Barrier Island Groundwater Dynamics

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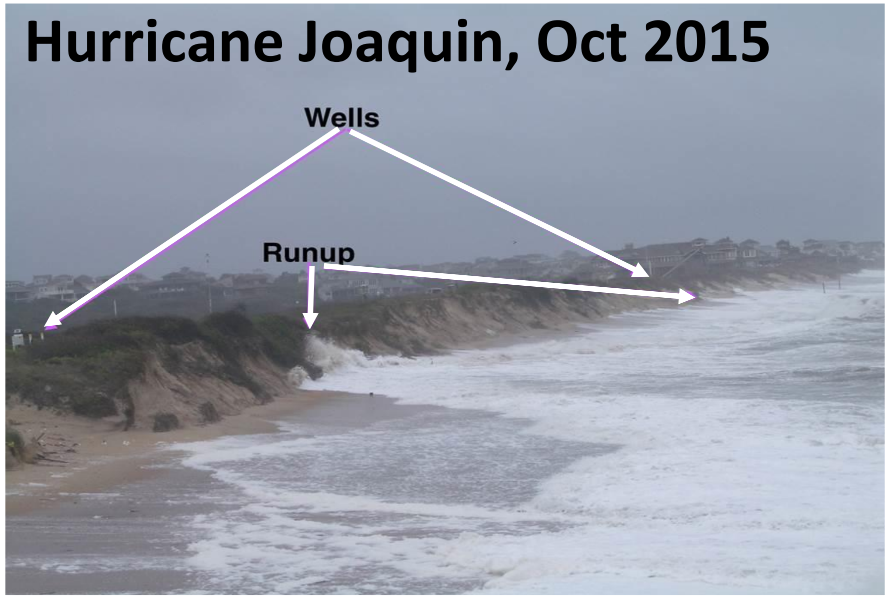
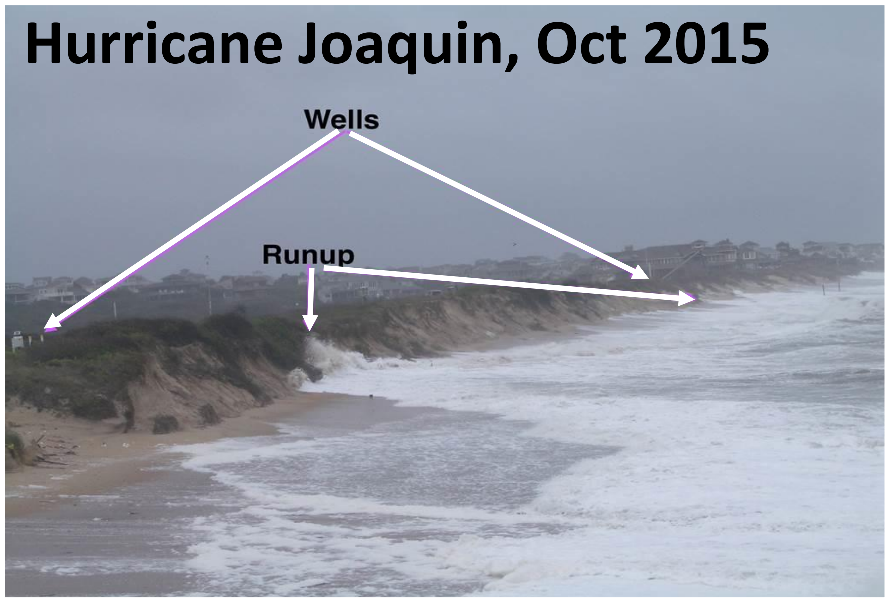
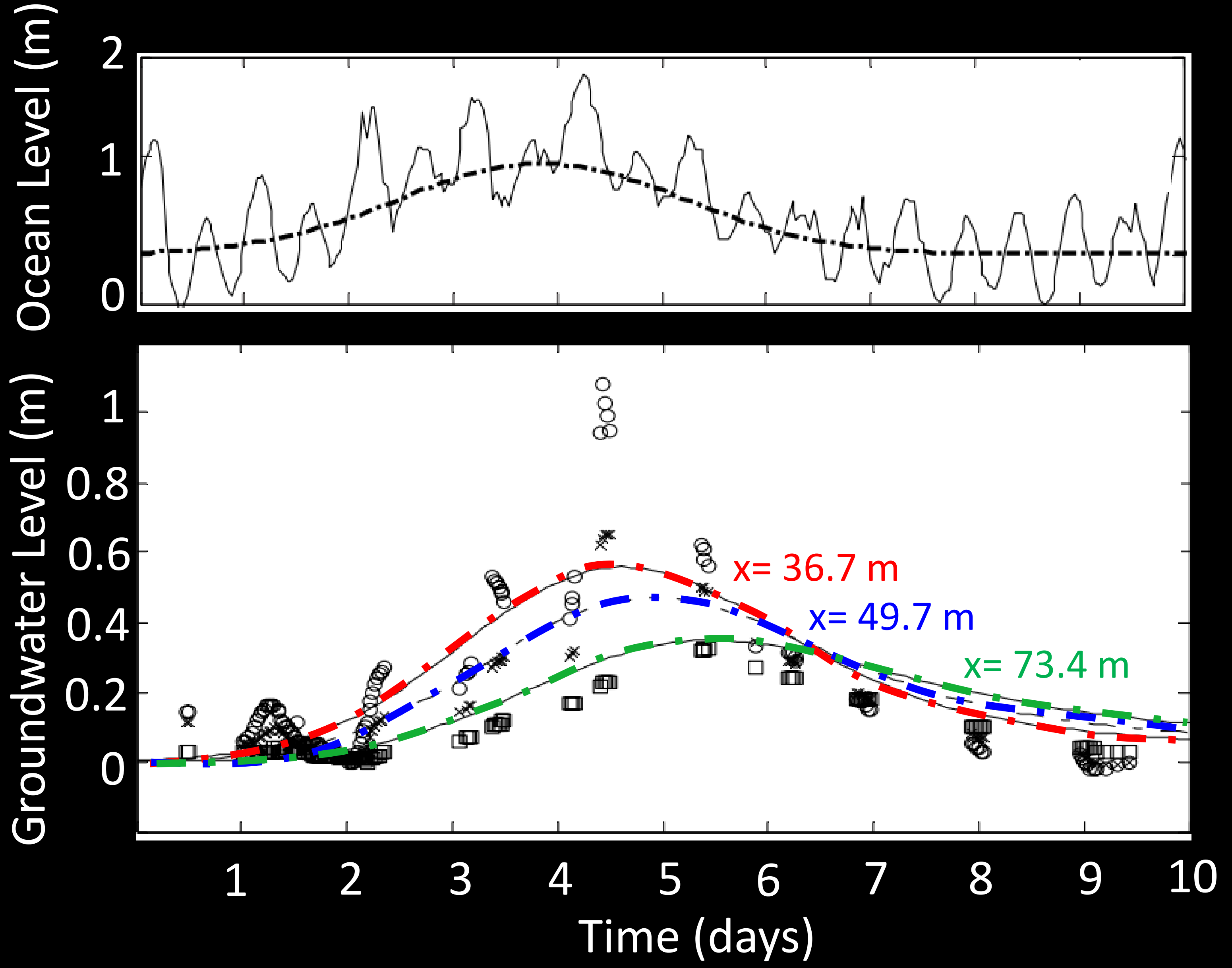
U.S. Army Engineer Research & Development Center


Hurricane Joaquin, Oct 2015
Wells
Runup


Hurricane Matthew, Oct 2016

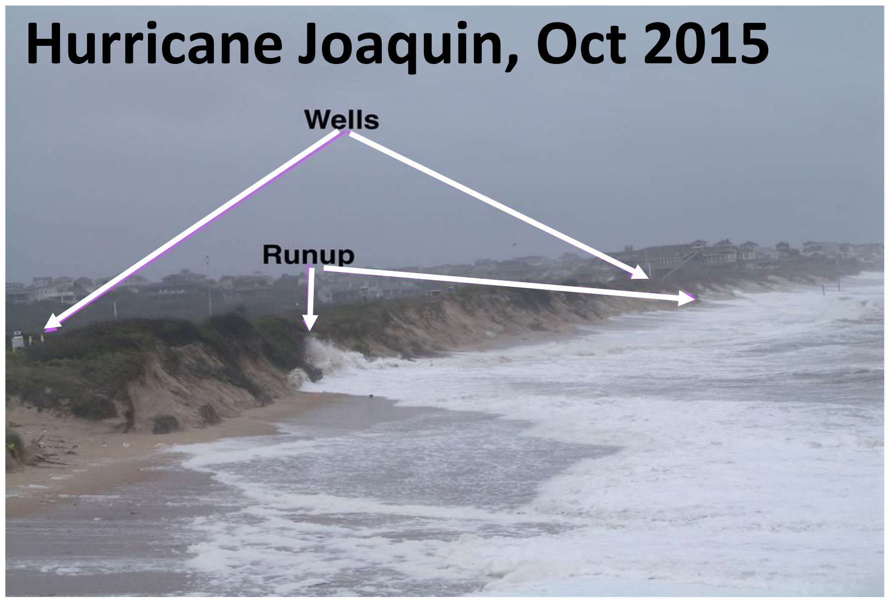


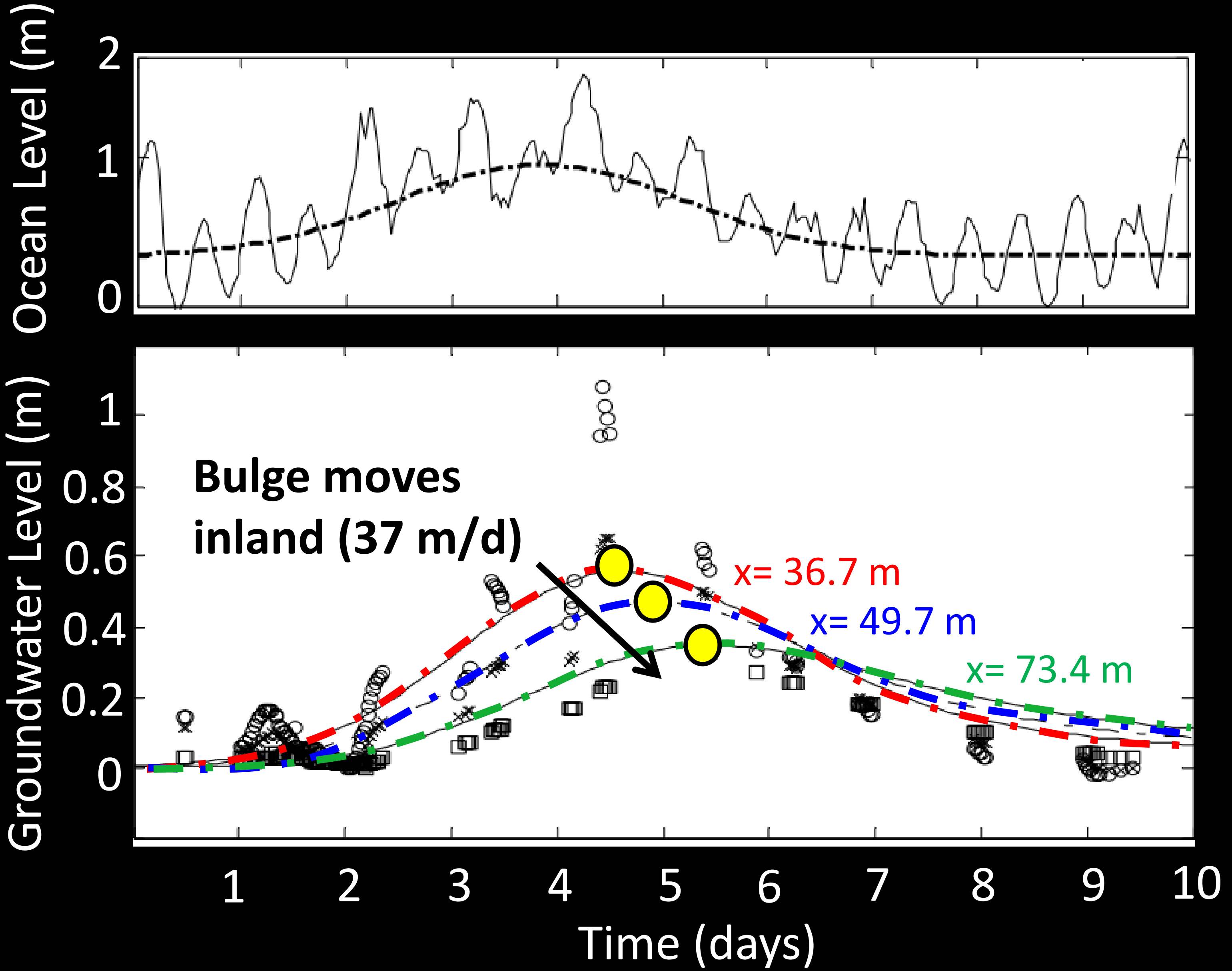
Groundwater level affected by tide, surge, & wave setup



