

Summary of study design and data collected at Sandy Hook Gateway National Recreation Area, NJ

The health of maritime forests in three Mid-Atlantic National Seashores, U.S. Geological Survey. Summary Presentation of Approved Data Associated with the National Resource Protection Program.

Introduction

Sandy Hook Study Area
Sandy Hook is a 10-kilometer (km)-long spit that extends from the bridge across the Navesink River at the southern end to New York Harbor at the northern tip (Figure 1). Sandy Hook has experienced long-term erosion at the southern, narrow end of the spit and deposition at the northern end. As is typical of barrier-island environments, Sandy Hook experiences overwash events during which areas that are normally above tide level are flooded (Carleton, et. al.). The 10 highest water levels at Sandy Hook since 1932 range from 1.091 to 2.709 m above mean higher high water (MHHW), including record high water for the period of record during Hurricane Sandy in 2012 (National Oceanic and Atmospheric Administration, 2018). Of the 10 highest water levels in the 85-year period of record, 4 are associated with tropical storms, 4 with late fall/early winter nor'easters, and 2 with spring nor'easters.

The Bayside Holly Forest on Sandy Hook, one of only two known old-growth American holly (Ilex opaca) maritime forests, is particularly vulnerable to global climate change because of the proximity of the water table to land surface in low-lying areas and the potential for saltwater intrusion and inundation. During Hurricane Sandy the peak storm surge was 2.44 m above mean higher high water (MHHW), almost a meter higher than the previous high of 1.48 m (1960 and 1992). The Bayshore Holly Maritime Forest on Sandy Hook suffered mortality in low-lying areas that were inundated during Hurricane Sandy. Stalter and Heuser (2015) conclude the mortality occurred in areas where standing saltwater remained for about two weeks after the storm. However, measurements of the timing and extent of the inundation were unavailable to verify this conclusion. Although flooding of roots with saltwater is hypothesized to be the cause of mortality, data on short-term and long-term water-levels and salinity in the affected areas are not available. Water-level and salinity data collected in this study in low-lying areas of the Bayshore Holly Forest may provide some of the information needed to estimate if saline water was the cause of mortality and attempt to reconstruct the duration and concentration of standing water.



Figure 1: Aerial view of Sandy Hook Gateway National Recreation Area, NJ

Well Locations

The study area was located approximately 3.5 miles south of the northern tip of Sandy Hook and to the west of the main road (Hartshorned Drive) (Figure 2). Wells near the shoreline were installed adjacent to a tidal marsh (Figure 3) and extended inland along a 55 ft. transect (Figures 4a and b). Three shallow wells (GWW31, GWW 32 AND GWW33) were hand augered and screened just below the water table (4-5 ft below Land Surface Datum [LSD]). A deep well (GWW34) was installed next to GWW33 and screened approximately 20 ft below LSD. The inland well, located in the middle of a high mortality zone, (GWW30) was hand augered and screened just below the water table (4-5 ft below Land Surface Datum [LSD]).

