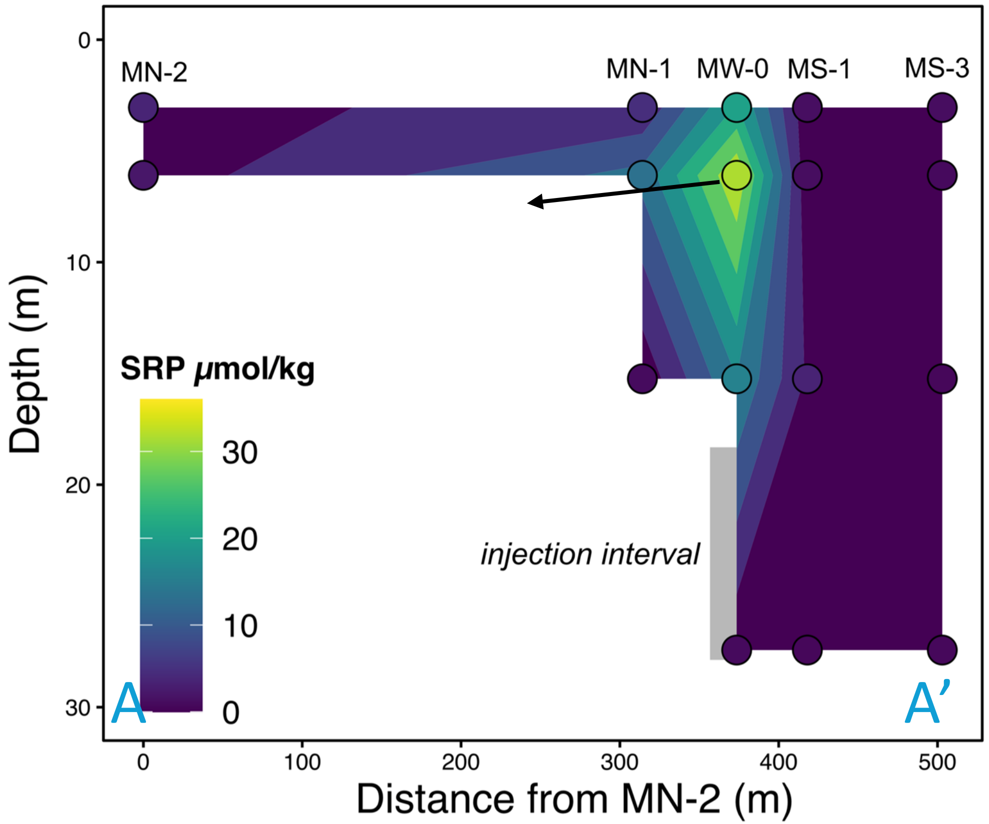
Consequences for nutrient transport?