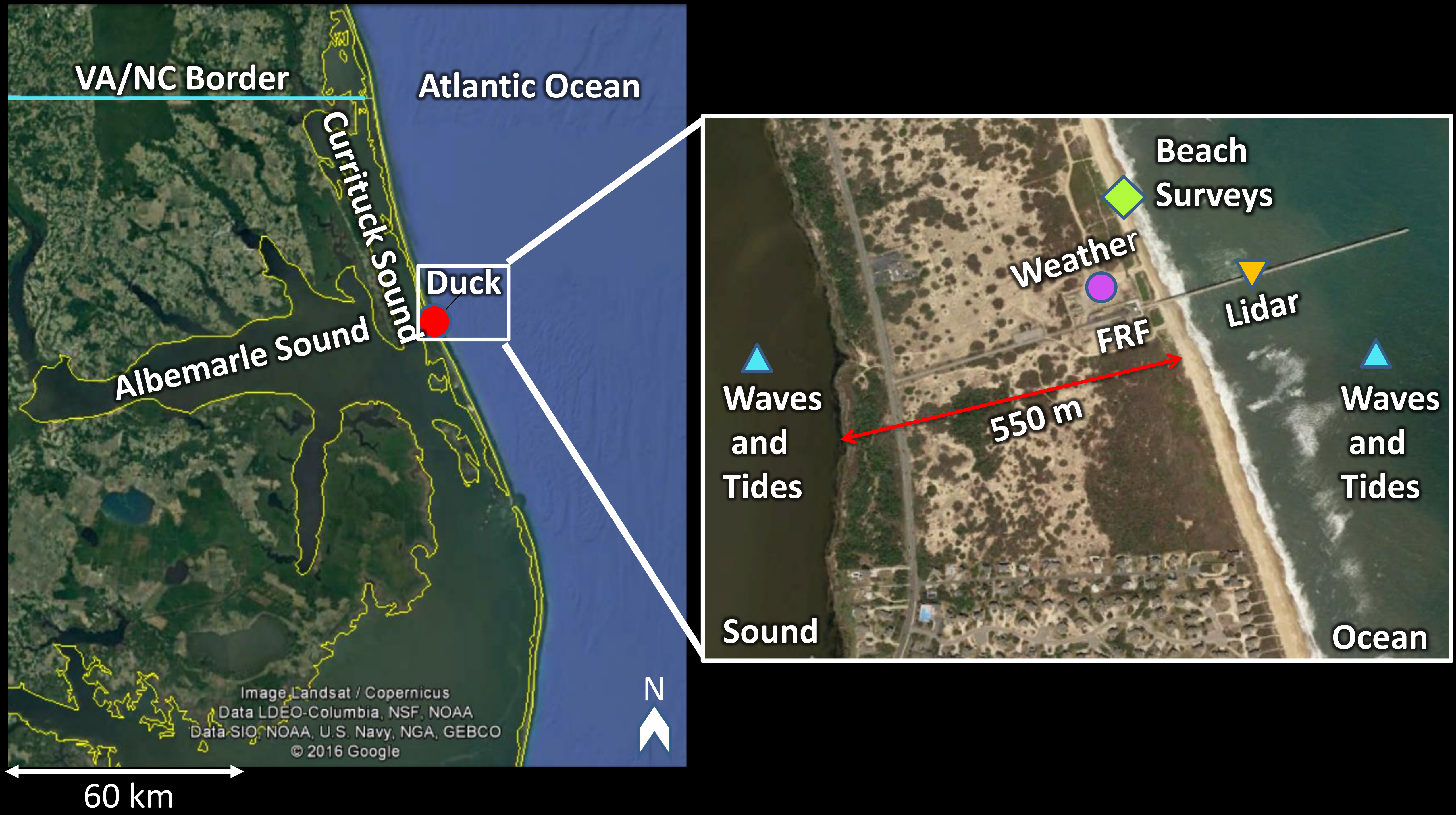
Cartwright et al. 2004, Li et al. 2004, Robinson et al. 2007, Trglavcnik et al. 2018

Groundwater level affected by tide, surge, & wave setup





Cartwright et al. 2004, Li et al. 2004, Robinson et al. 2007, Trglavcnik et al. 2018


VA/NC Border
Atlantic Ocean
Currituck Sound
Duck
Albemarle Sound
Image Landsat / Copernicus
Data LDEO-Columbia, NSF, NOAA
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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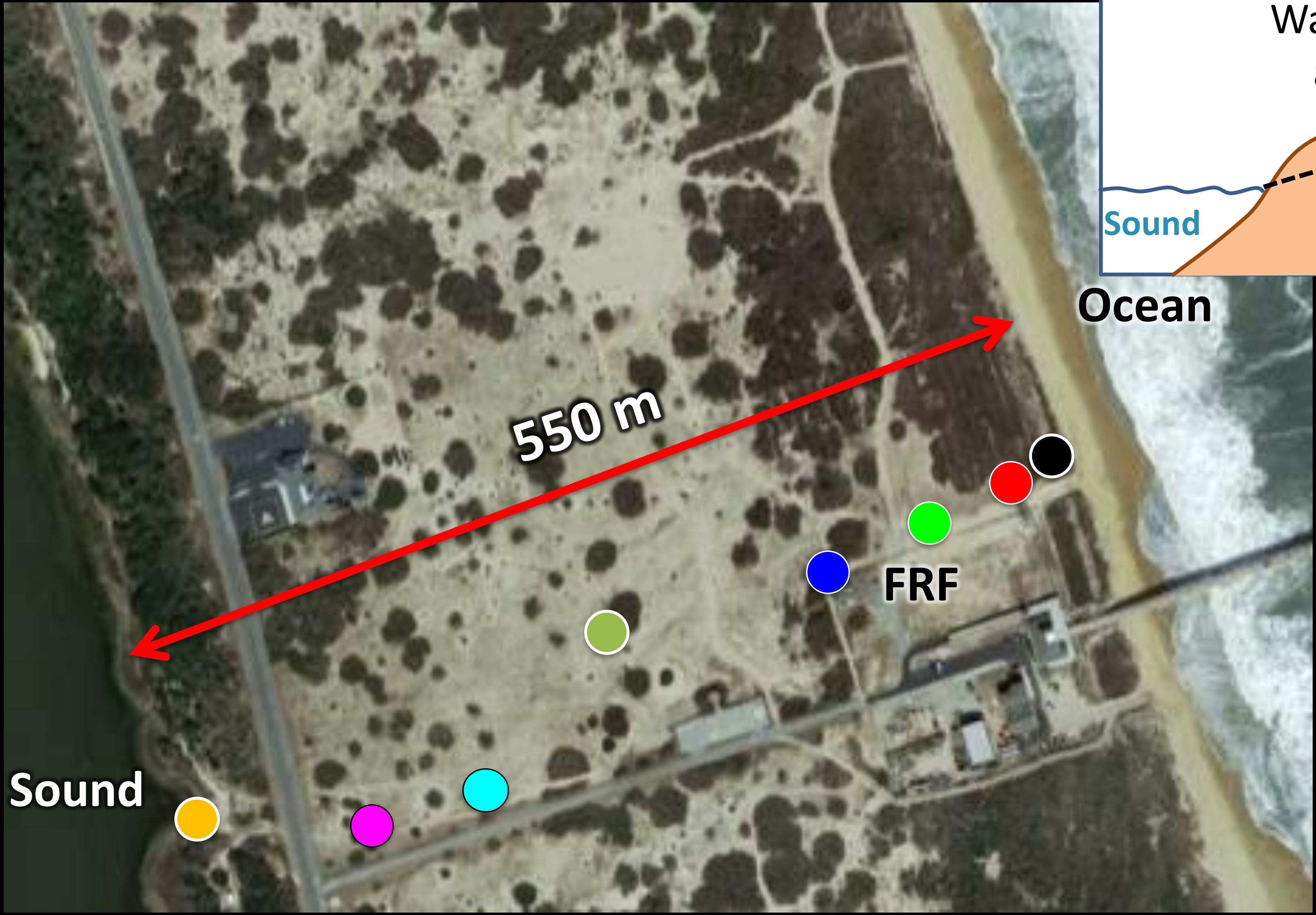
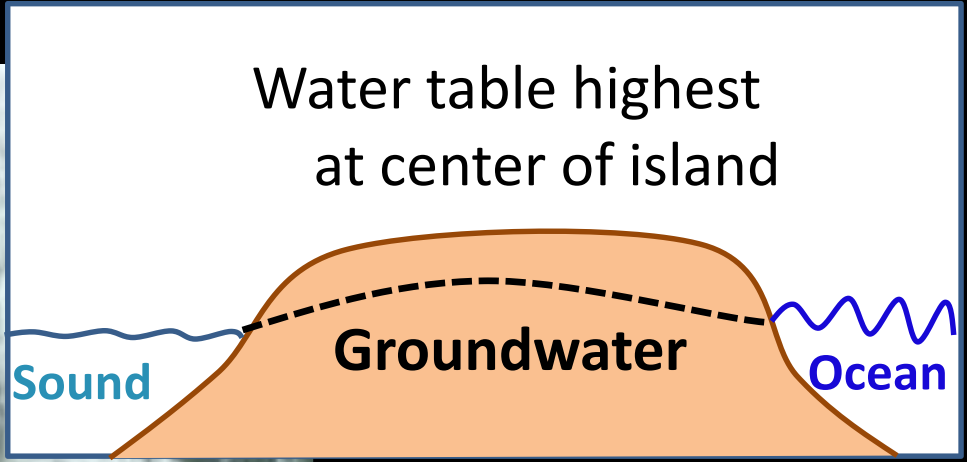
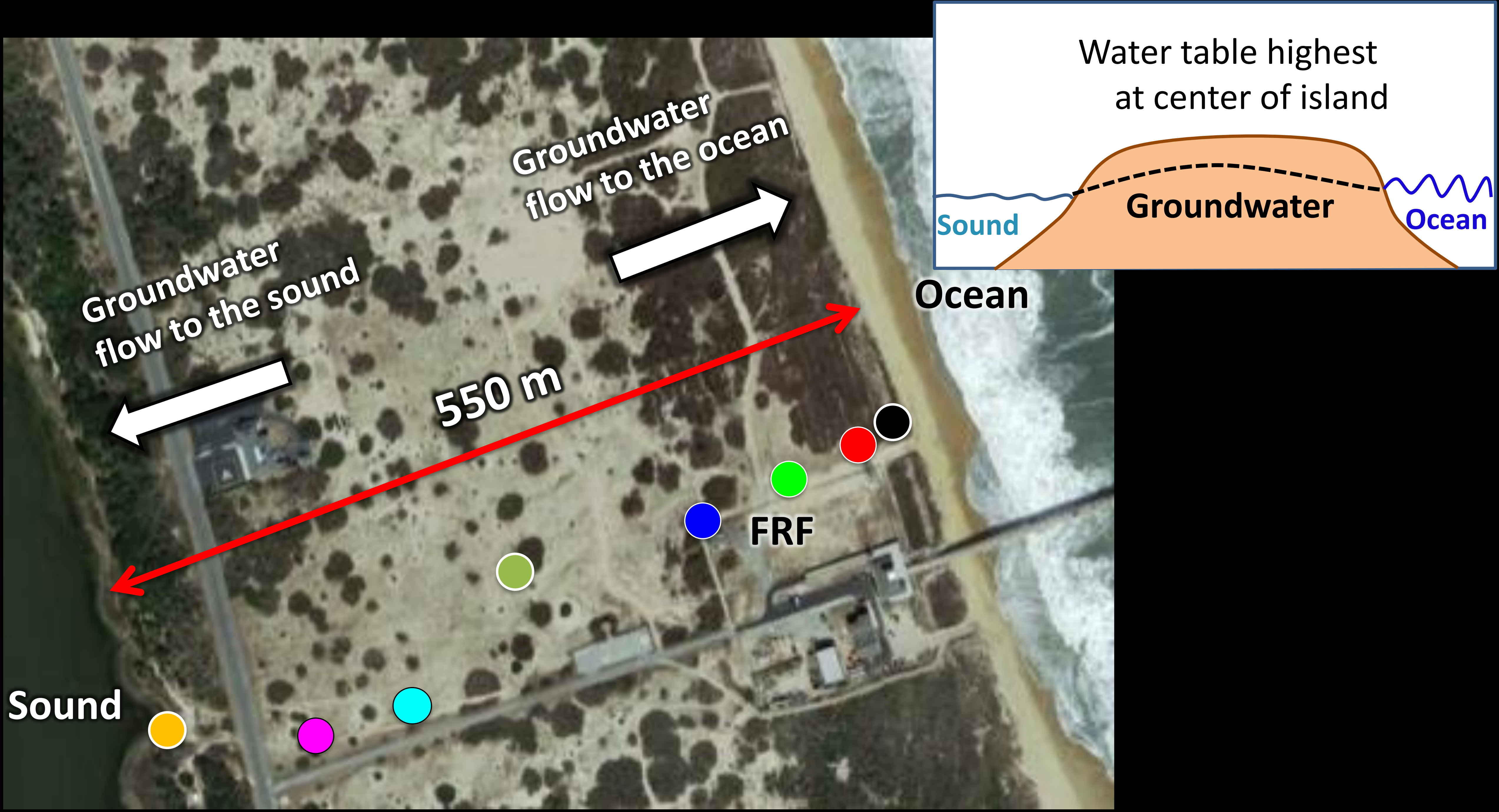
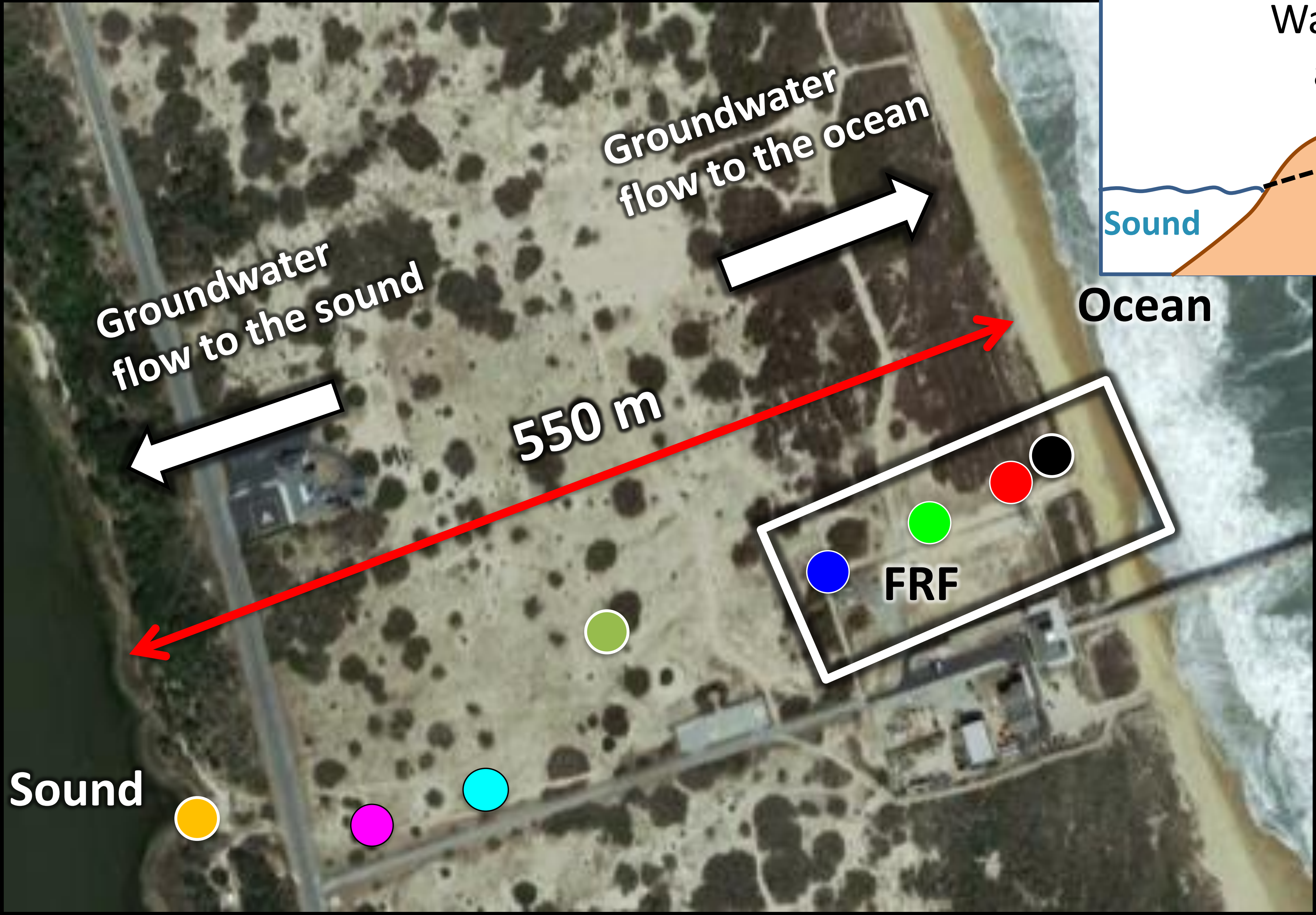
N
60 km
Beach Surveys
Weather
Lidar
FRF
550 m
Waves and Tides
Waves and Tides
Sound
Ocean