Characterizing plume geometry: Soluble Reactive Phosphorus

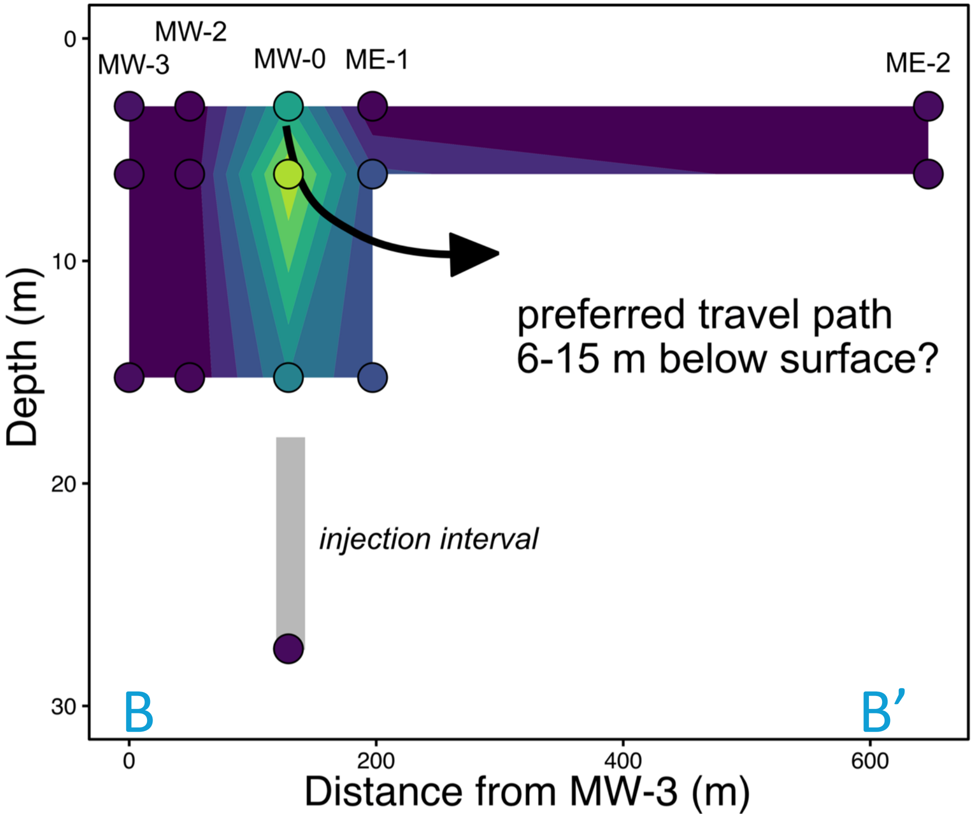
$SRP_{EWW} = 75 - 100\ \mu mol/kg$



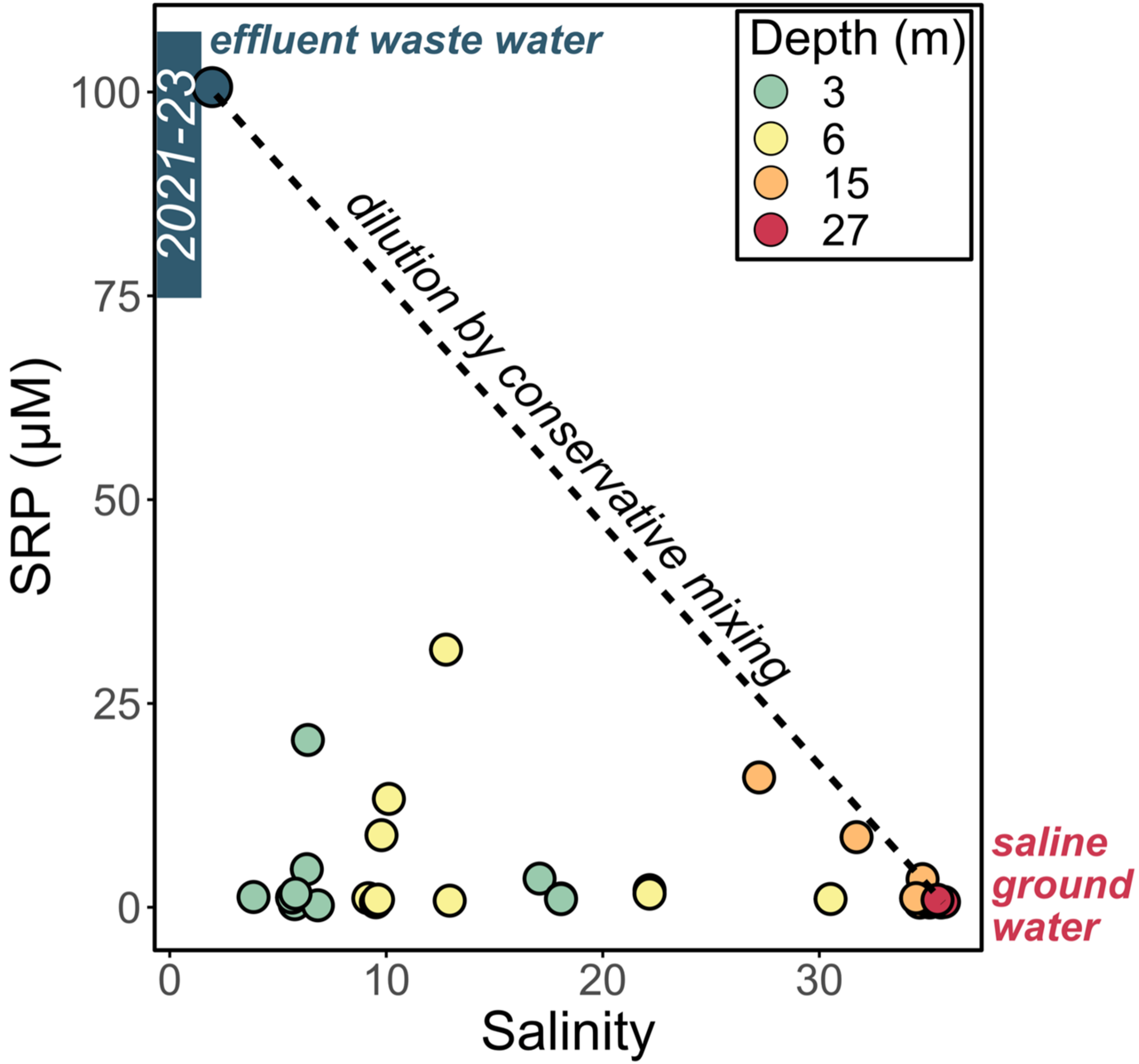
January 2023 – North–South



January 2023 –East-West

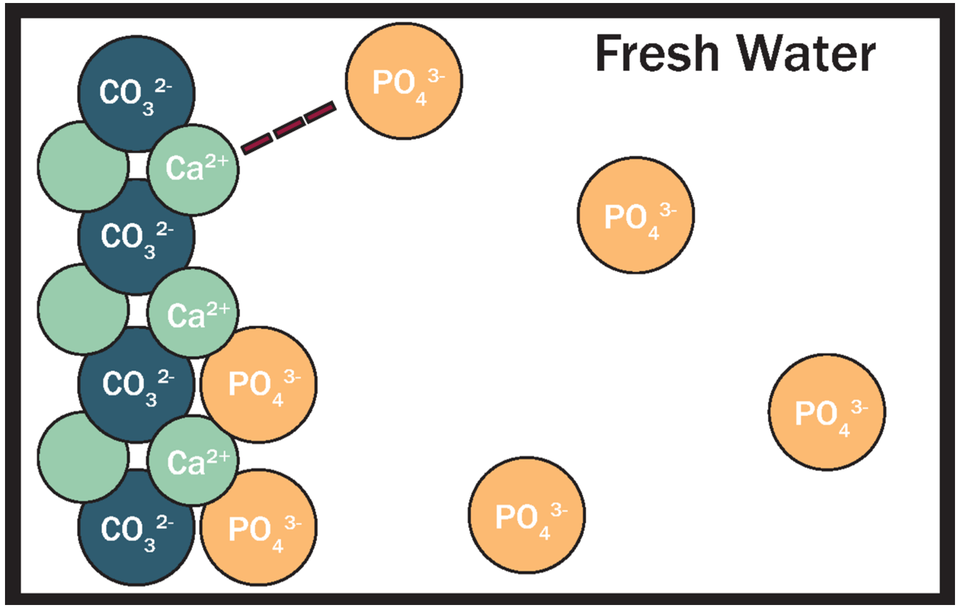


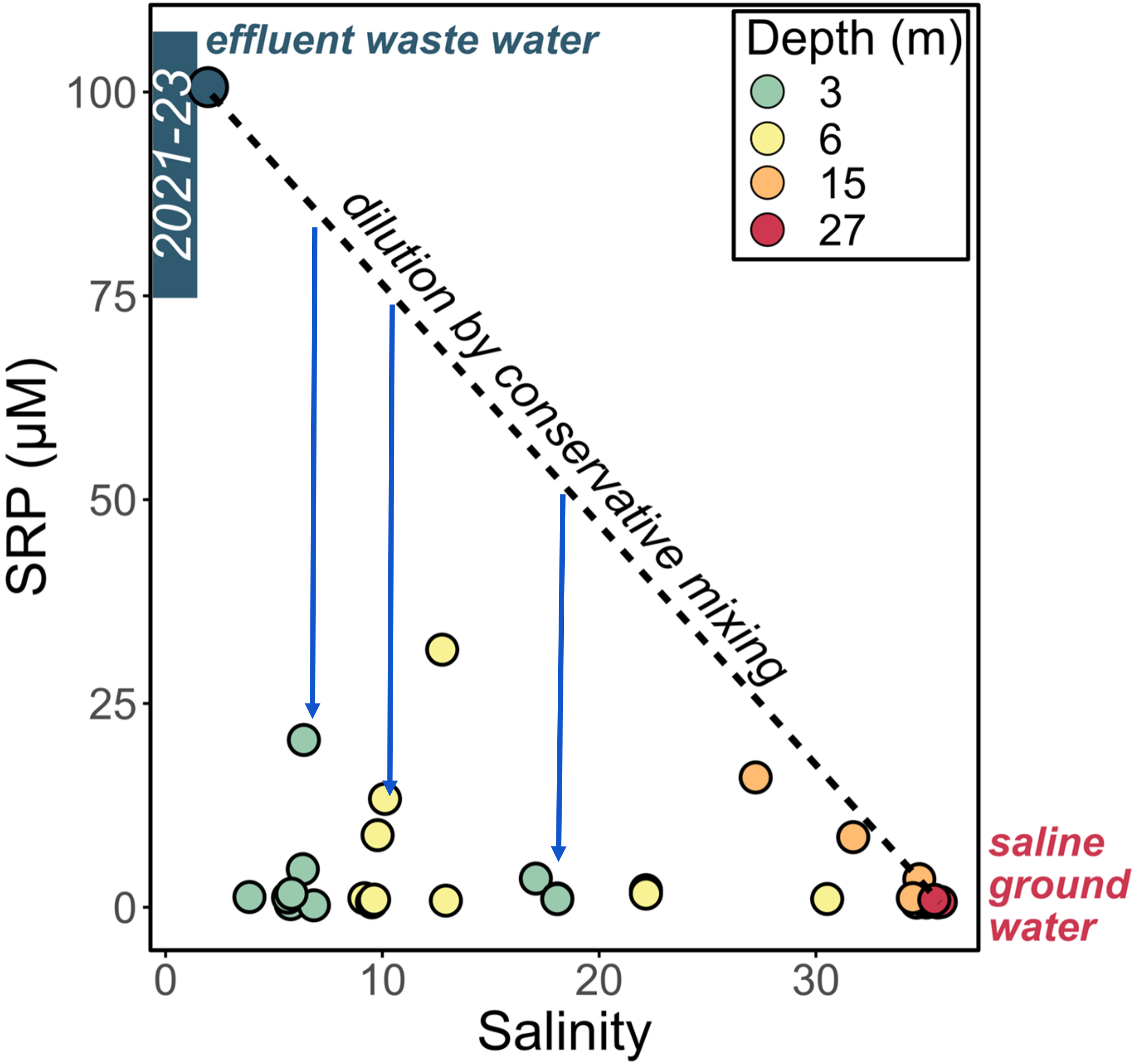
Groundwater phosphate does not follow conservative mixing



Groundwater phosphate does not follow conservative mixing

ADSORPTION?



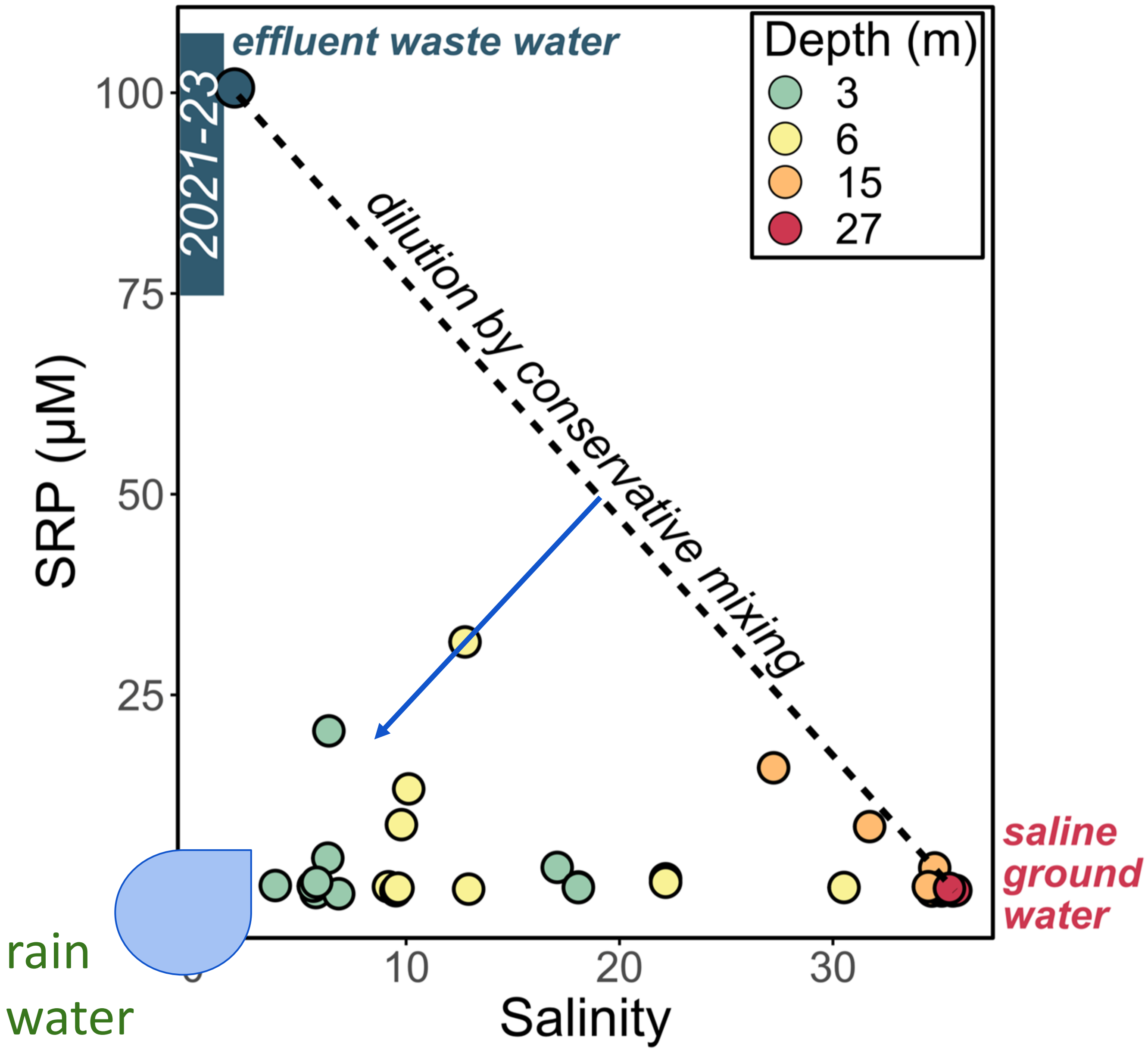


Groundwater phosphate does not follow conservative mixing

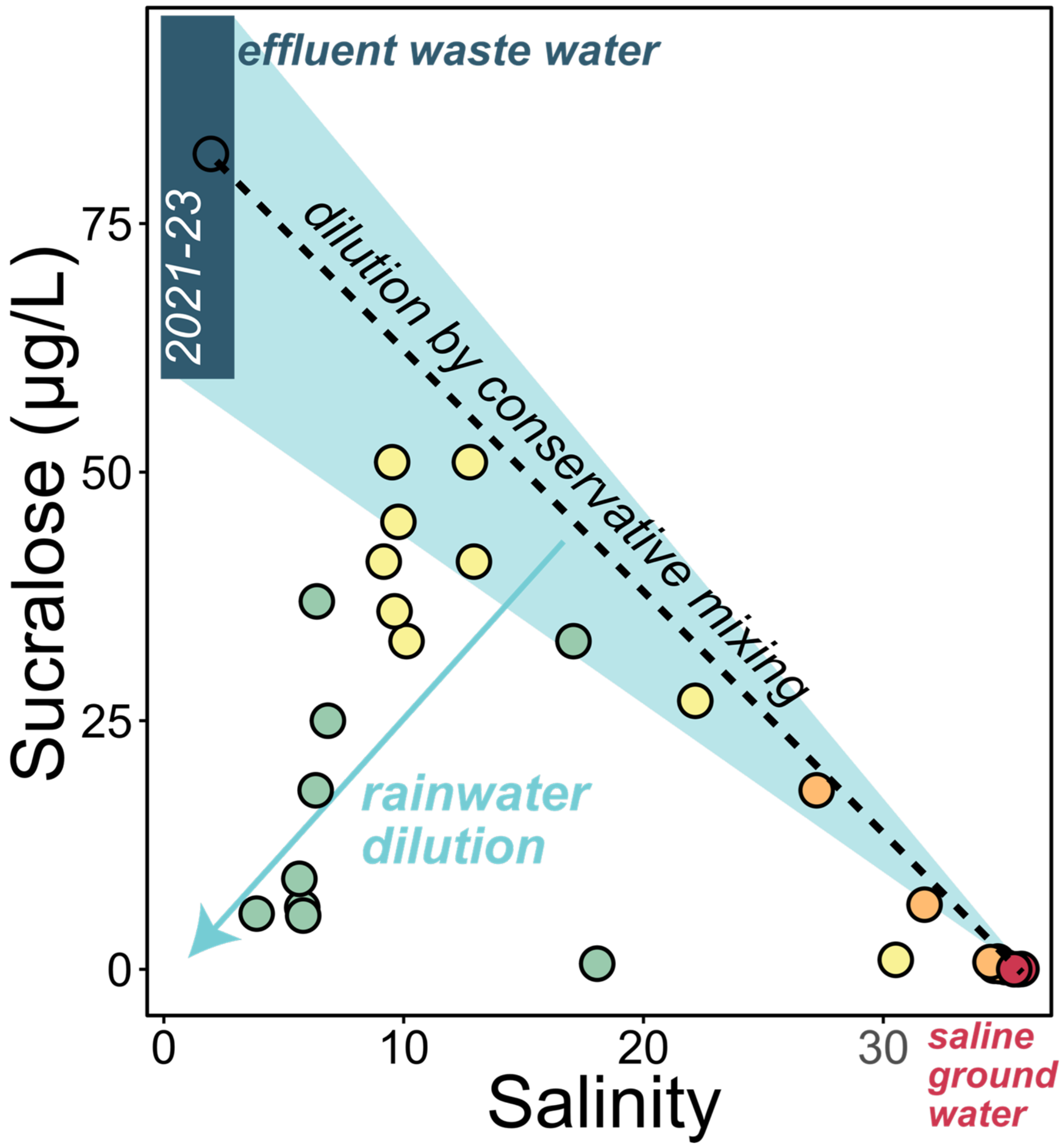
Three end members:

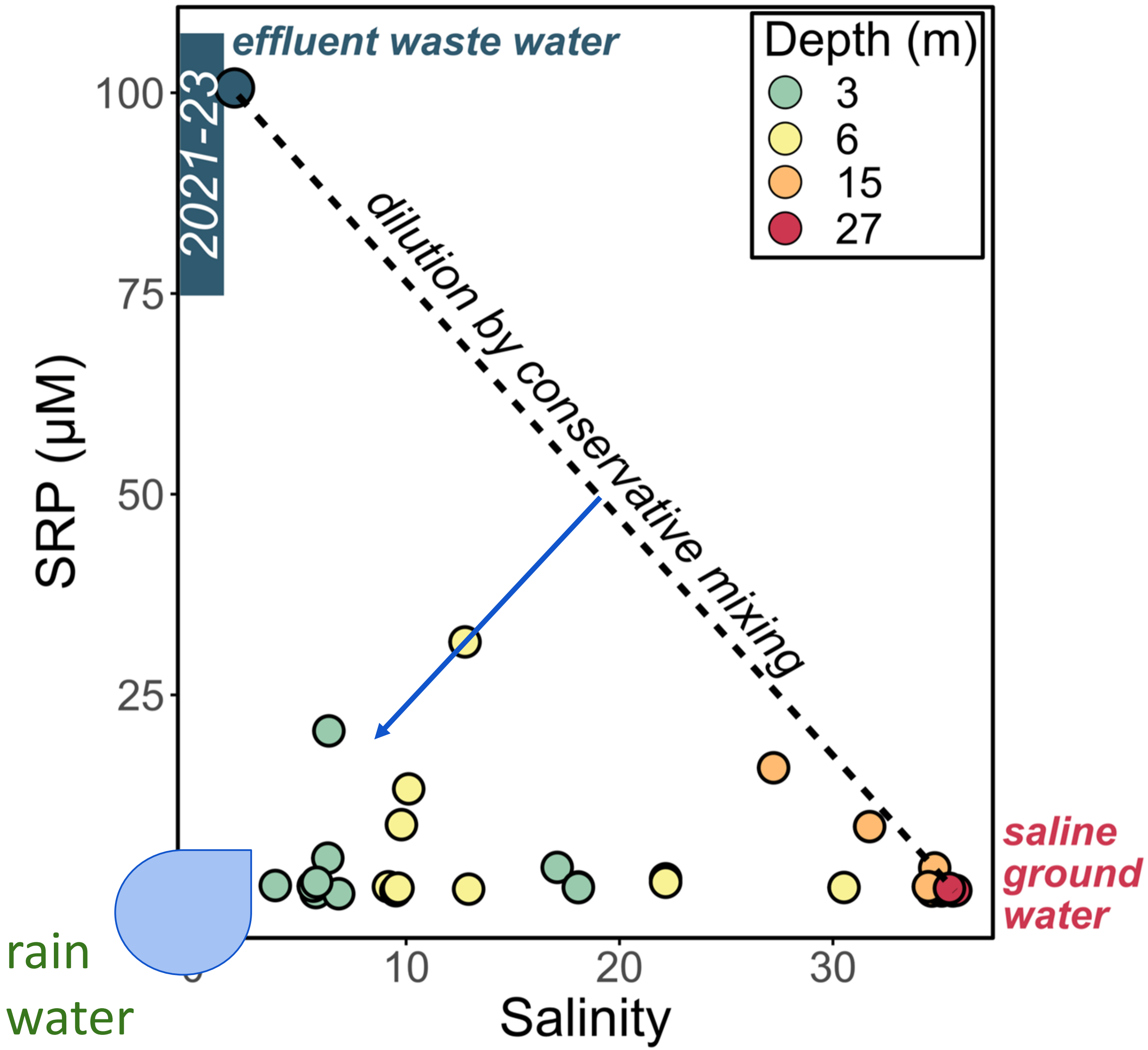
1. Rainwater (low S, low SRP)
2. Saline Groundwater (high S, low SRP)
3. Wastewater (low S, high SRP)

Use S to trace seawater, sucralose to trace wastewater



Using sucralose as a conservative tracer of waste water





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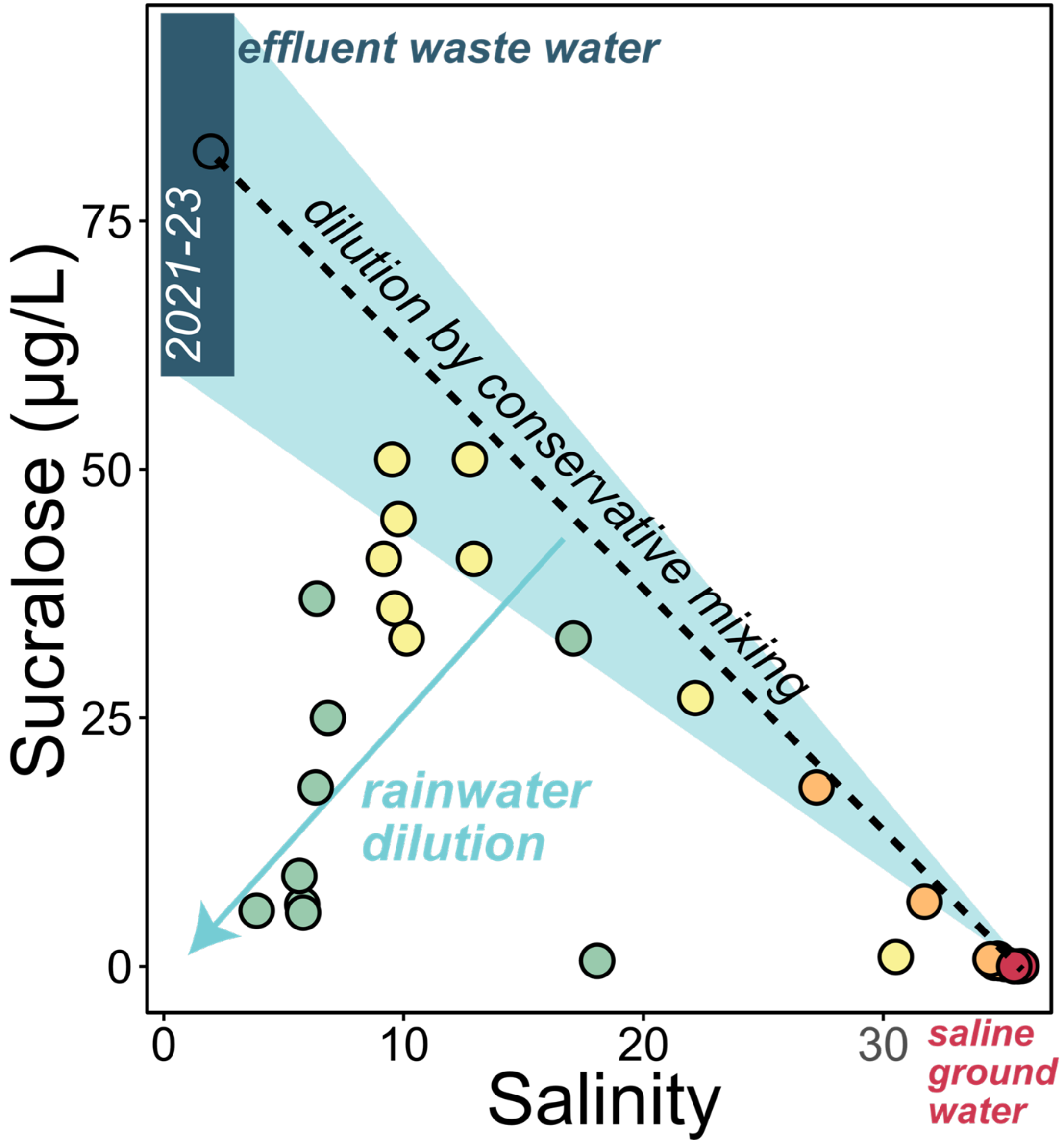
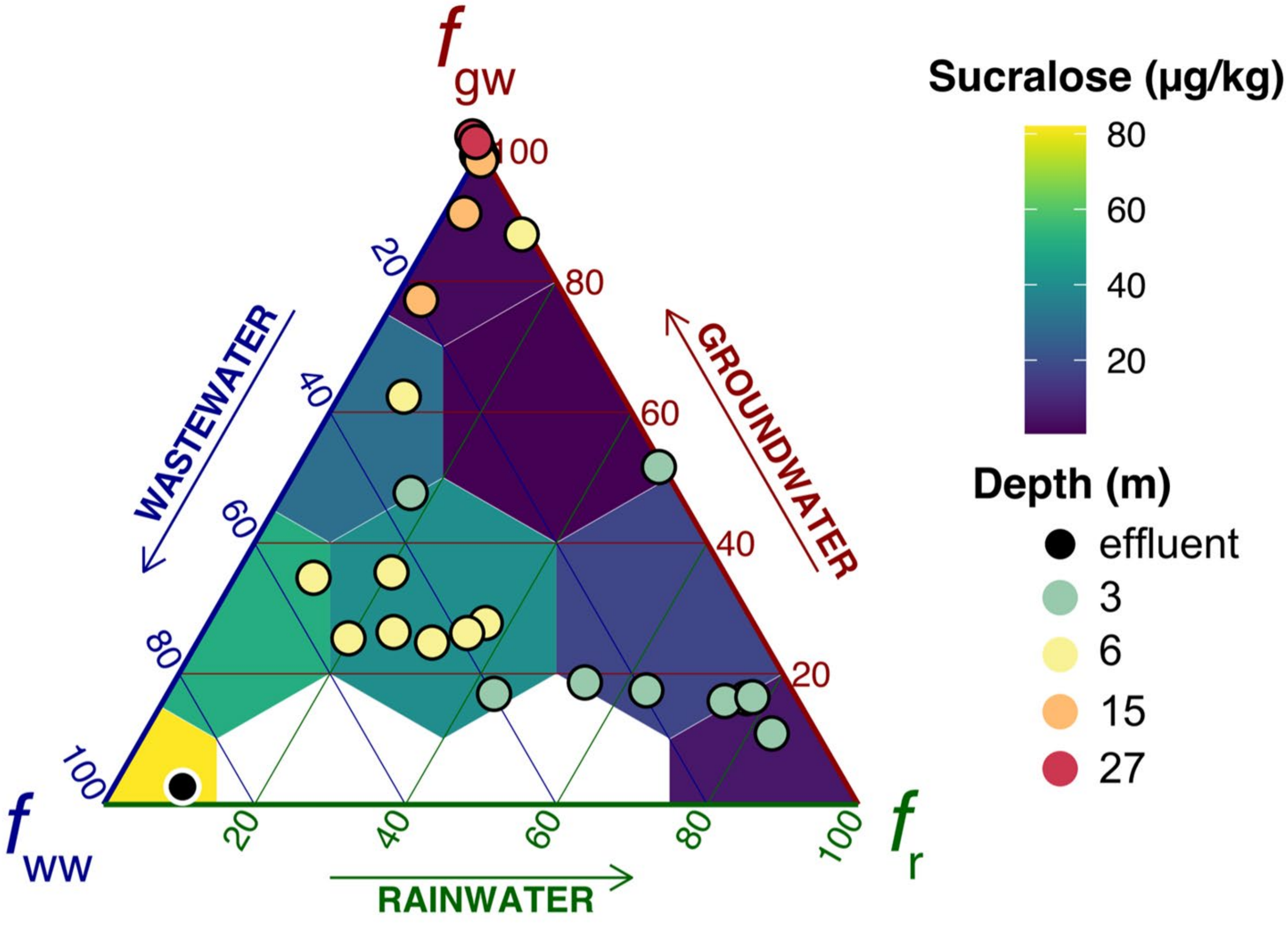
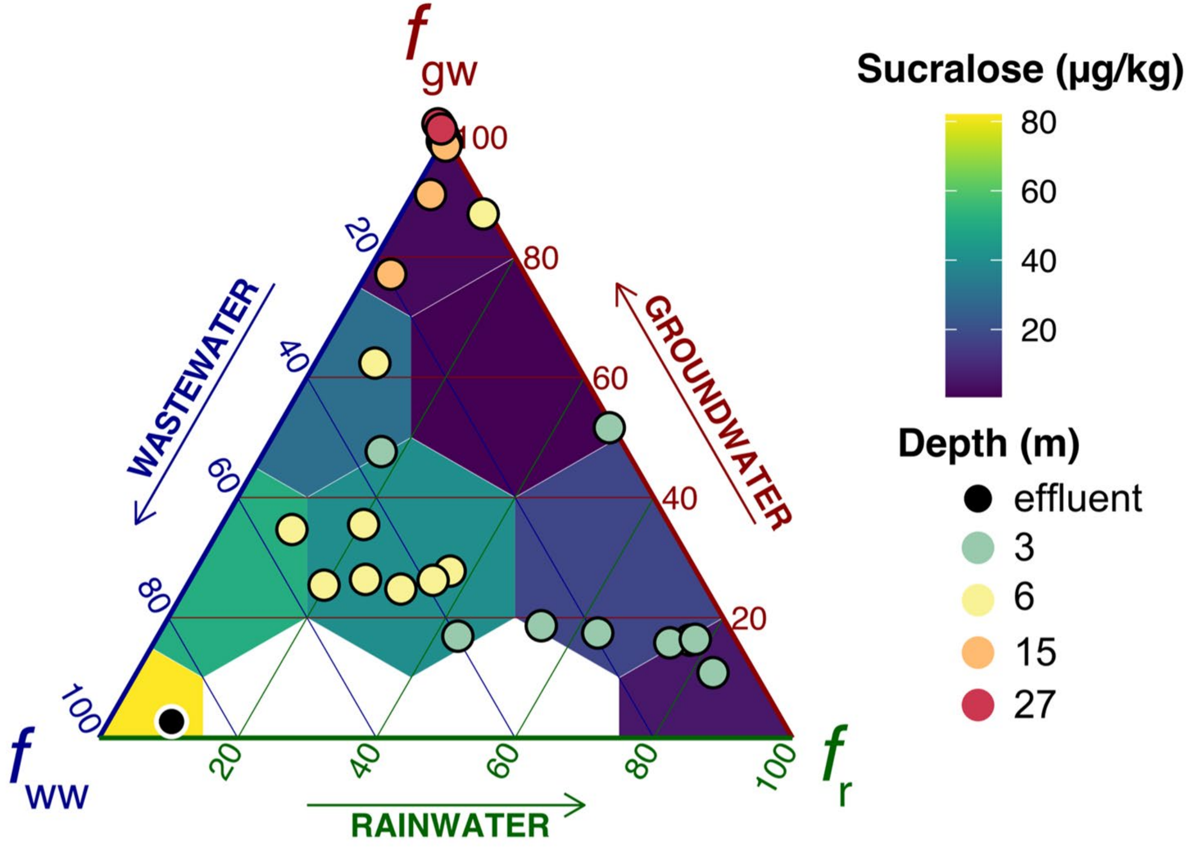
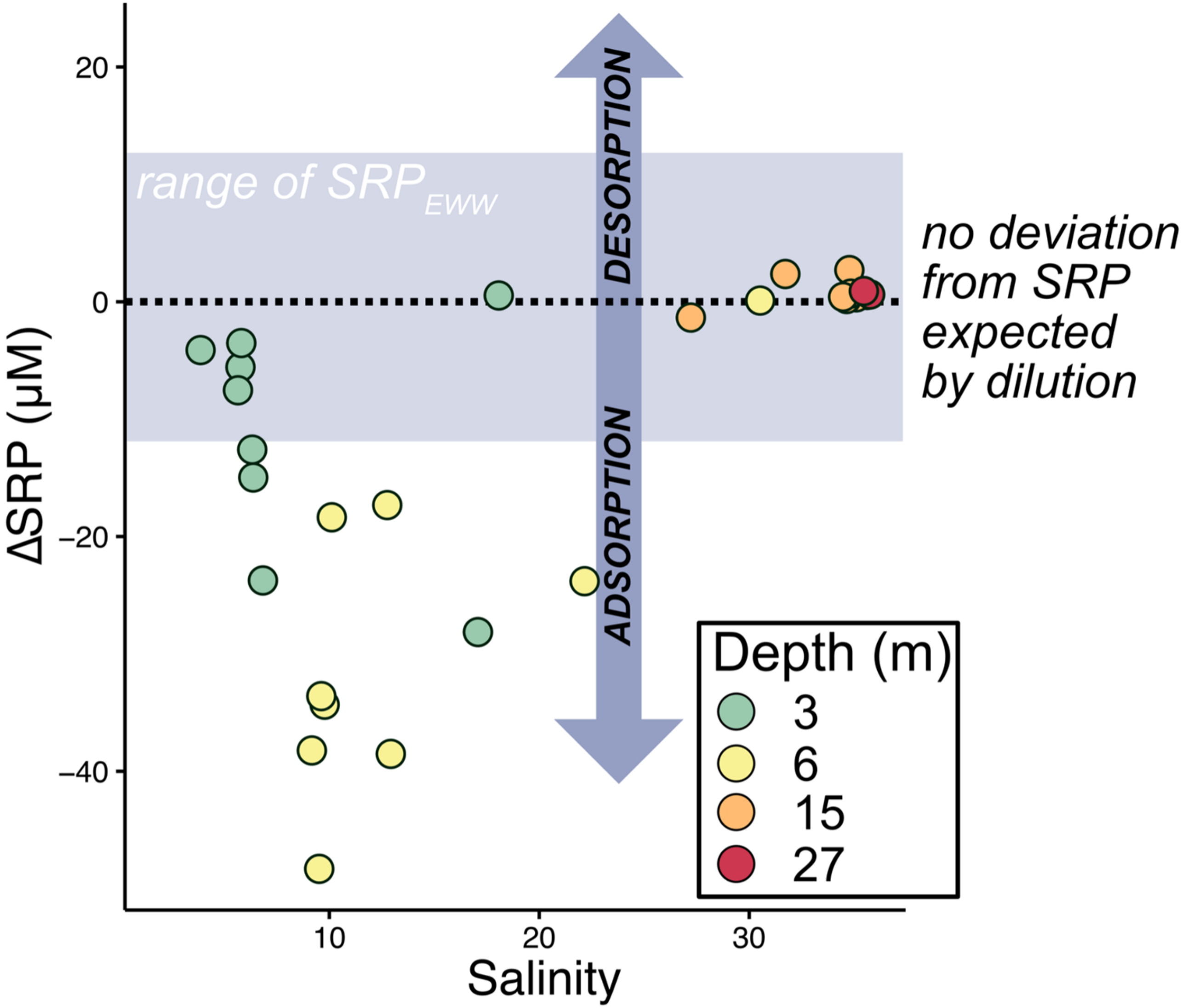




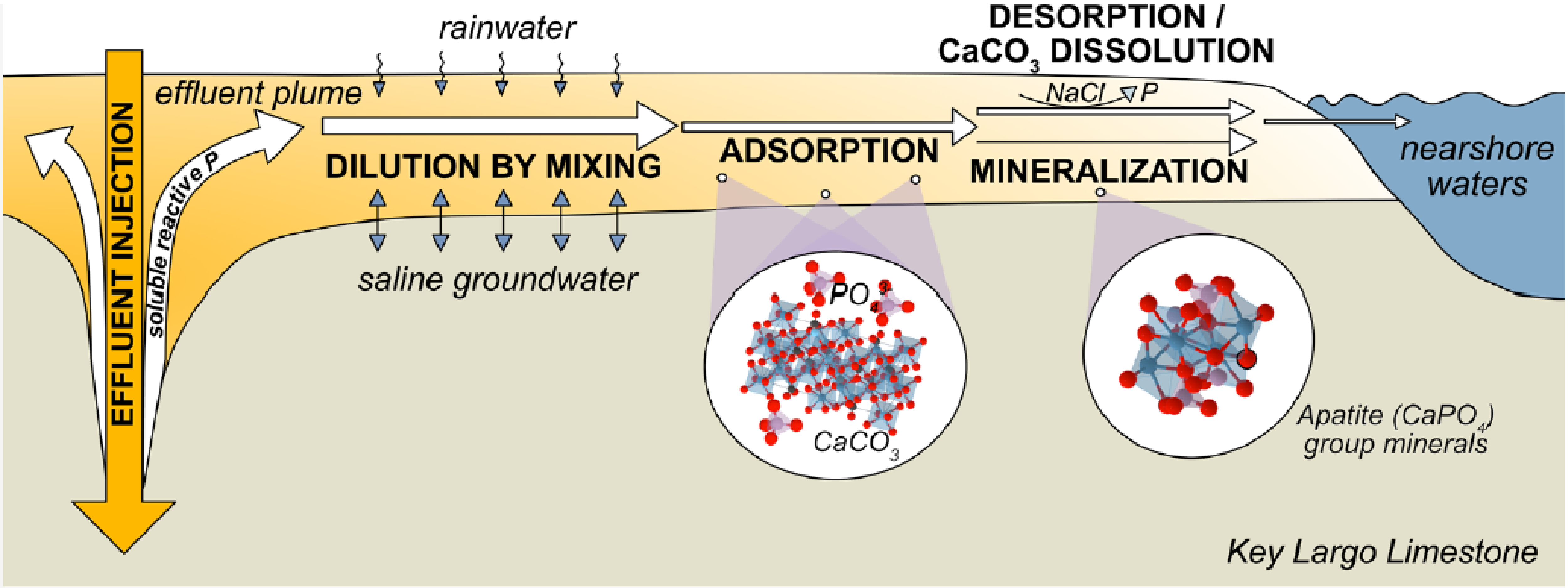
Water in the plume migration pathway show net adsorption





$$SRP_{EWW} \times f_{ww} = SRP_{expected}$$

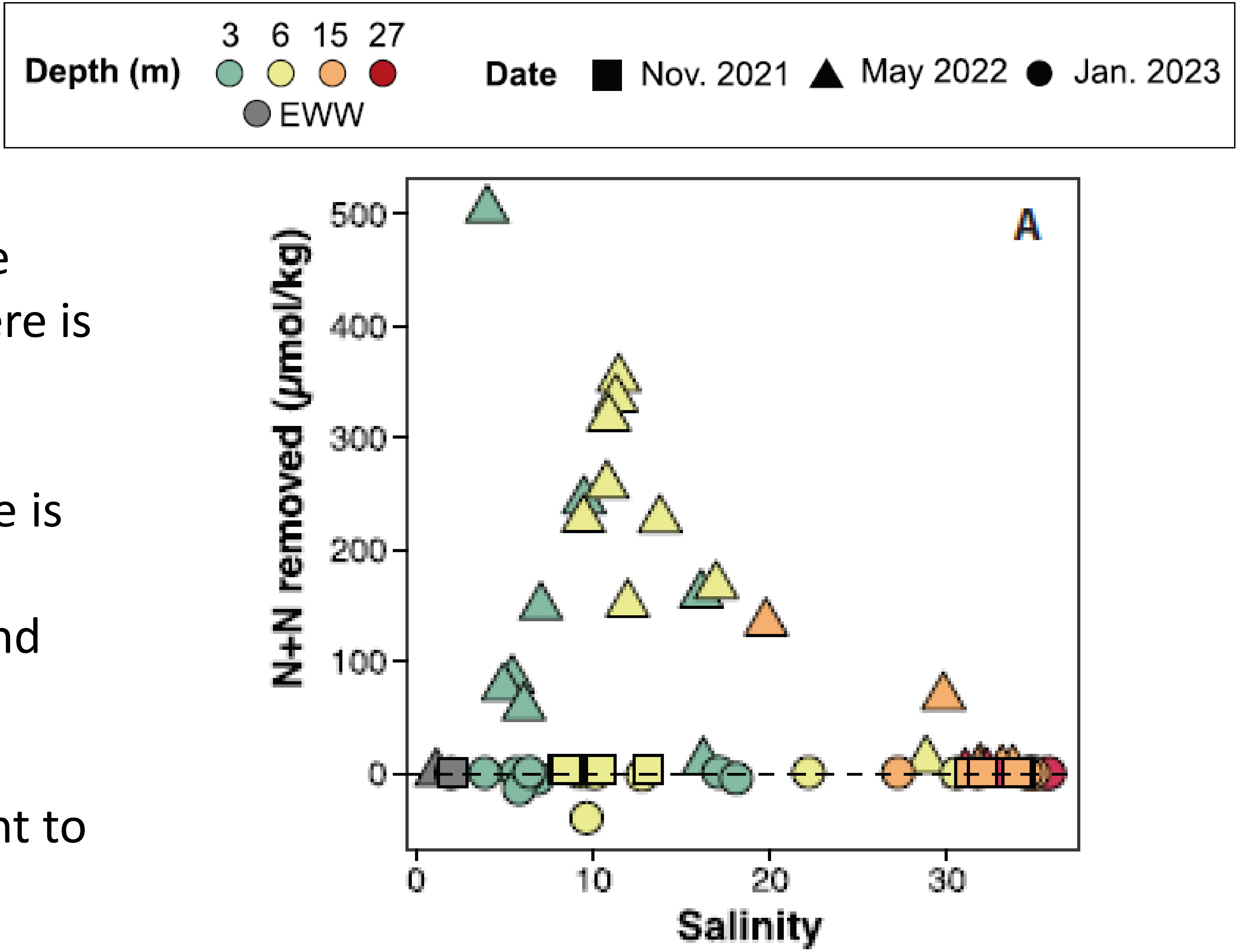
(SRP_{EWW} = 75 - 100 µmol/kg)