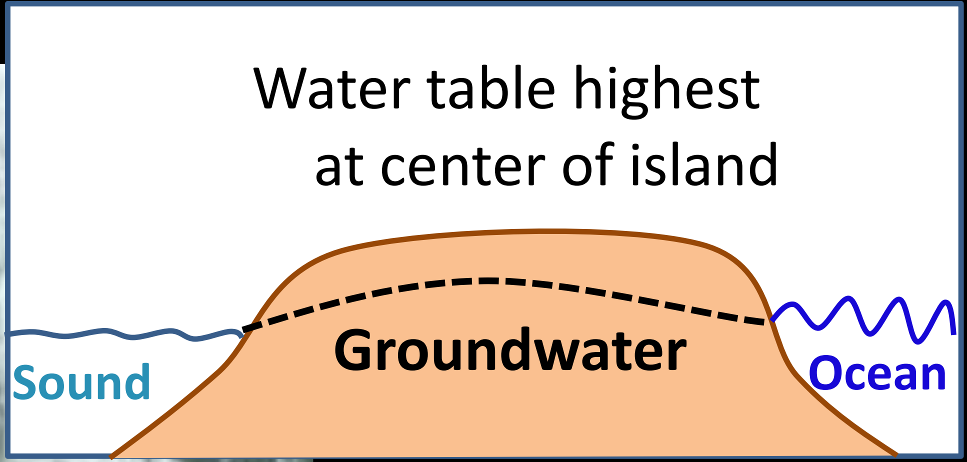
- Conductivity
- Temperature
- Pressure
- Recorded at 10 minute intervals

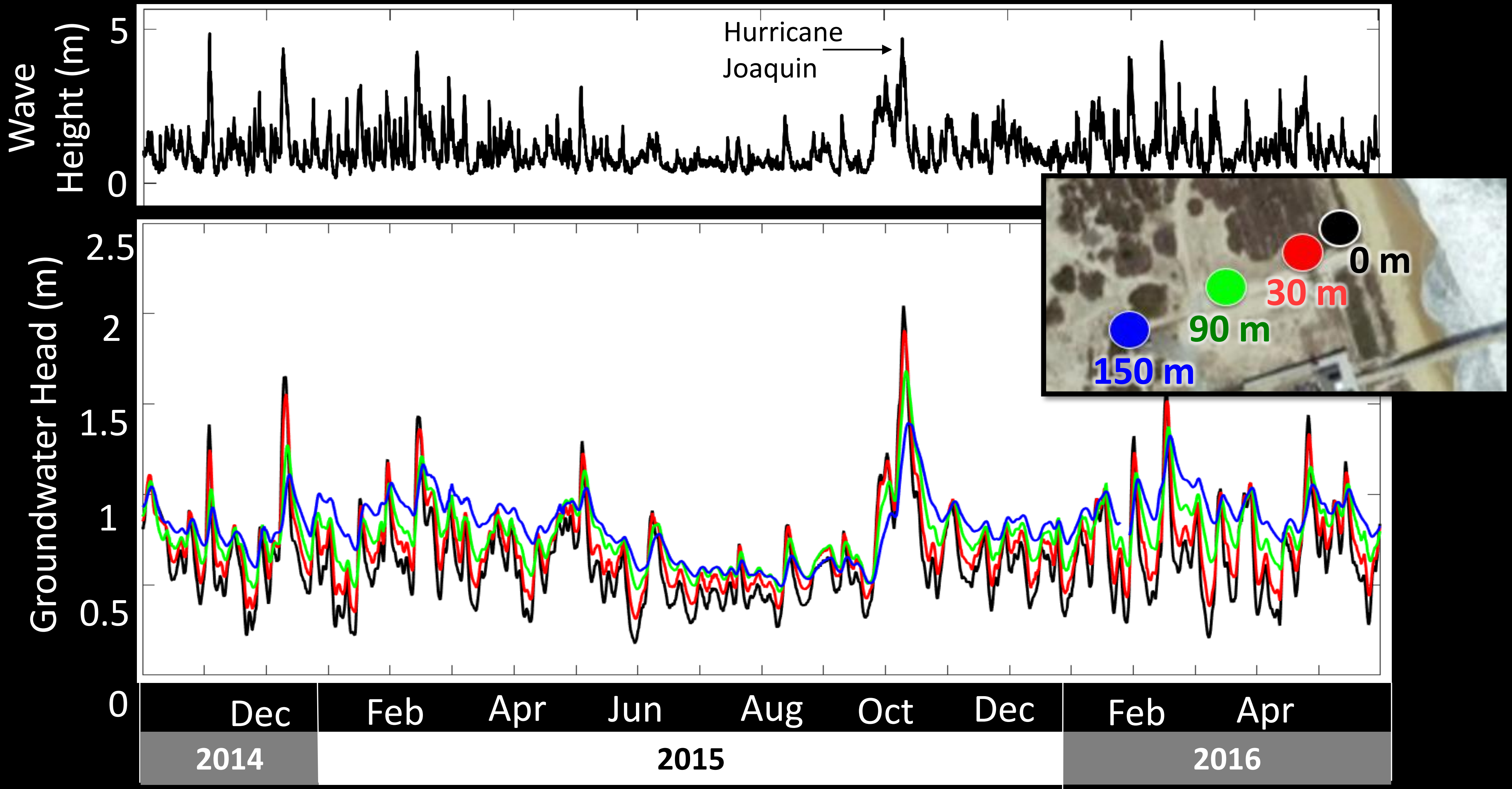

Ocean
550 m
FRF
Sound


Water table highest
at center of island
Groundwater
Sound
Ocean

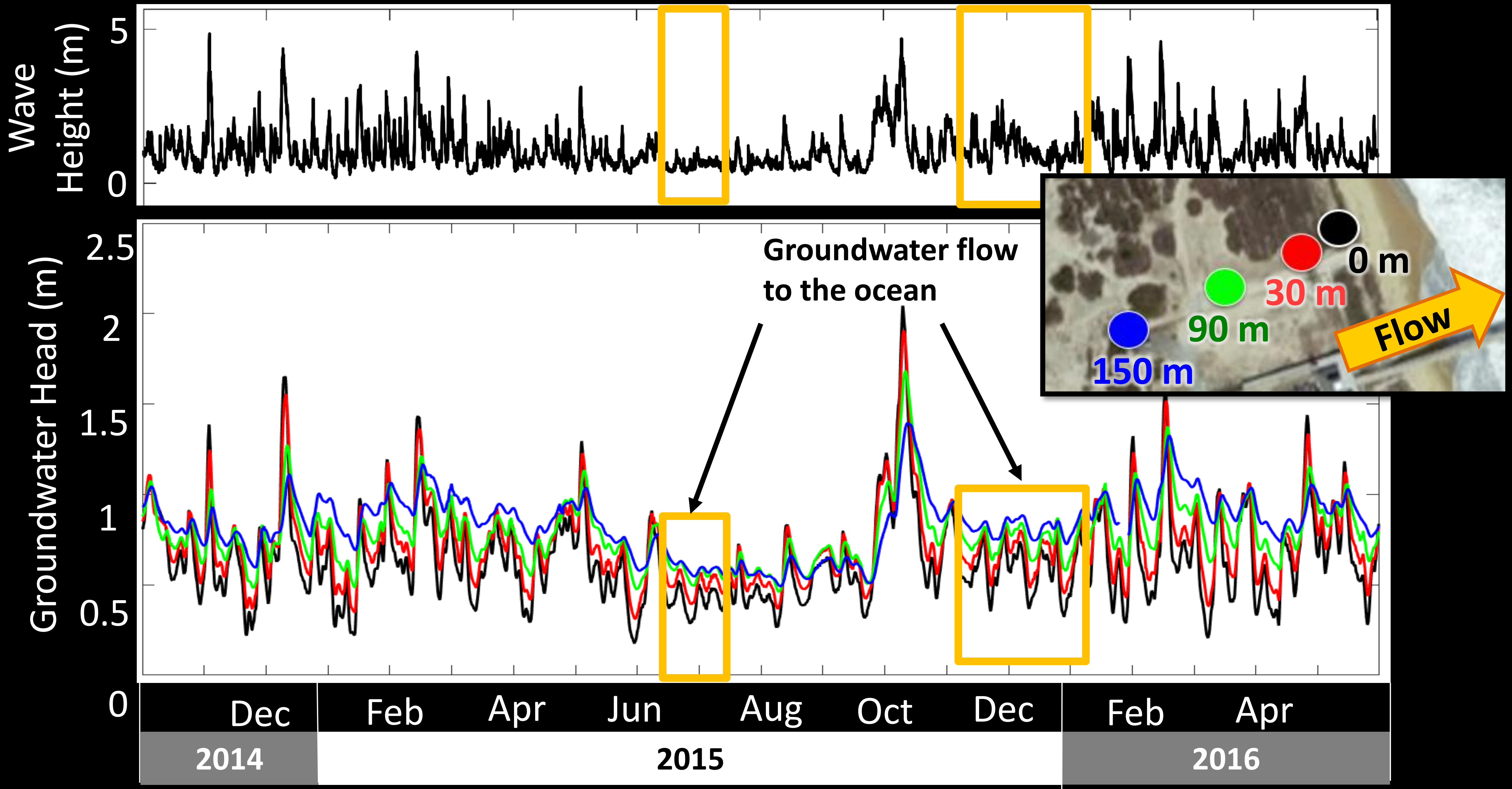

Water table highest
at center of island
Sound
Groundwater
Ocean
Groundwater
flow to the ocean
Groundwater
flow to the sound
550 m
Ocean
FRF
Sound