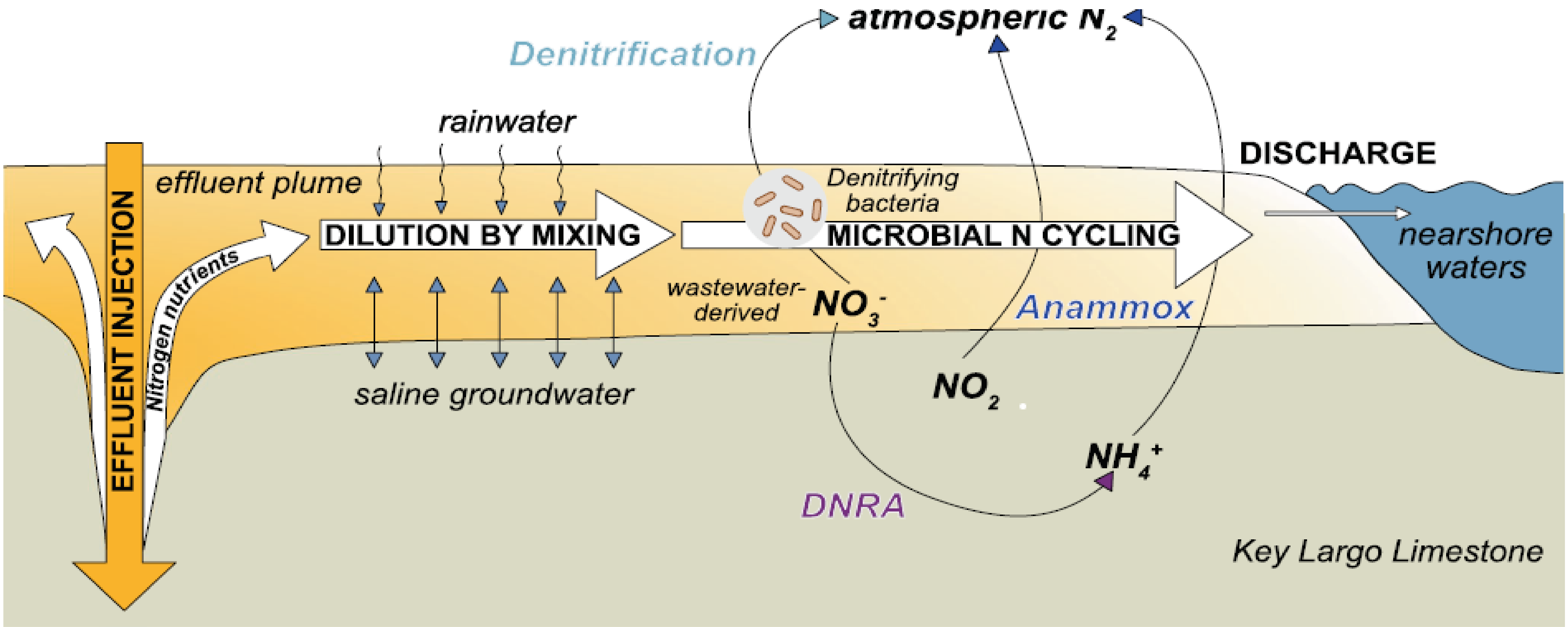


rainwater
DESORPTION / $CaCO_3$ DISSOLUTION
effluent plume
NaCl P
soluble reactive P
EFFLUENT INJECTION
DILUTION BY MIXING
ADSORPTION
MINERALIZATION
nearshore waters
saline groundwater
PO_4^{3-}
$CaCO_3$
Apatite ($CaPO_4$) group minerals
Key Largo Limestone

Nitrogen

- Evidence for extensive denitrification but there is significant temporal variability
- Time in the subsurface is an important control
- Wastewater tracers and wastewater-derived nutrient nitrogen are found at wells adjacent to Florida Bay

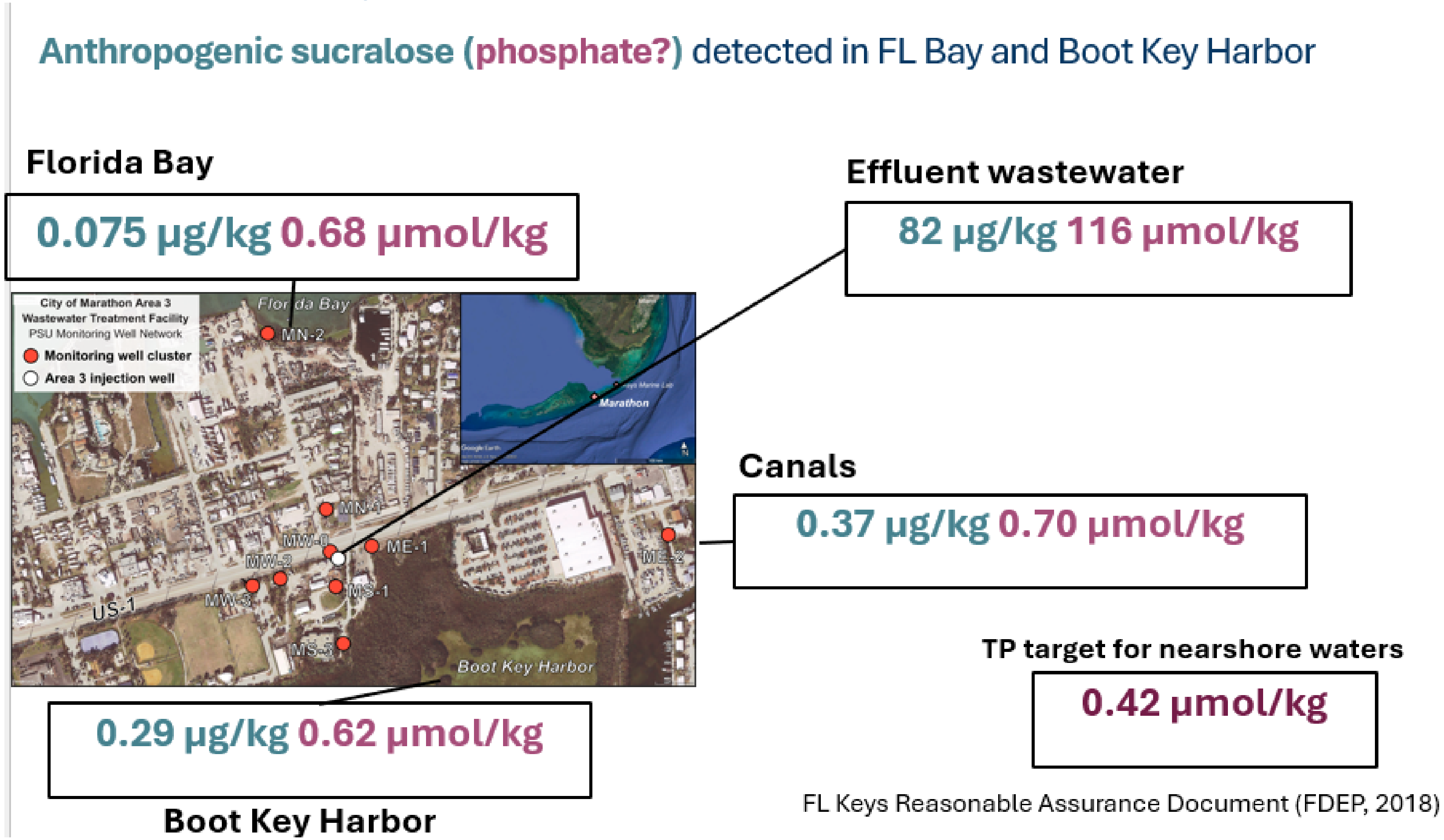




atmospheric N_2
Denitrification
rainwater
DISCHARGE
effluent plume
Denitrifying
bacteria
EFFLUENT INJECTION
Nitrogen nutrients
DILUTION BY MIXING
MICROBIAL N CYCLING
nearshore
waters
wastewater-
derived
NO_3^-
Anammox
saline groundwater
NO_2
NH_4^+
DNRA
Key Largo Limestone

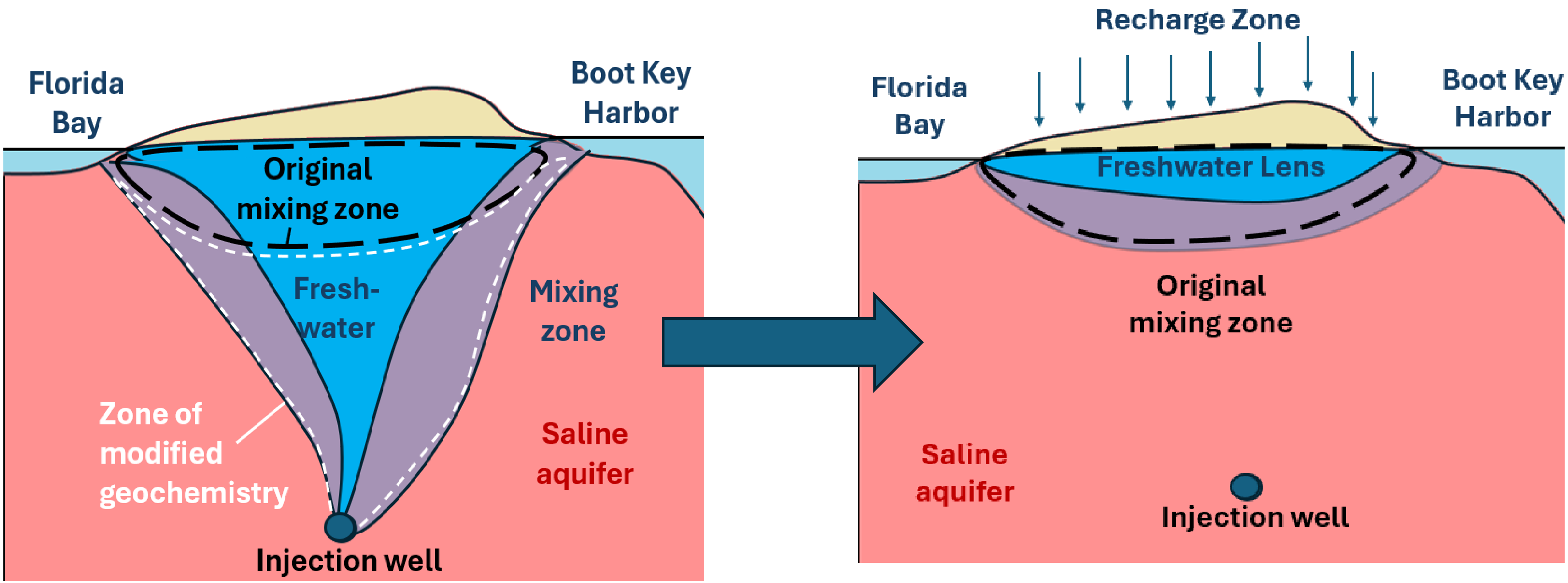
Nutrient key takeaways

- Both nitrate and phosphate removed along flow path from injection well to surface waters
- Measurable quantities of anthropogenic pollutants likely discharging from subsurface to adjacent surface waters



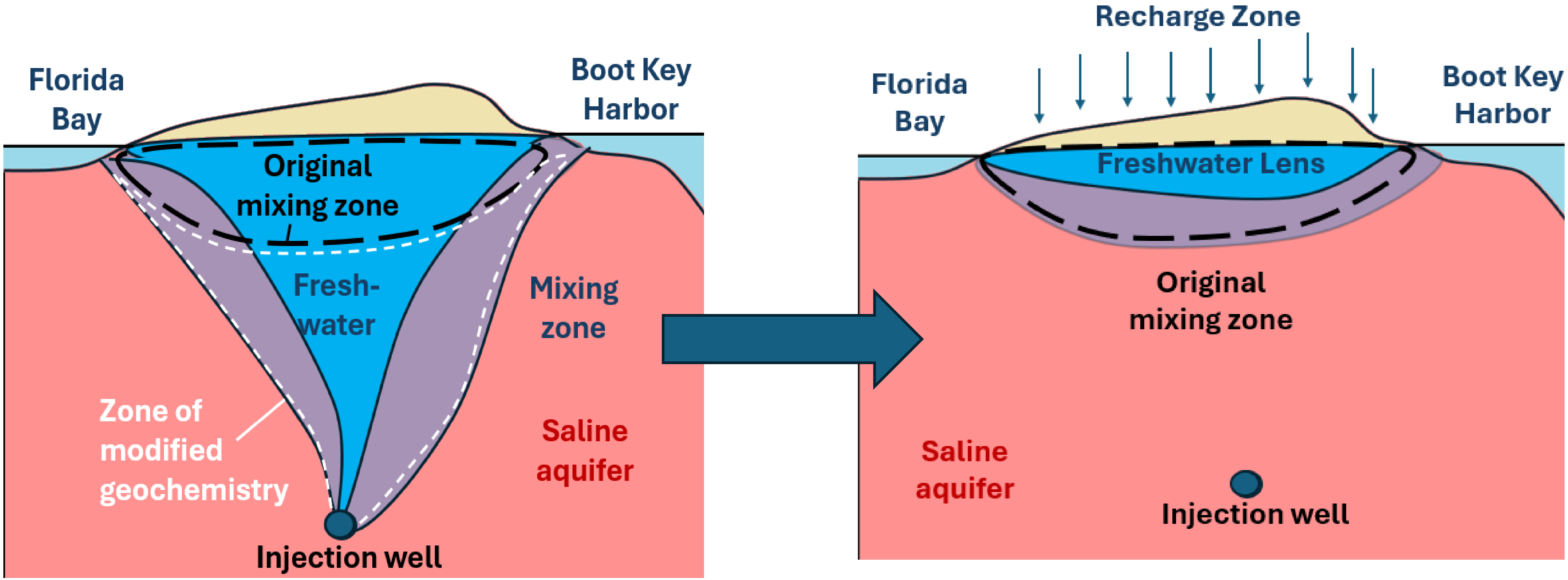
Looking to the transition to deep injection

- What are the possible consequences for water quality?
- What is the time scale of recovery?



Looking to the transition to deep injection

- High salinity water can cause phosphorous desorption of non-stable phosphorous minerals



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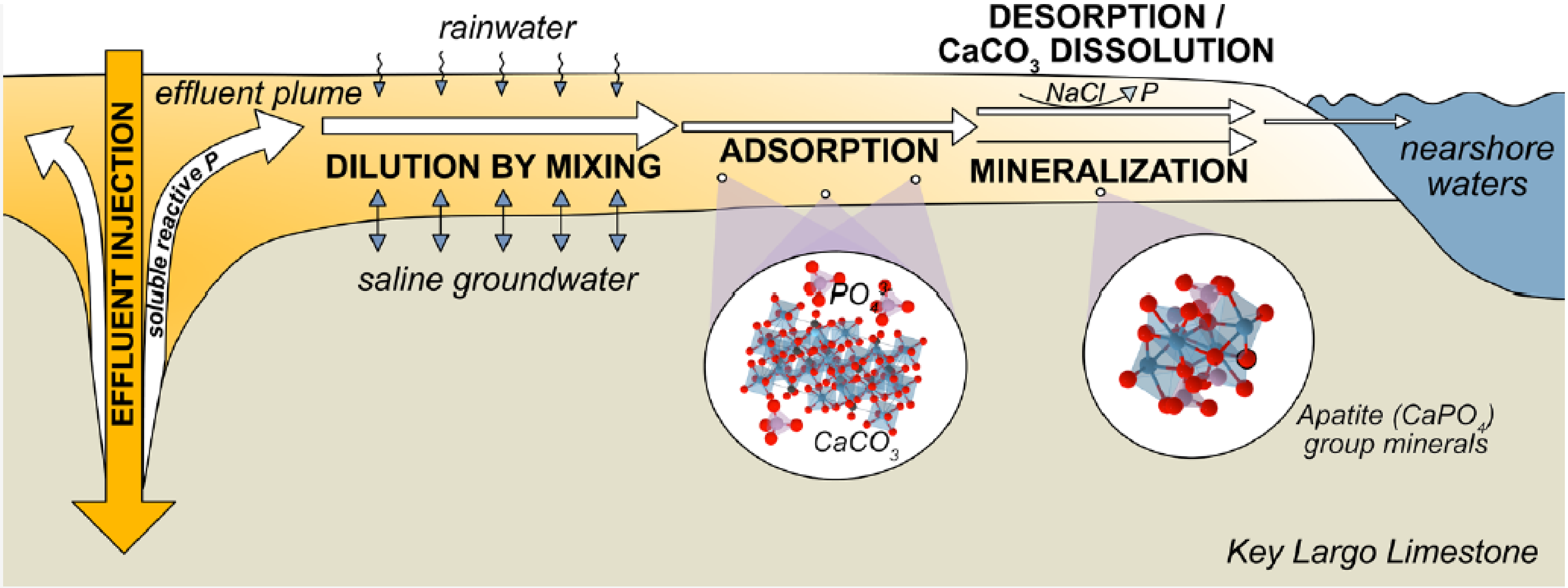
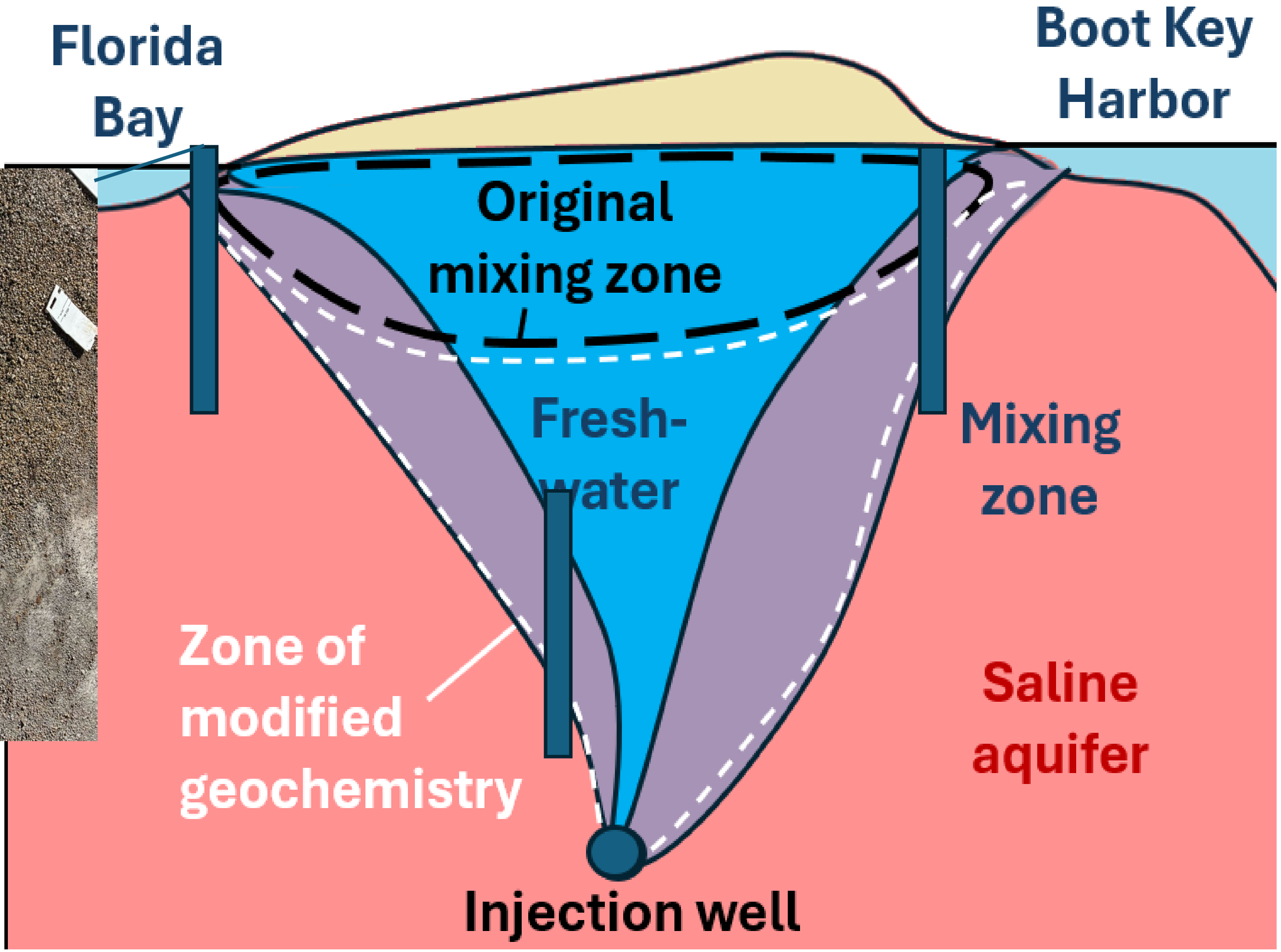


Christian Lundy

How much phosphorous is in the limestone? What are the mineral phases?

Collected 3, 30 ft carbonate cores from different salinity zones in Sept 2025



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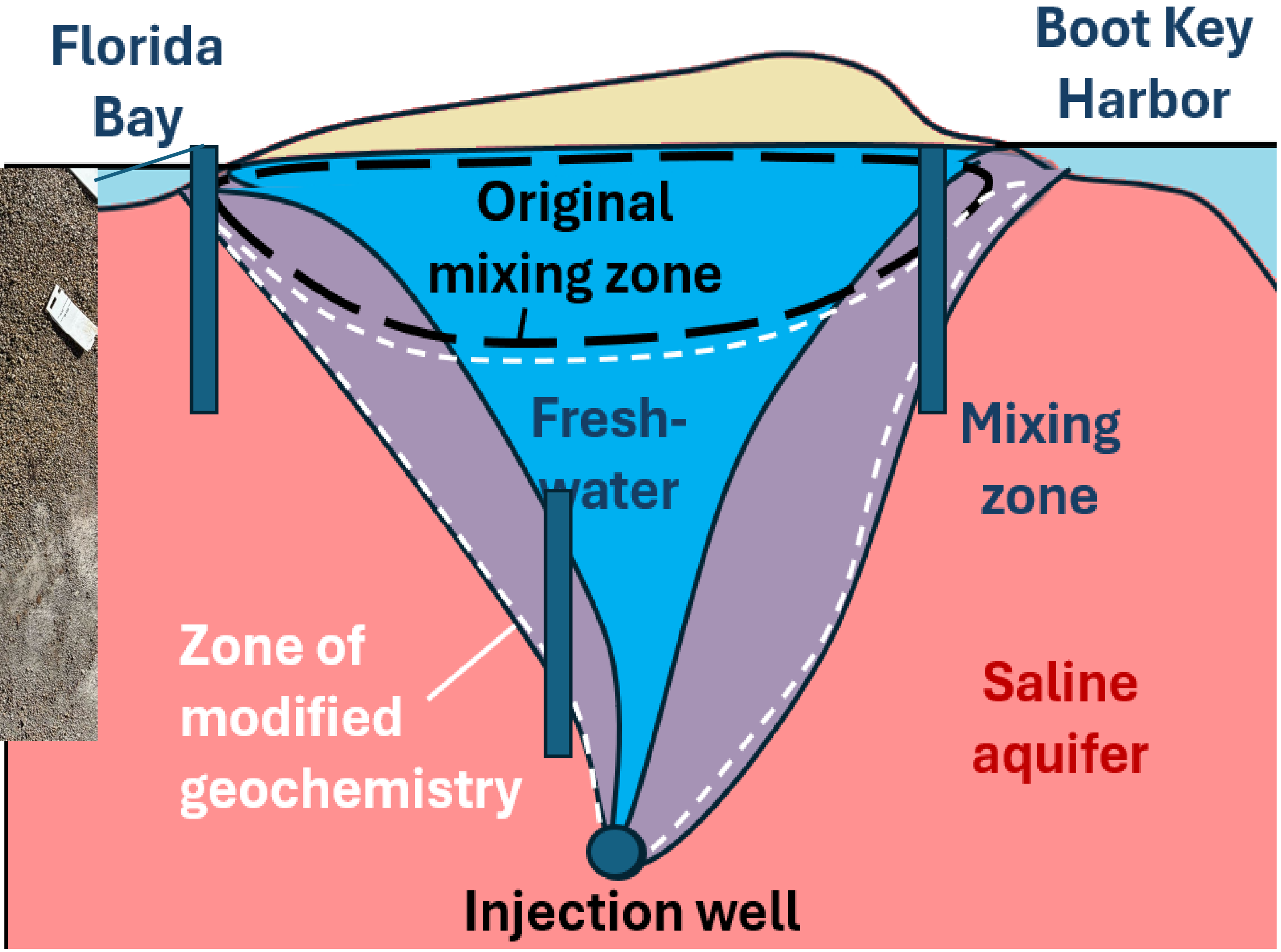
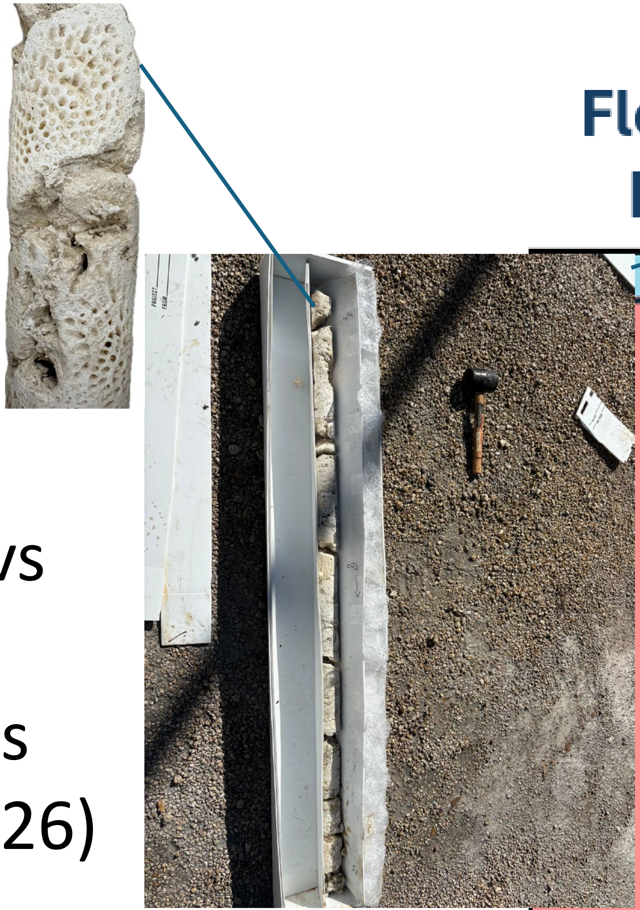