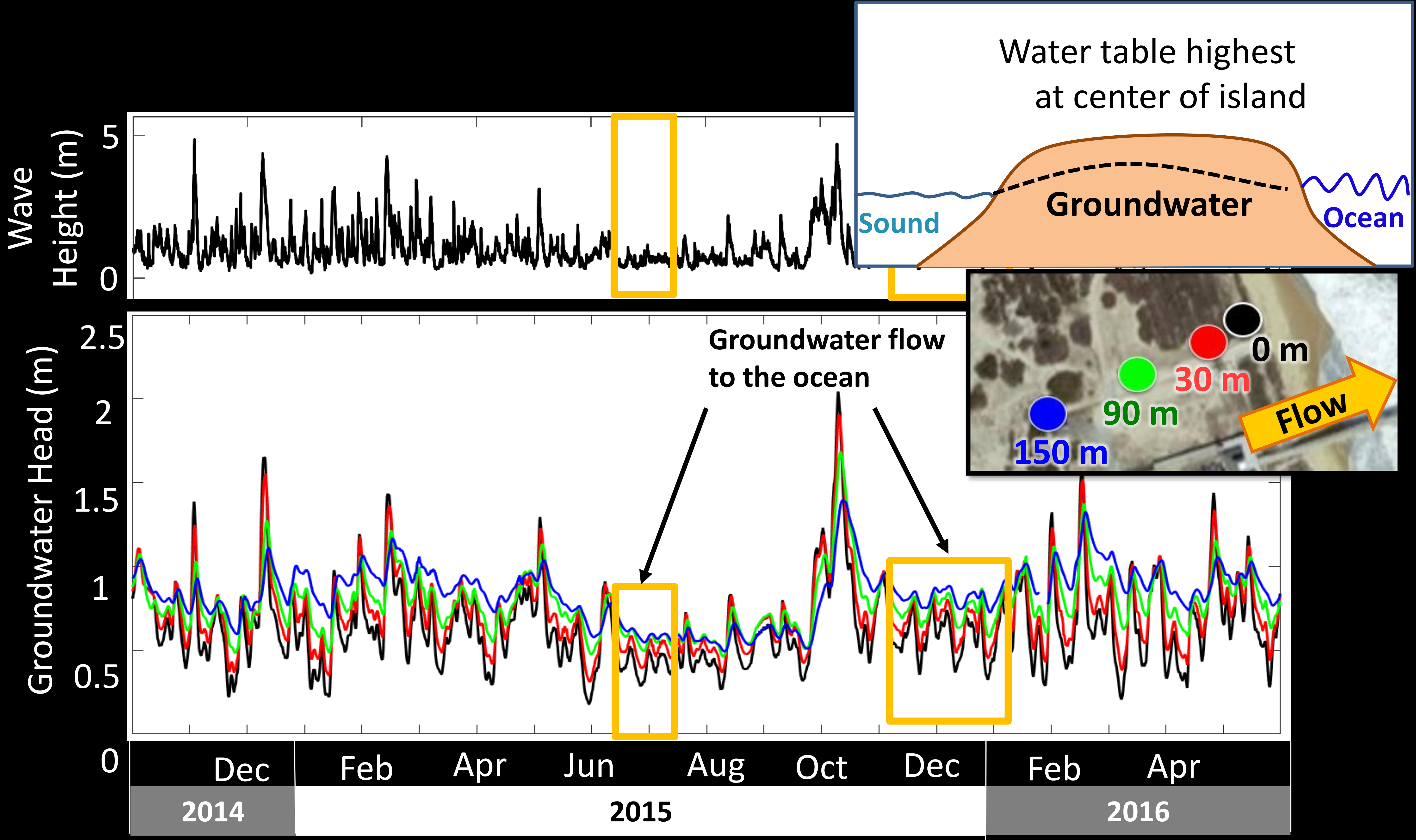

Groundwater
flow to the ocean
Groundwater
flow to the sound
550 m
Ocean
FRF
Sound


Water table highest
at center of island
Groundwater
Sound
Ocean

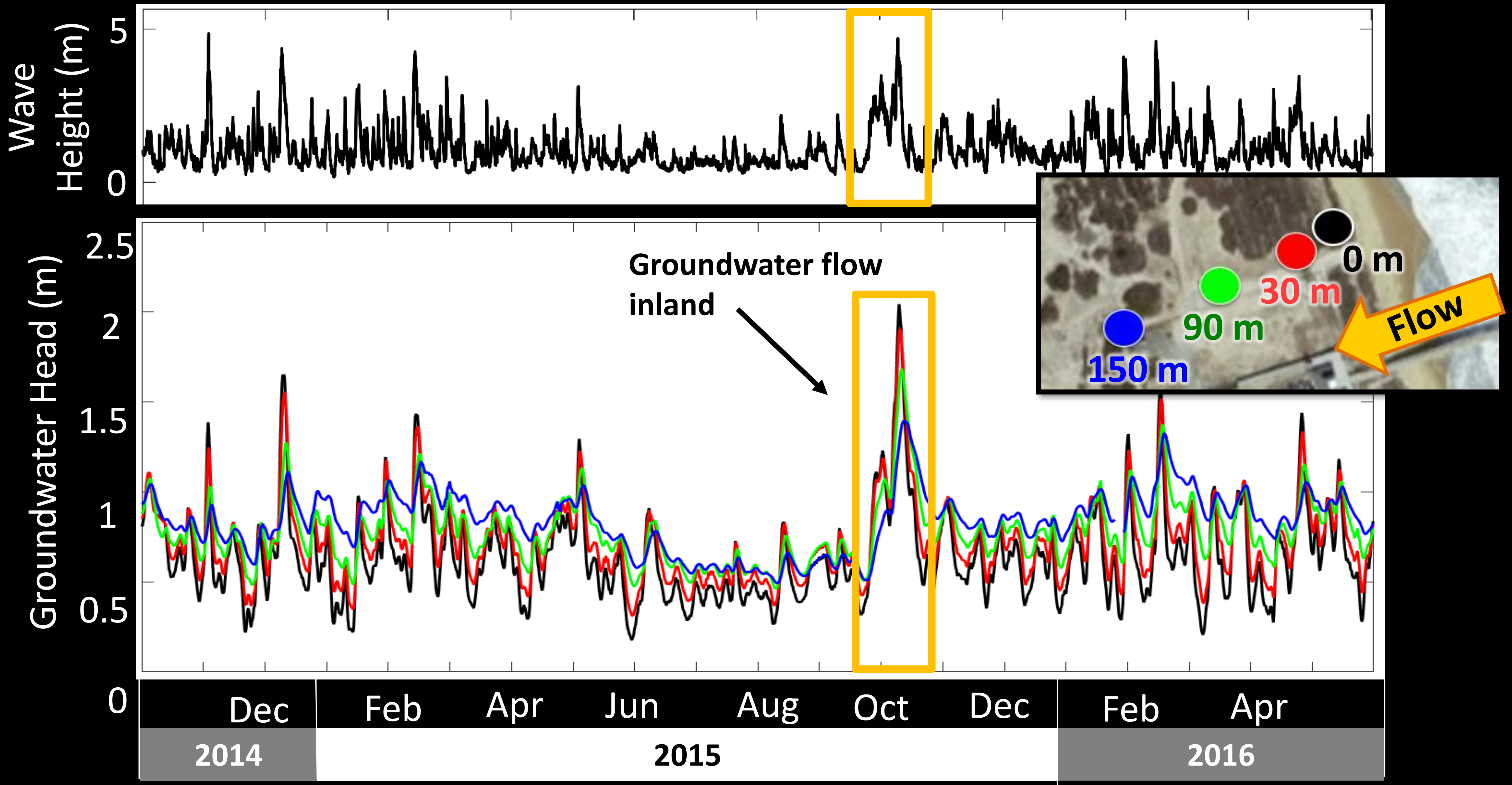


Wave Height (m)
5
0
Hurricane Joaquin
Groundwater Head (m)
2.5
2
1.5
1
0.5
0
0 m
30 m
90 m
150 m
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2014
2015
2016

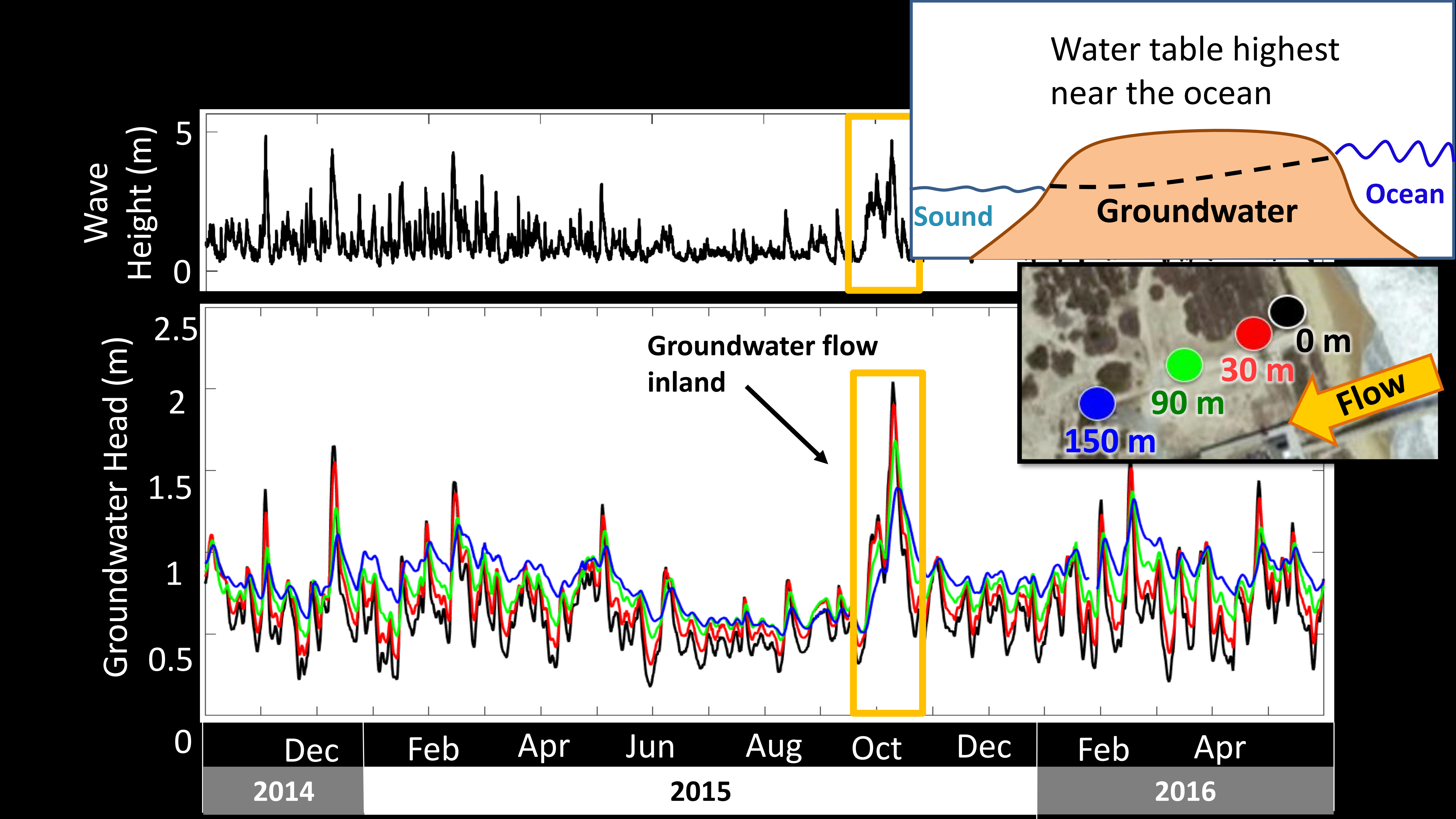

Wave Height (m)
5
0
Groundwater Head (m)
2.5
2
1.5
1
0.5
0
Groundwater flow to the ocean
0 m
30 m
90 m
150 m
Flow
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2014
2015
2016