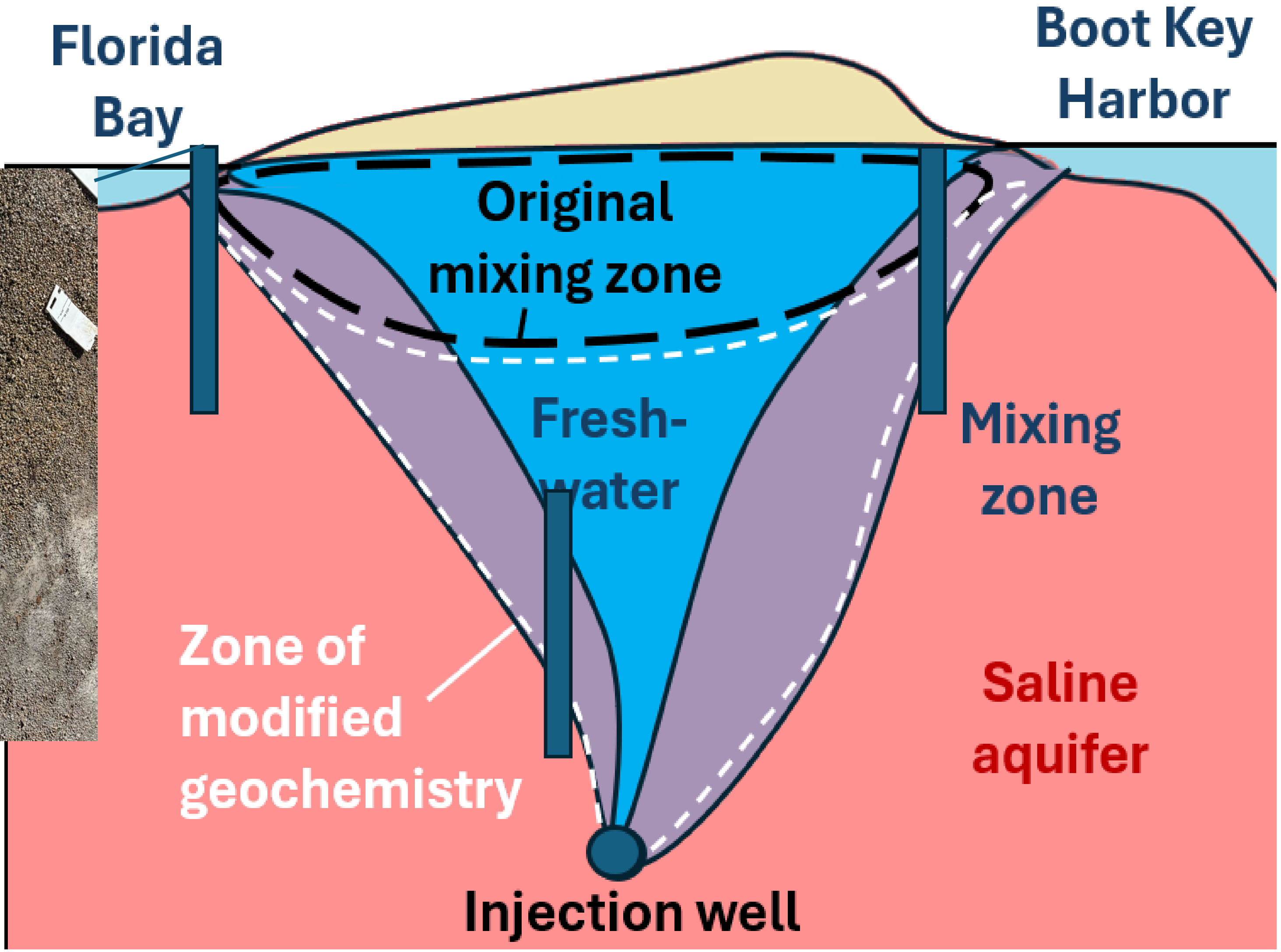
Analyzing for

- Phosphorous vs depth
- Mineral phases (SLAC, May 2026)

How much phosphorous is in the limestone? What are the mineral phases?

Christian Lundy





Analyzing for
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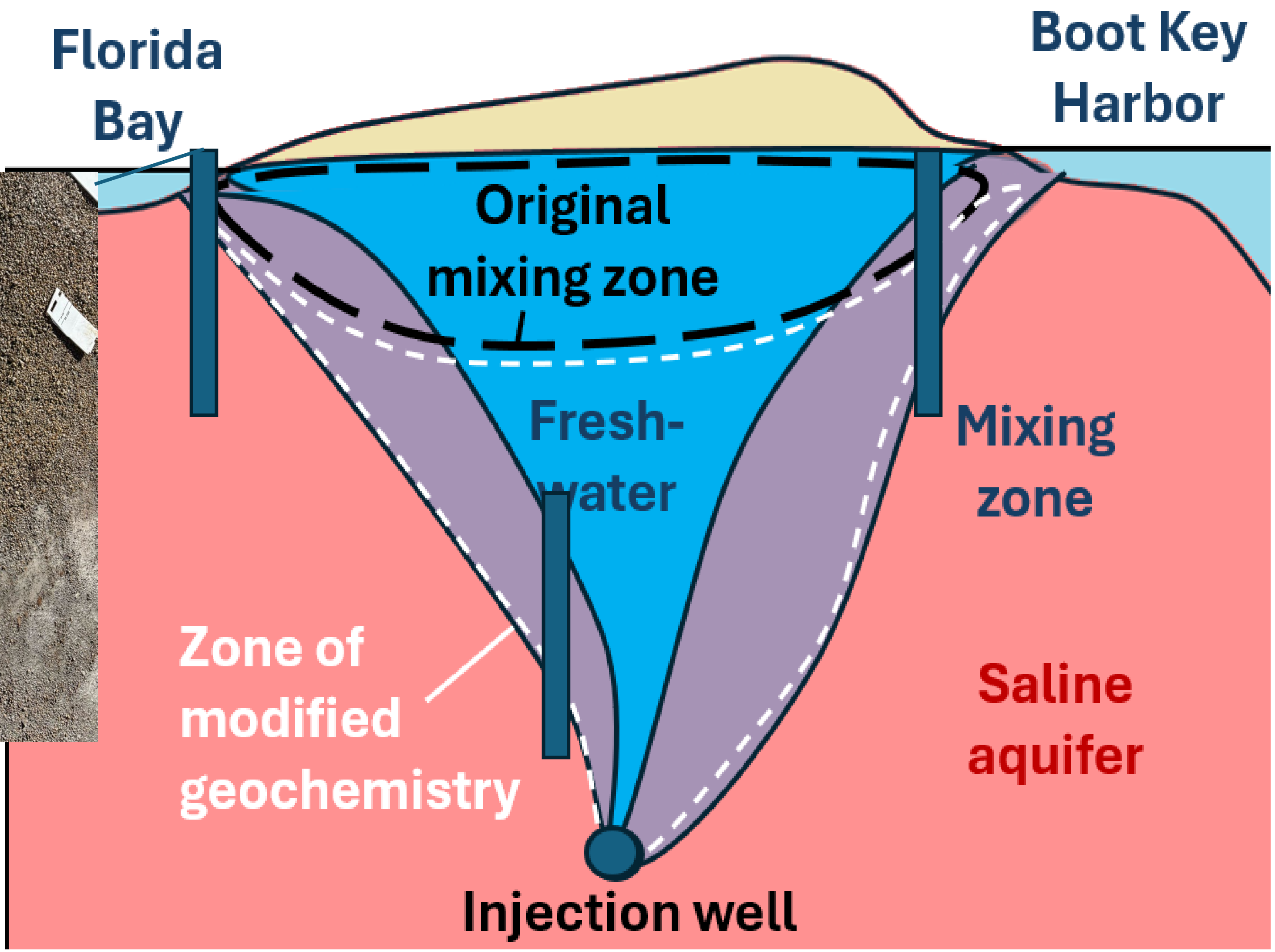
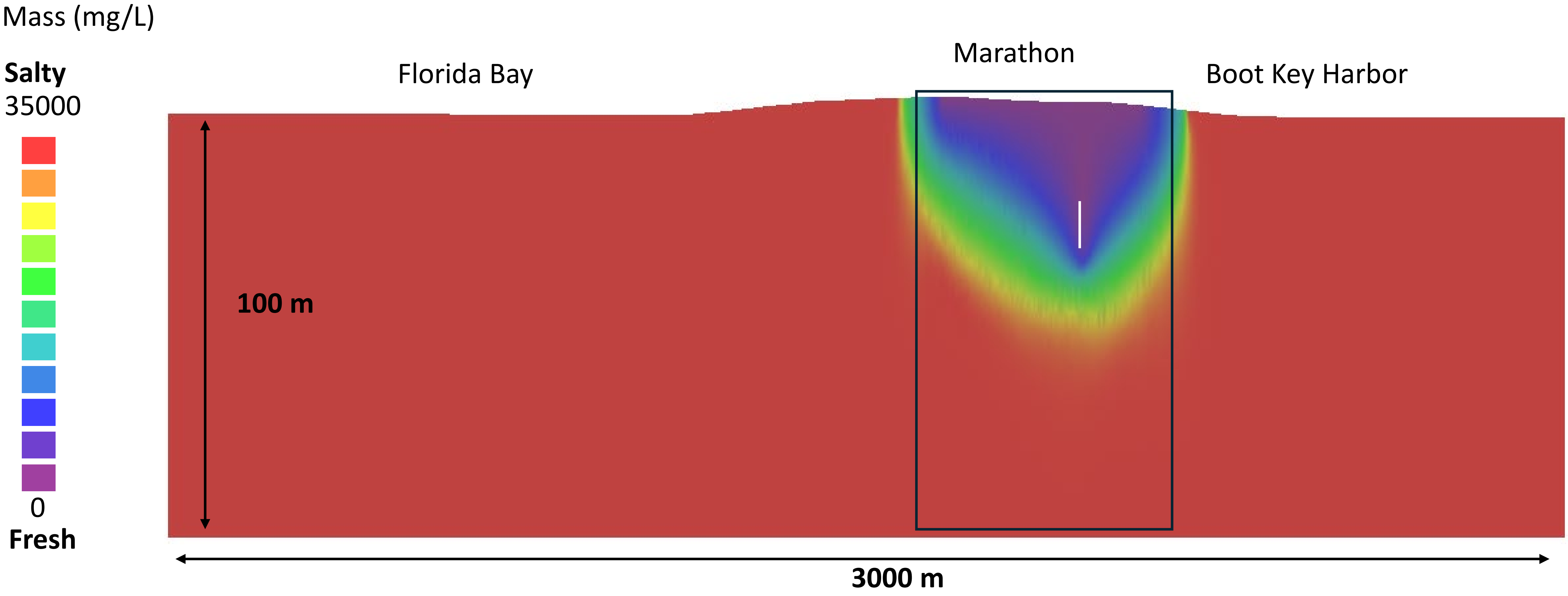
Christian Lundy