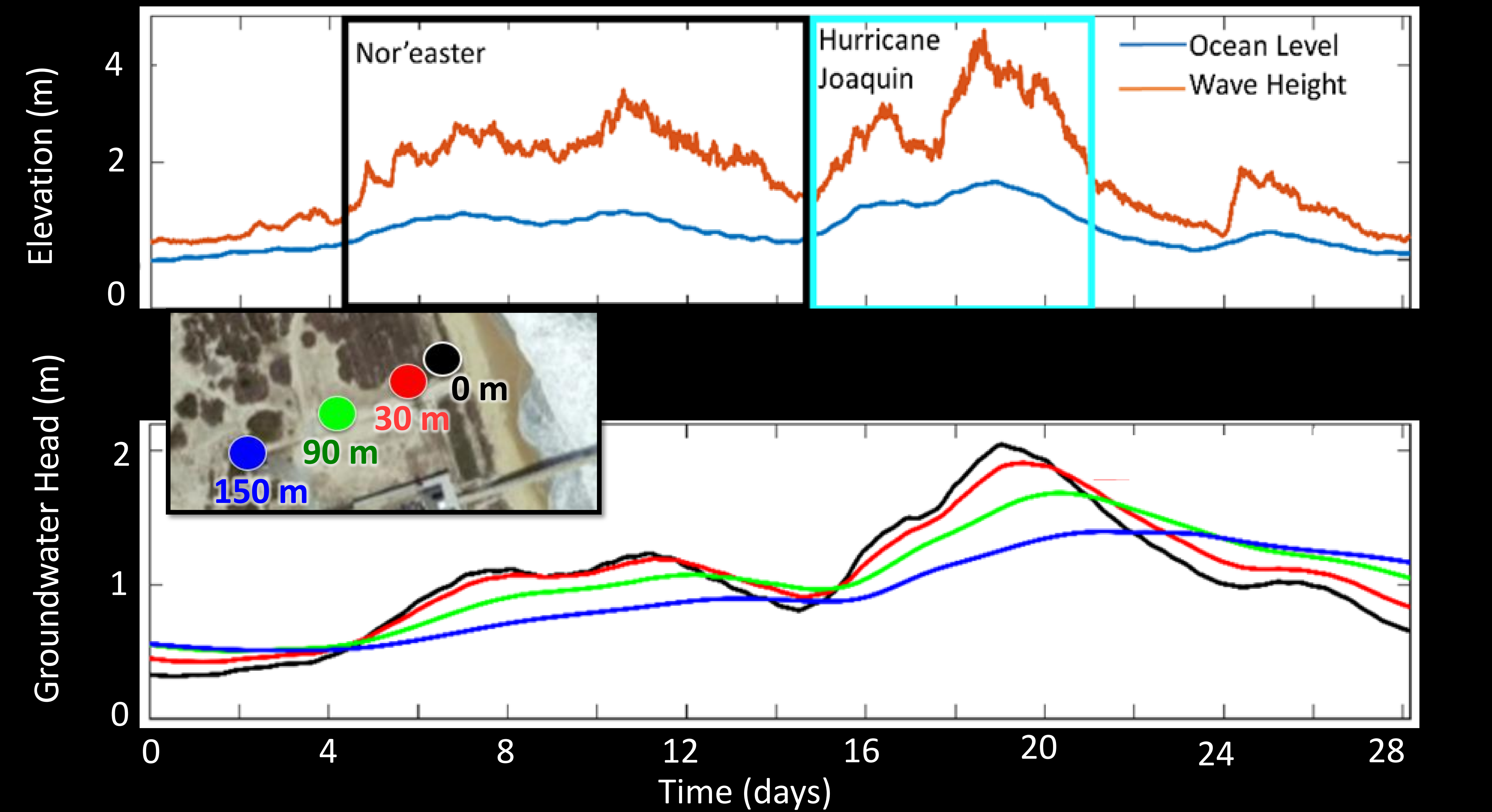


Wave Height (m)
5
0
Groundwater Head (m)
2.5
2
1.5
1
0.5
0
Groundwater flow to the ocean
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2014
2015
2016
Water table highest at center of island
Sound
Groundwater
Ocean
0 m
30 m
90 m
150 m
Flow

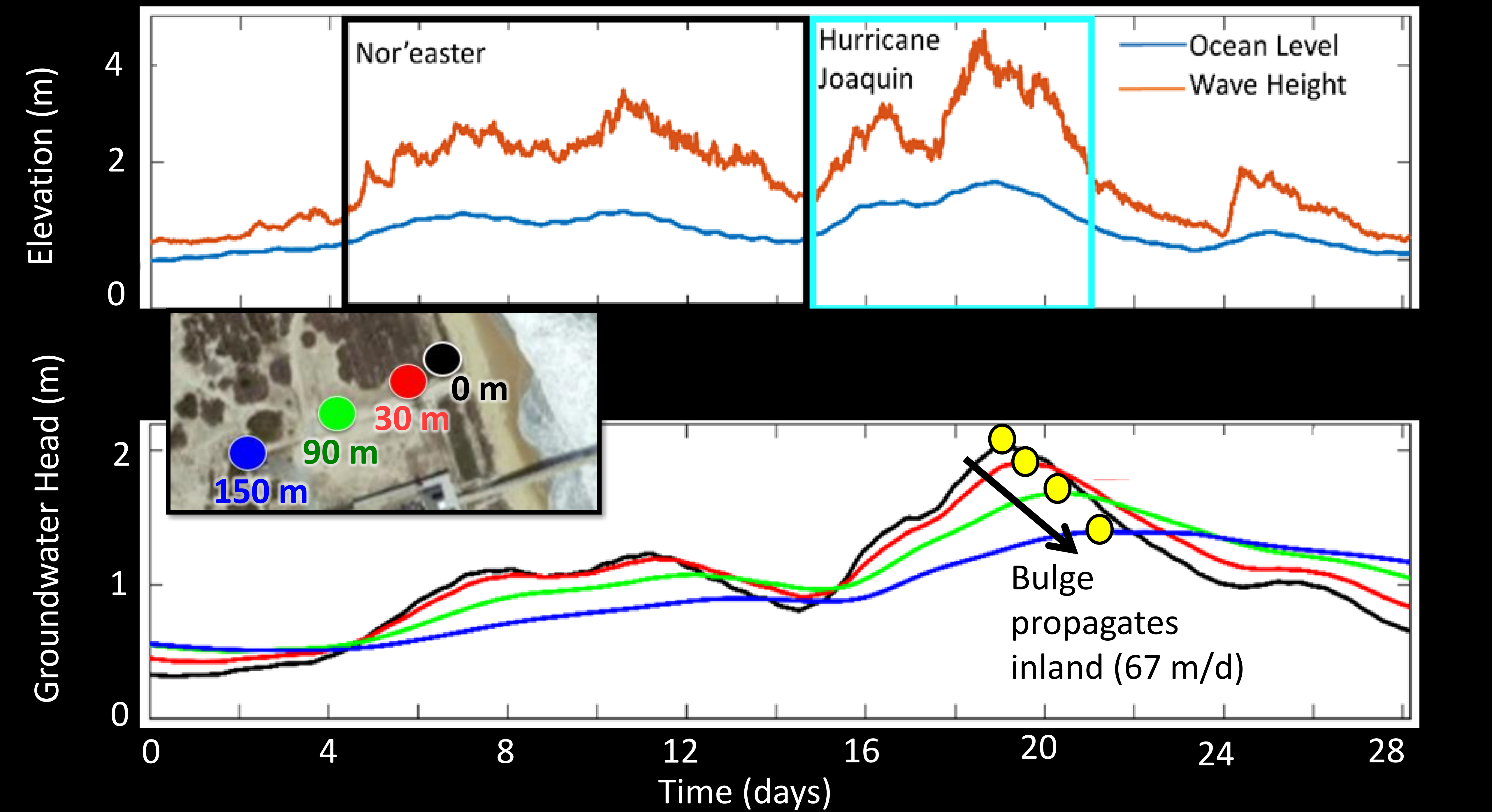


Wave Height (m)
5
0
Groundwater Head (m)
2.5
2
1.5
1
0.5
0
Groundwater flow inland
0 m
30 m
90 m
150 m
Flow
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2014
2015
2016


Water table highest
near the ocean
Sound
Groundwater
Ocean
Wave
Height (m)
5
0
Groundwater Head (m)
2.5
2
1.5
1
0.5
0
Groundwater flow
inland
0 m
30 m
90 m
150 m
Flow
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2014
2015
2016



Nor'easter
Hurricane Joaquin
Ocean Level
Wave Height
Elevation (m)
4
2
0
0 m
30 m
90 m
150 m
Groundwater Head (m)
2
1
0
0
4
8
12
16
20
24
28
Time (days)



Elevation (m)
Nor'easter
Hurricane Joaquin
Ocean Level
Wave Height
Groundwater Head (m)
0 m
30 m
90 m
150 m
Bulge propagates inland (67 m/d)
Time (days)
0
4
8
12
16
20
24
28

Analytical Theory

Li et al. 2004

$$h(x,t) = \int_{-\infty}^{t} \frac{dh_0}{d\tau} erfc\left[\frac{x}{2\sqrt{D(t-\tau)}}\right] d\tau$$

Pulse evolution

Assumptions

- Homogeneous and isotropic
- Shallow aquifer
- Vertical Beach
- Small Amplitude
  (A<< aquifer depth)
- Negligible capillary fringe

Analytical Theory

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Pulse evolution

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$$h_0 = A\exp[-B(t-t_0)^2]$$

Shoreline Amplitude

Time Factor

Storm Duration=$B^{-1/2}$

Time of peak water level

Analytical Theory

Li et al. 2004

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Pulse evolution

$$h_0 = A\exp[-B(t-t_0)^2]$$

Shoreline amplitude

Time factor

Storm duration=$B^{-1/2}$

Time of peak water level

Hydraulic conductivity

$$D = \frac{K \cdot z}{S}$$

Aquifer depth

Specific yield

Assumptions

- Homogeneous and isotropic
- Shallow aquifer
- Vertical Beach
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Pulse evolution

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$$h_0 = A\exp[-B(t-t_0)^2]$$

Shoreline amplitude

Time factor
Storm duration=$B^{-1/2}$

Time of peak water level

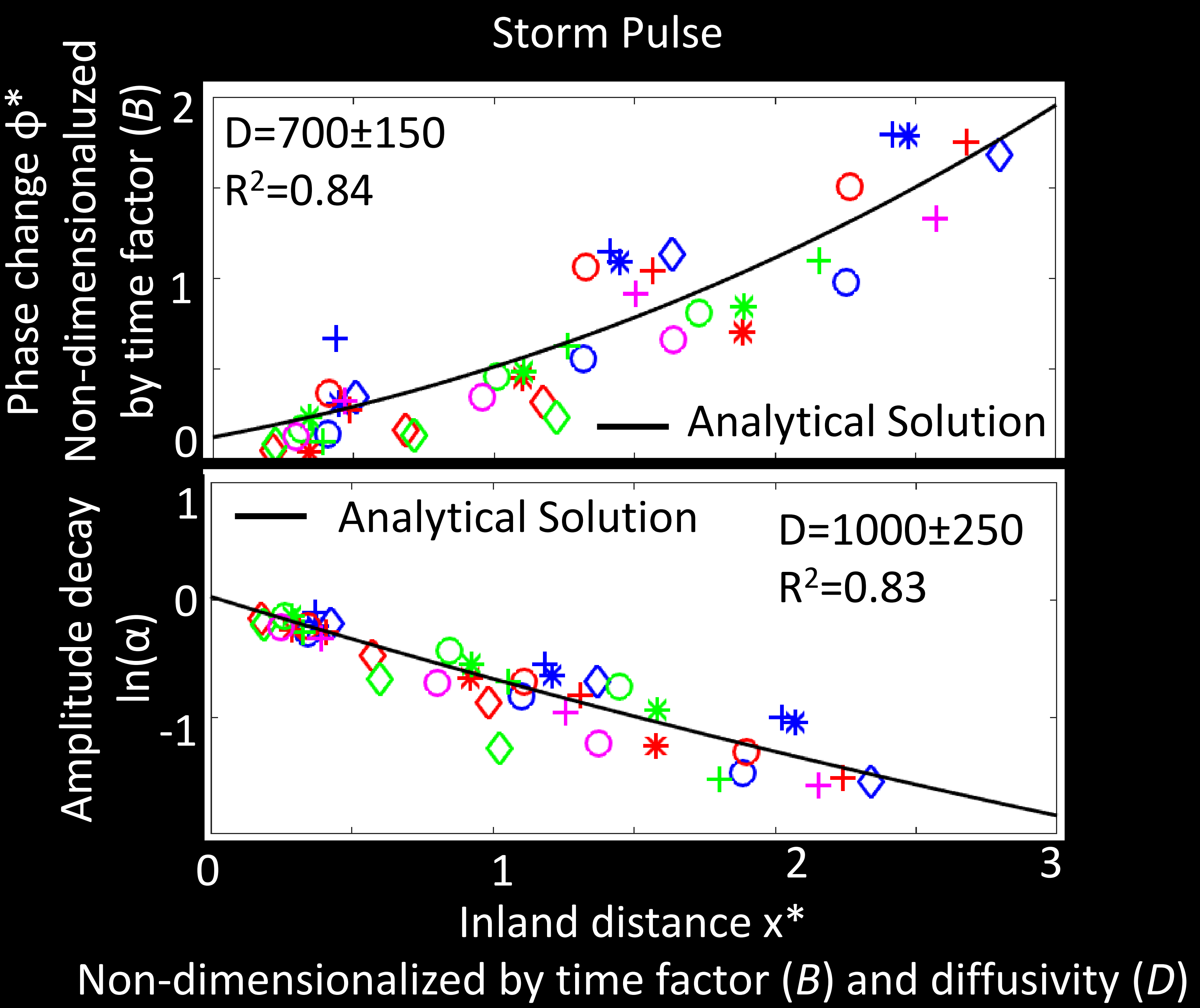
Hydraulic conductivity

$$D = \frac{K \cdot z}{S}$$

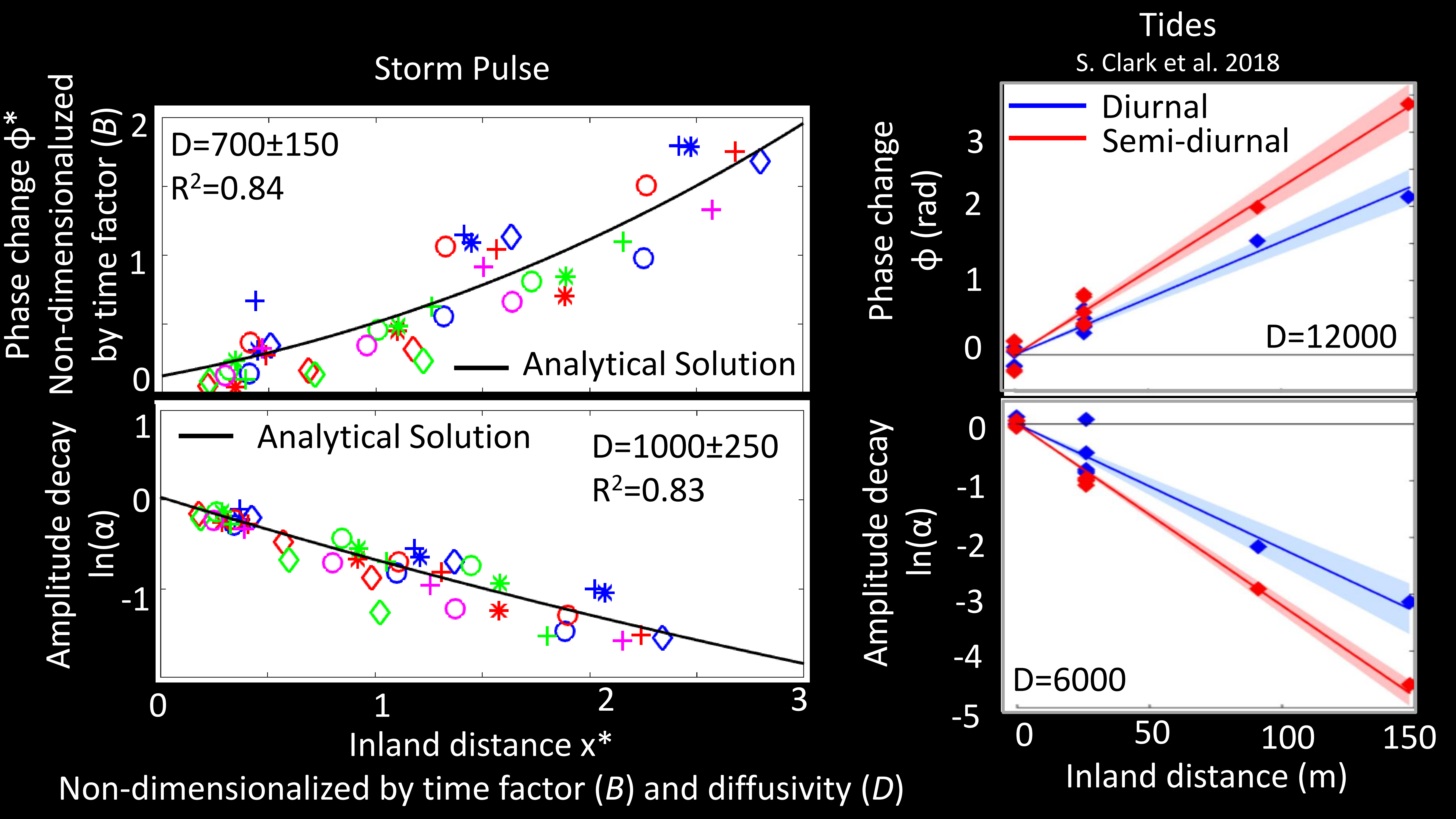
Aquifer depth

Specific yield

Applied analytical theory to 14 storm events



Storm Pulse
Phase change ϕ*
Non-dimensionaluzed
by time factor (B)
D=700±150
R2=0.84
Analytical Solution
0
1
2
Amplitude decay
ln(α)
Analytical Solution
D=1000±250
R2=0.83
1
0
-1
0
1
2
3
Inland distance x*
Non-dimensionalized by time factor (B) and diffusivity (D)



Storm Pulse
Phase change ϕ*
Non-dimensionaluzed
by time factor (B)
D=700±150
R2=0.84
Analytical Solution
Amplitude decay
ln(α)
Analytical Solution
D=1000±250
R2=0.83
Inland distance x*
Non-dimensionalized by time factor (B) and diffusivity (D)
Tides
S. Clark et al. 2018
Diurnal
Semi-diurnal
Phase change
ϕ (rad)
D=12000
Amplitude decay
ln(α)
D=6000
Inland distance (m)

Hypotheses for difference in estimated diffusivity between tides and storm pulse

- Wavelength

Shallow aquifer assumption: $\frac{S\omega z}{K} << 1$

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Assuming S=0.2, z= 30 m, and K= 13 m/day:

Storm Pulse

$$\frac{S\omega z}{K} = 0.08 - 0.4$$

Hypotheses for difference in estimated diffusivity between tides and storm pulse

- Wavelength

Shallow aquifer assumption: $\frac{S\omega z}{K} \ll 1$

Assuming S=0.2, z= 30 m, and K= 13 m/day:

Storm Pulse

$$\frac{S\omega z}{K} = 0.08 - 0.4$$

Diurnal Tide

$$\frac{S\omega z}{K} = 2.9$$

Semi-diurnal Tide

$$\frac{S\omega z}{K} = 5.7$$

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- Inland head level

Hypotheses for difference in estimated diffusivity between tides and storm pulse

- Wavelength

Shallow aquifer assumption: $\frac{S\omega z}{K} << 1$

Assuming S=0.2, z= 30 m, and K= 13 m/day:

Storm Pulse

$$\frac{S\omega z}{K} = 0.08 - 0.4$$

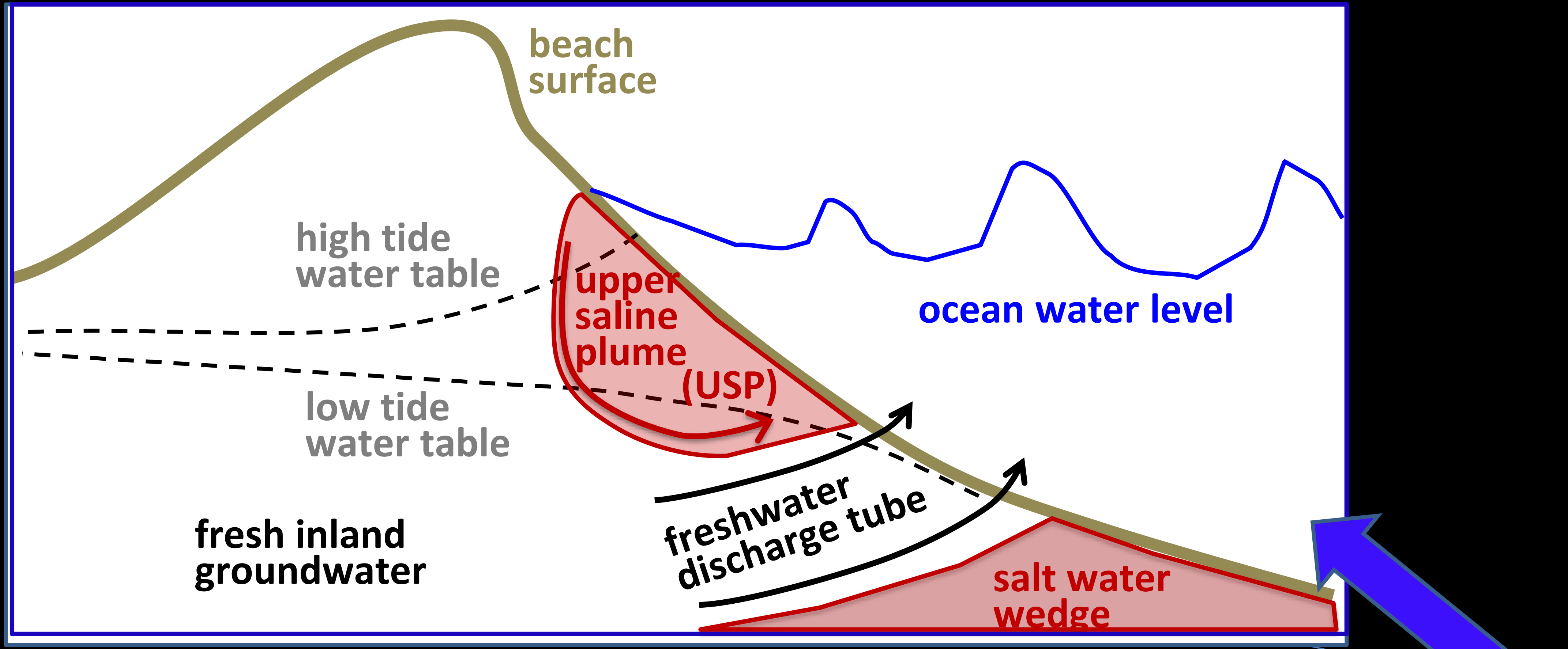
Diurnal Tide

$$\frac{S\omega z}{K} = 2.9$$

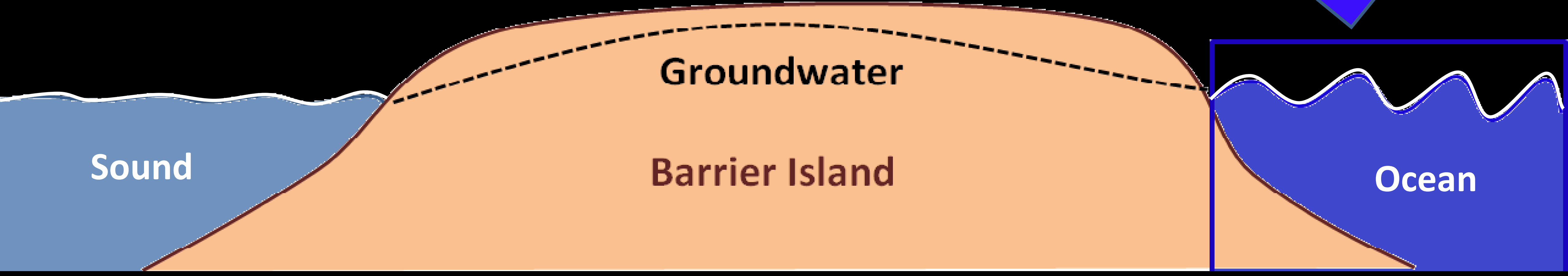
Semi-diurnal Tide

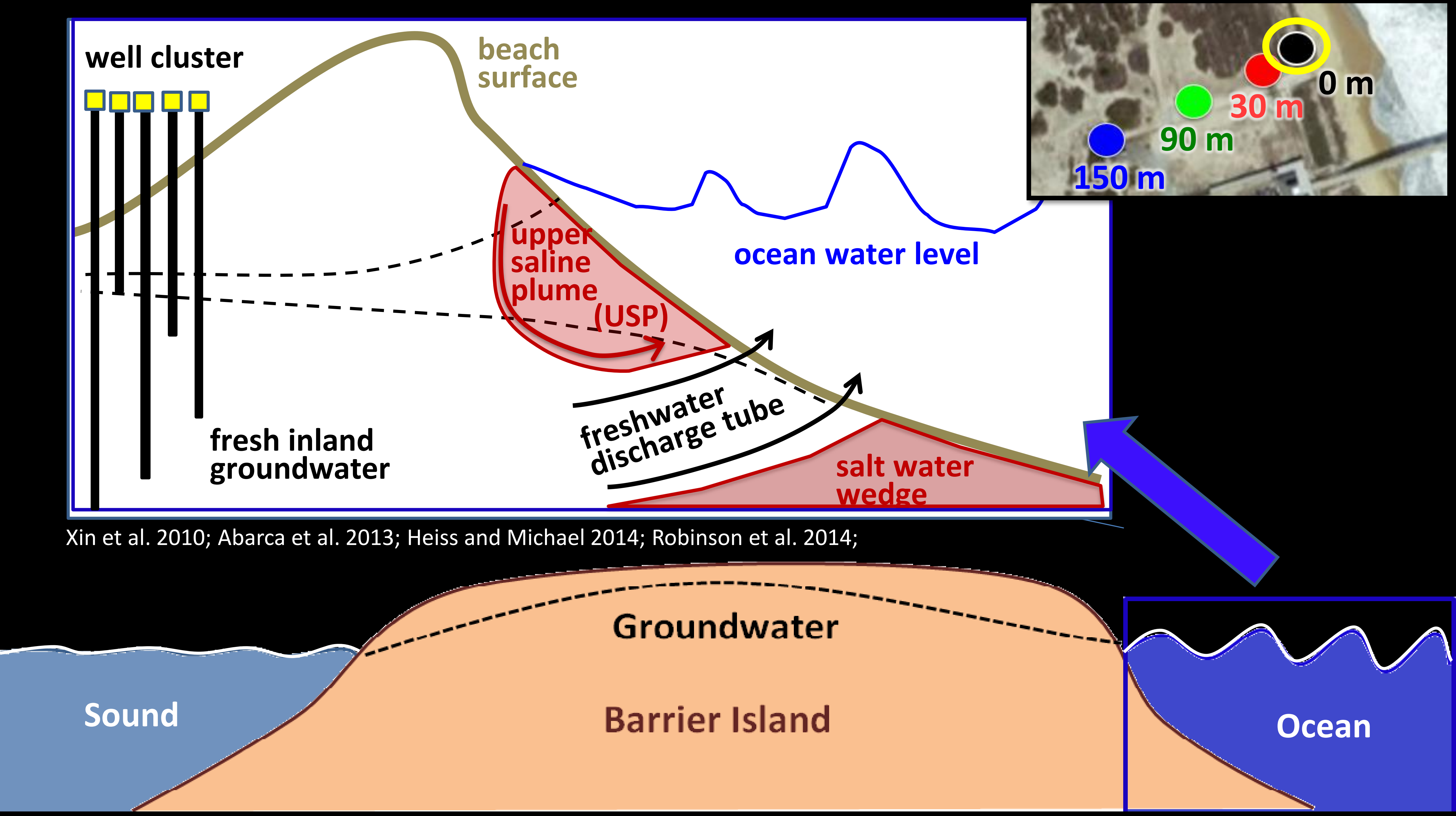
$$\frac{S\omega z}{K} = 5.7$$

- Inland head level ⇨ Salinity

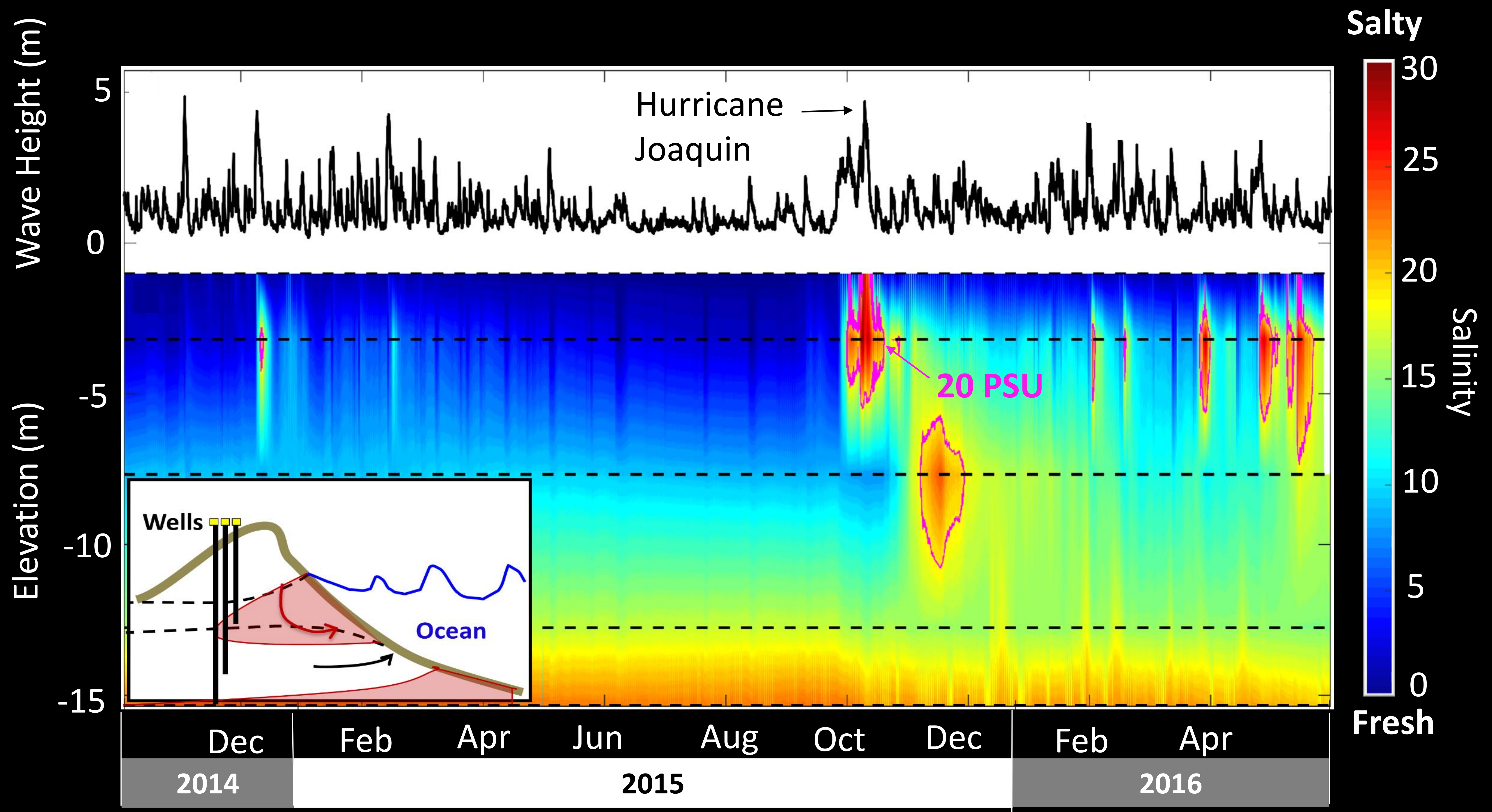


Xin et al. 2010; Abarca et al. 2013; Heiss and Michael 2014; Robinson et al. 2014;