Goal:
Understand aquifer vulnerability to phosphorous remobilization

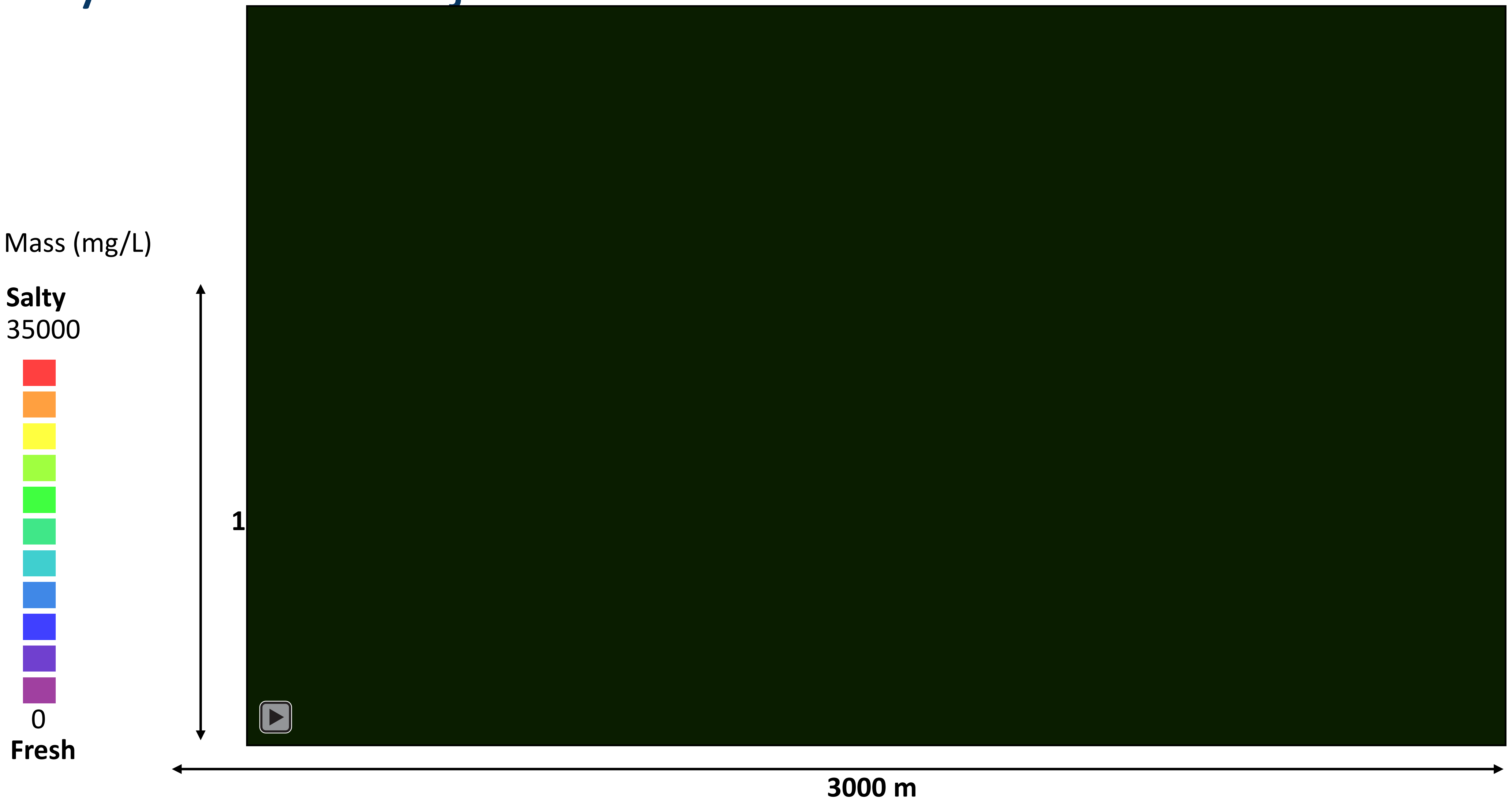


What is the recovery time?
What are best practices for ongoing shallow injection?

FEFLOW variable density, groundwater flow and transport model



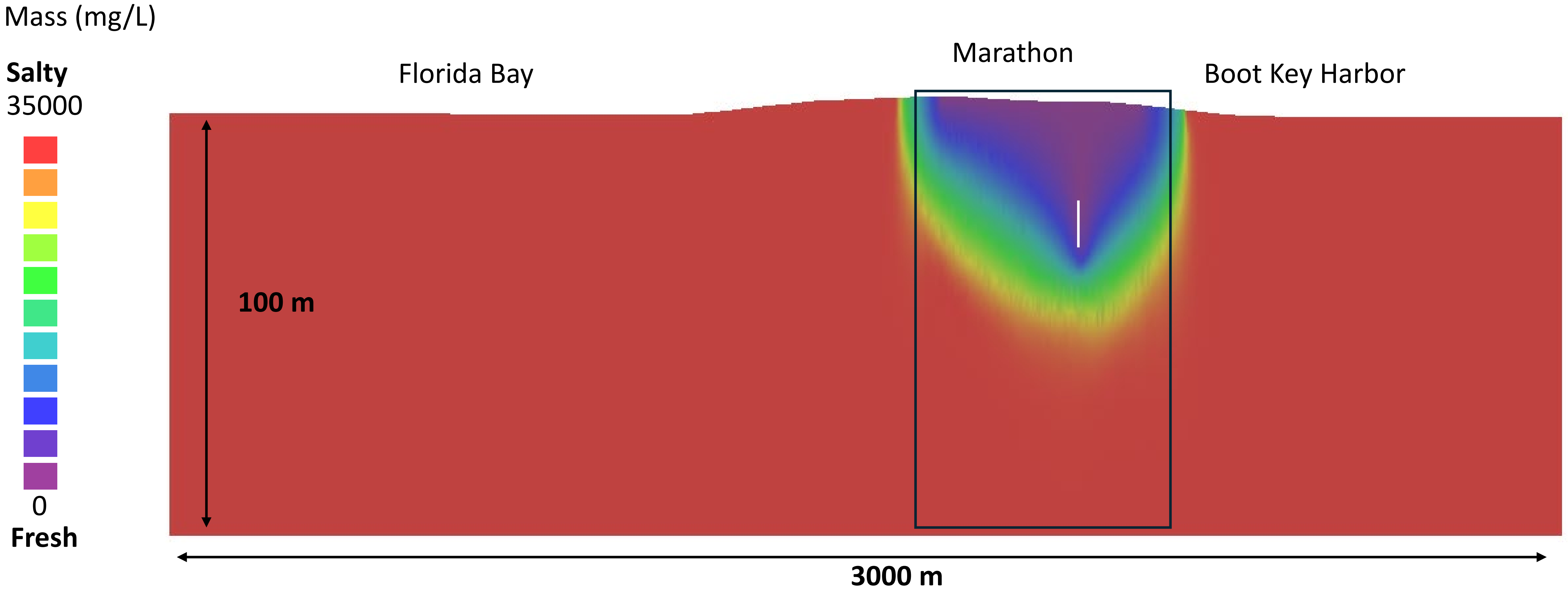
1-year of zero injection



What is the recovery time?
What are best practices for ongoing shallow injection?

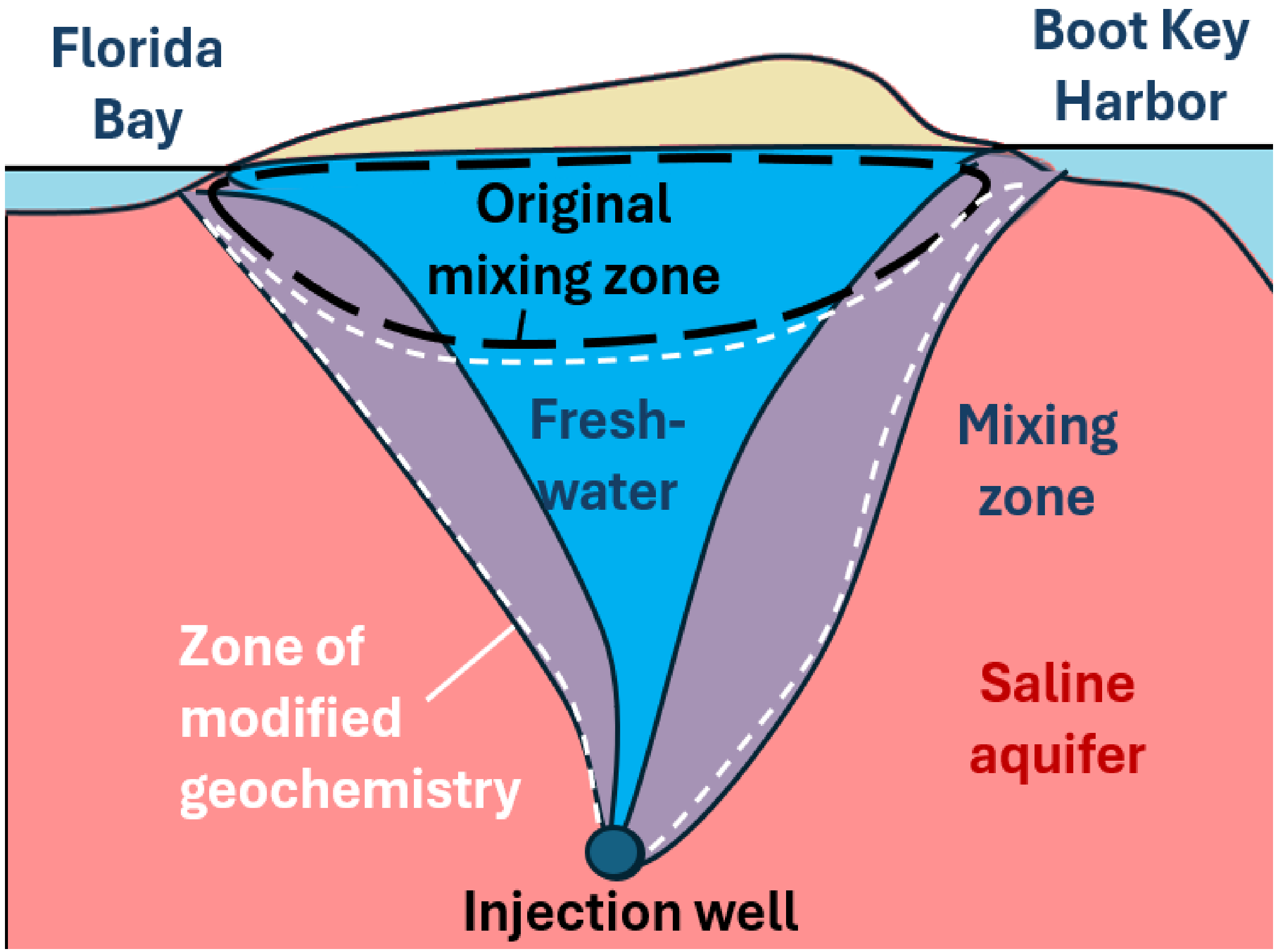
Apply model to evaluate best management practices for ongoing shallow injection

- Injection strategies to increase residence time (blending to densify)
- Max. injection rate and variable injection rates



Conclusions

- Shallow injection creates a buoyant plume that is transporting nitrate, phosphate, and other anthropogenic pollutants to adjacent surface waters
- Transport rates and interface positions dynamically evolve with tidal forcing
- Ongoing geochemistry and modeling work to understand water quality over the transition to deep injection



Thank you!

- City of Marathon
- EPA SFL

Find out more about our research:

Phosphorous Paper

Nitrogen Paper

Housego Lab

rhousego@psu.edu