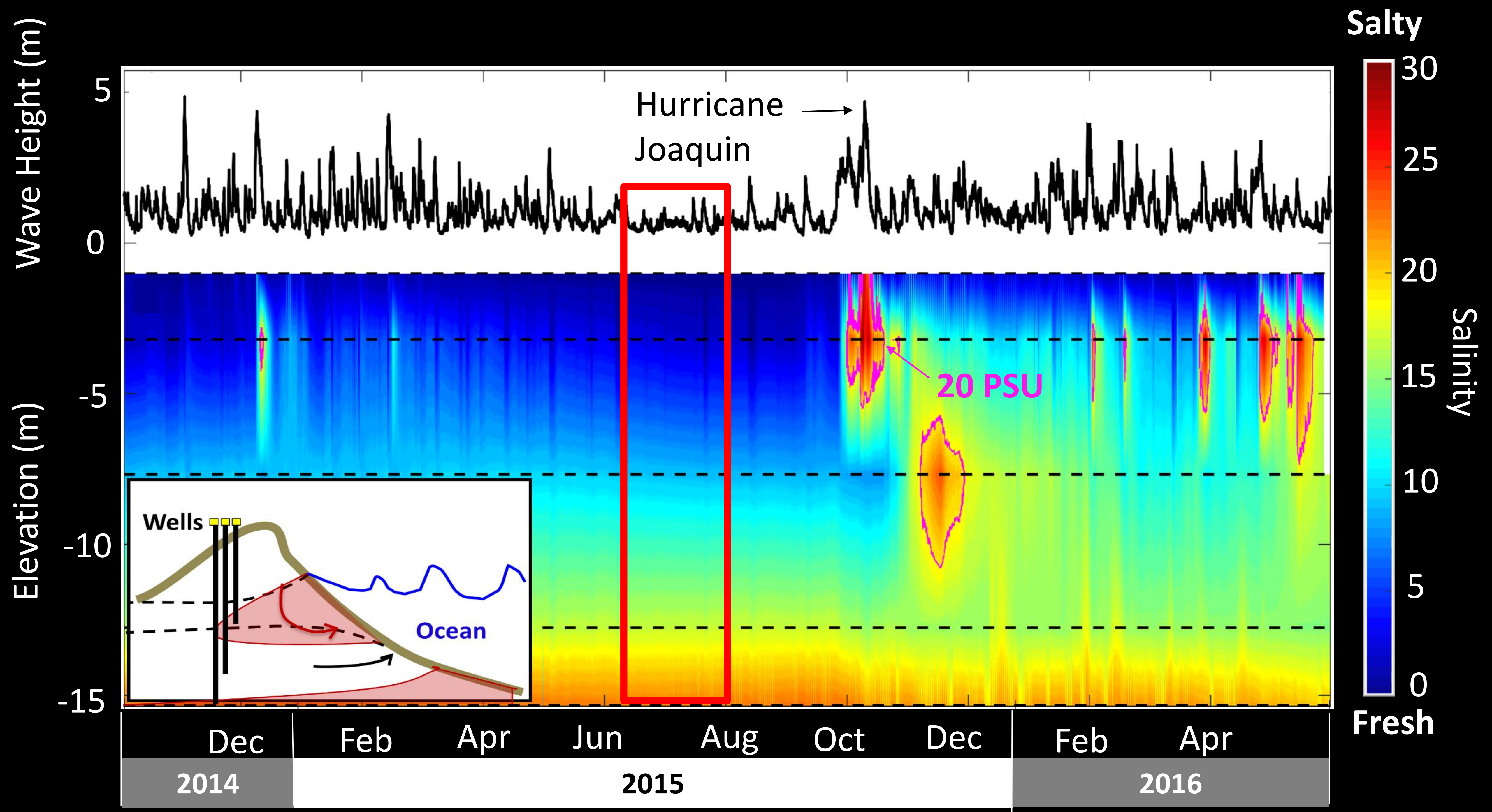




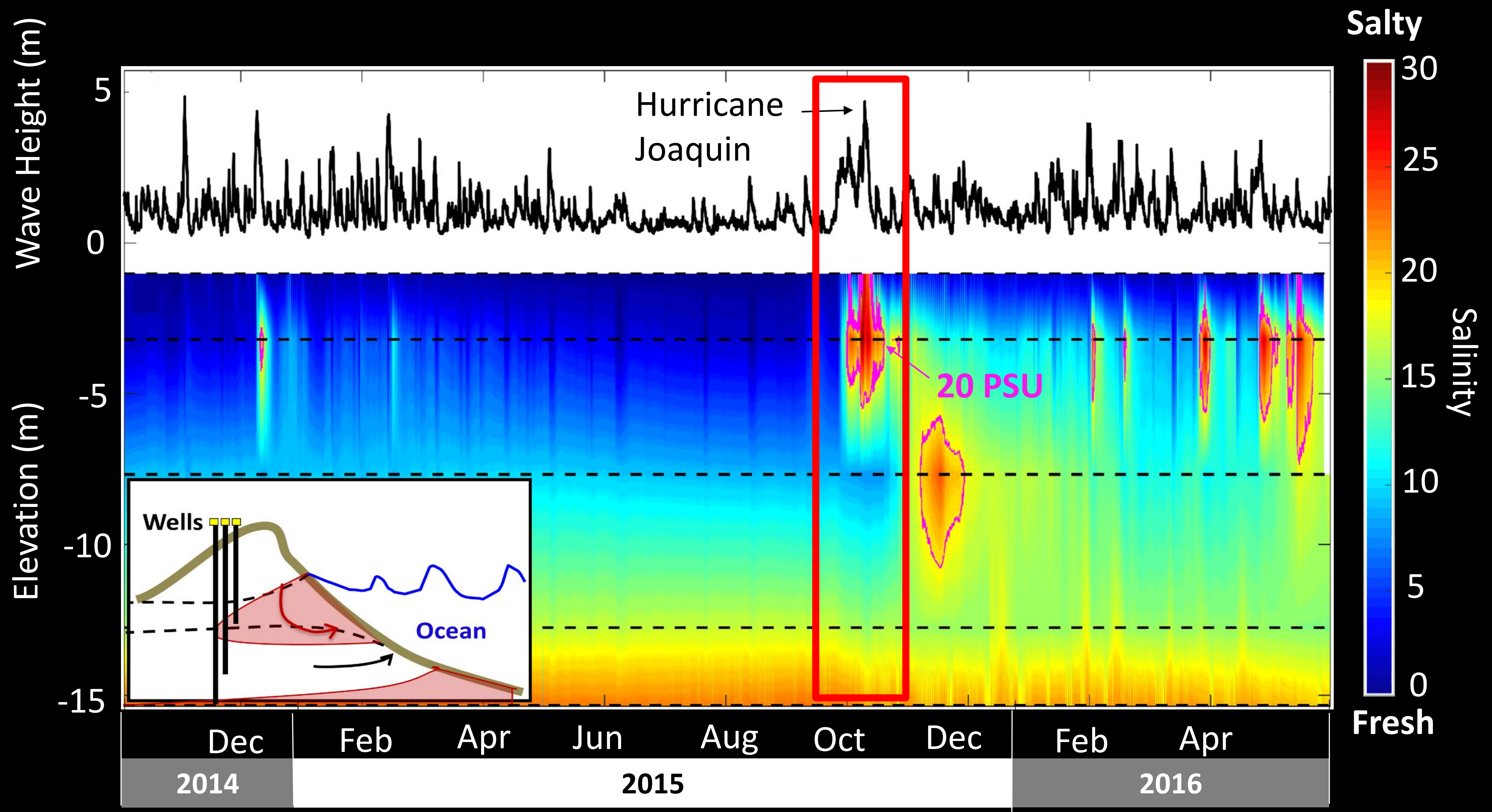
Xin et al. 2010; Abarca et al. 2013; Heiss and Michael 2014; Robinson et al. 2014;



Wave Height (m)
5
0
Hurricane Joaquin
Elevation (m)
-5
-10
-15
20 PSU
Wells
Ocean
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2014
2015
2016
Salty
Fresh
Salinity
30
25
20
15
10
5
0



Salty
Wave Height (m)
5
0
Hurricane Joaquin
Elevation (m)
-5
-10
-15
20 PSU
Wells
Ocean
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2014
2015
2016
30
25
20
15
10
5
0
Salinity
Fresh



Salty
Fresh
Salinity
30
25
20
15
10
5
0
Wave Height (m)
Elevation (m)
5
0
-5
-10
-15
Hurricane
Joaquin
20 PSU
Wells
Ocean
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2014
2015
2016

Summary

- Storm increases in groundwater level (bulge) at dune cause inland flow.
- Time and space evolution of bulge reproduced with analytical theory.
- Diffusivity estimated for bulge smaller than that for tides??

Summary

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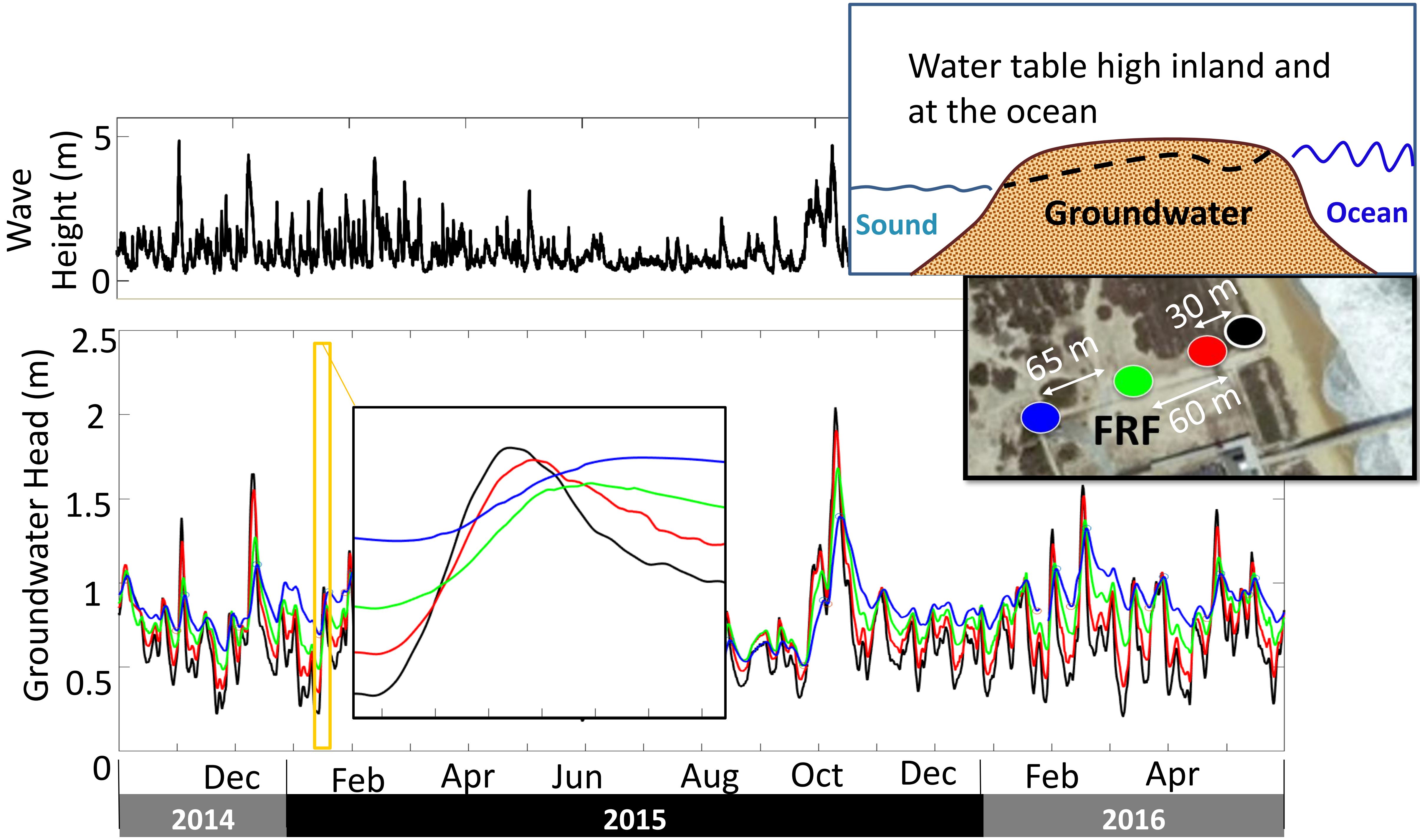
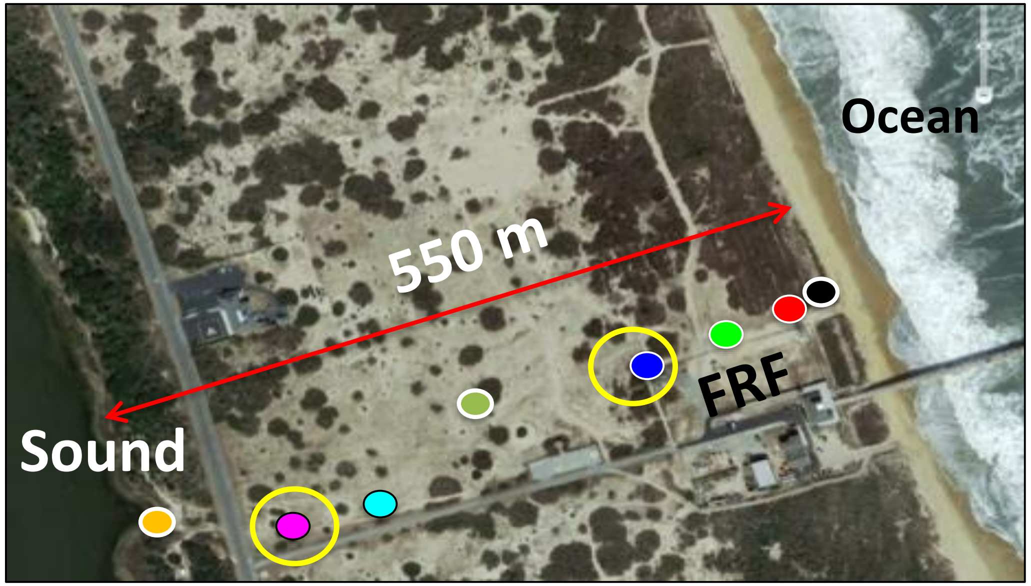
- Time and space evolution of bulge reproduced with analytical theory.
- Diffusivity estimated for bulge smaller than that for tides?

Future Work

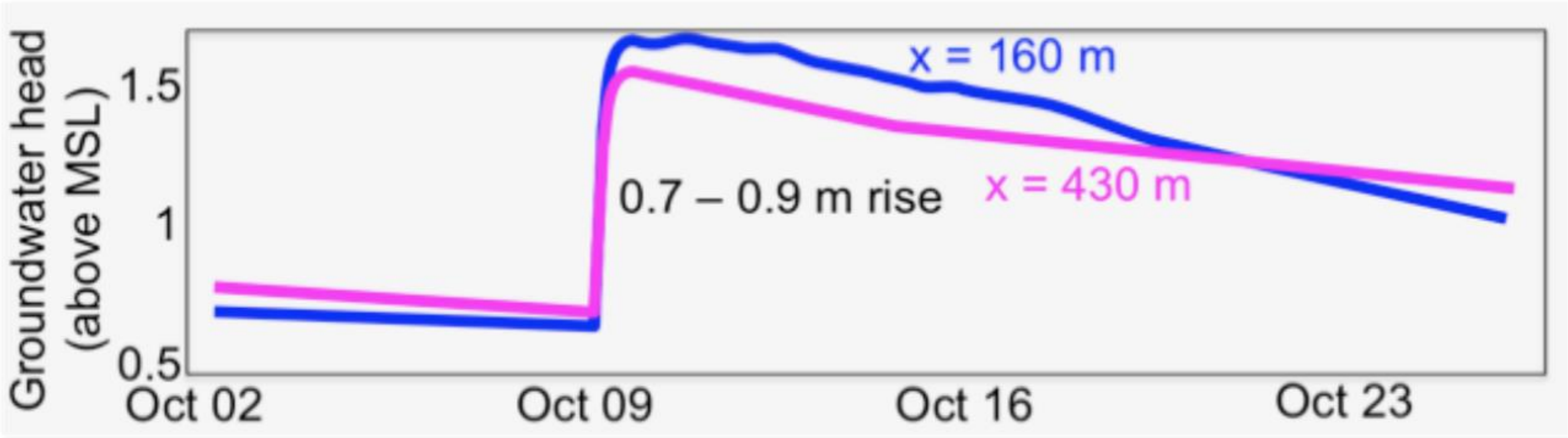
- Determine whether salt plume under dune results from inland flow
- Determine whether plume affects bulge propagation
- Combine analytical theory with precipitation to flooding



Water table high inland and at the ocean
Sound
Groundwater
Ocean
30 m
65 m
60 m
FRF
Wave Height (m)
5
0
Groundwater Head (m)
2.5
2
1.5
1
0.5
0
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
2014
2015
2016



Ocean
550 m
FRF
Sound



Groundwater head (above MSL)
1.5
1
0.5
Oct 02
Oct 09
Oct 16
Oct 23
x = 160 m
x = 430 m
0.7 – 0.9 m rise

$$h_0 = A\exp[-B(t - t_0)^2]$$