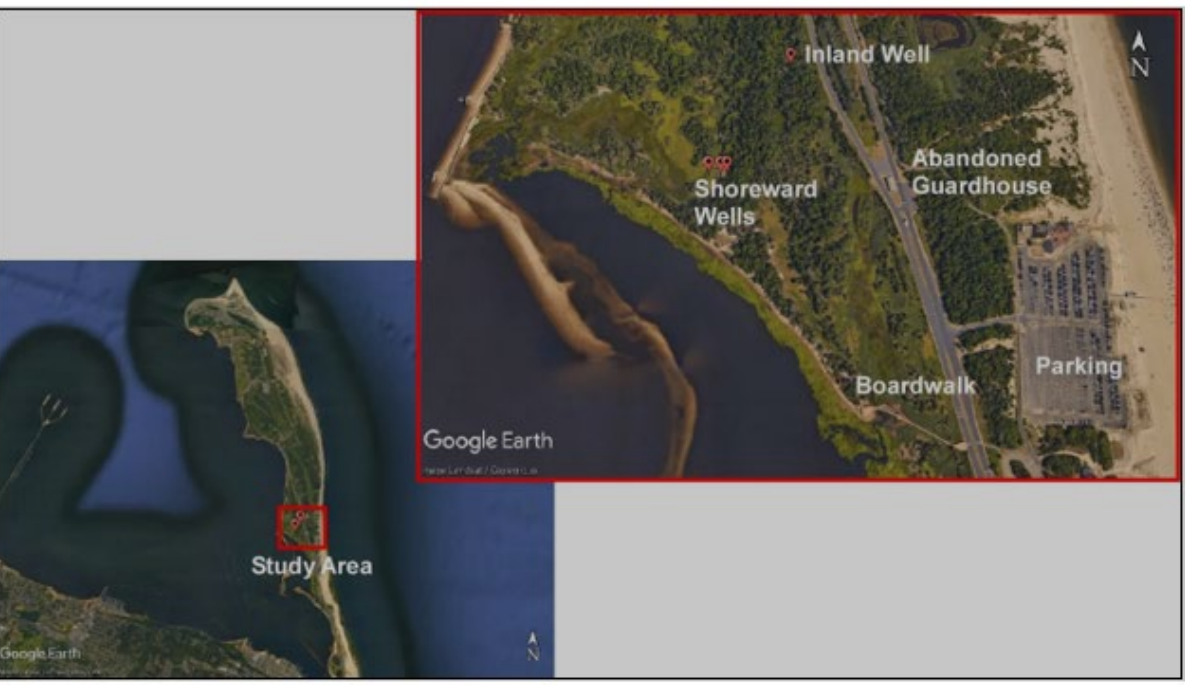


Figure 2. Location of Sandy Hook study area



Figure 3. Position of the shoreward and inland wells relative to the tidal marsh



Figure 4a: Transect of shoreward wells.



Figure 4b. Landscape view of shoreward wells.

Sandy Hook Storm Events

Storm events were illustrated by overlaying water level and specific conductance readings for each of the wells on a hydrograph of tidal elevations. Forcing conditions were represented on a graph plot of windspeeds and daily precipitation. Tidal data was retrieved from the Tides/water Levels page of the National Oceanographic and Atmospheric Administration (NOAA) Sandy Hook, NJ Station (ID: 8531680) website (<https://tidesandcurrents.noaa.gov/stationhome.html?id=8531680>). Wind speed data was retrieved from the NOAA Meteorologic Observations page NOAA for the Sandy Hook, NJ Station (ID: 8531680) website (<https://tidesandcurrents.noaa.gov/met.html?id=8531680>) Precipitation data was retrieved from the New Jersey Department of Environmental Protection Division of Water Monitoring and Standards (DWM&S) Rainfall Data Acquisition website (NJDEP New Jersey Department of Environmental Protection - Rainfall (rutgers.edu); Site: Highlands RABCH022; 2.5 X 2.5-mile area).

Five storms impacting the Sandy Hook study area were selected for analysis and are summarized in Table 1. Storms selected for analysis had either rainfall greater than 1 in. and/or wind speeds greater than 20 mph. Winter storms with significant accumulation and wind speeds greater than 20 mph were not included in the set. The duration of events was defined as the extent of either the water level or specific conductance response. The actual forcing condition was usually of shorter duration occurring at the start of the event.

In general, over the course of the study, GWW 31 was inundated by high tide most weeks and GWW 32 was inundated frequently by storm surges or very high tides. GWW 33/34, which were the furthest upslope on the transect, were inundated only a few times during large storm events with severe flooding. Inundation of the inland well (GWW30) was not observed during the study, but water levels did exhibit a slight response to sustained sea level oscillations during highest of high tide events and a slight to significant response during storm events.

Table 1: List of Events										
Event Number	Event Type	Event Start Date	Event End Date	Event Precipitation as rain (in.) ¹	Maximum Daily precipitation as rain (in.) ²	Maximum Daily Precipitation Date ³	Maximum Sustained Wind speed (knots) ²	Maximum Sustained Wind Speed Date ²	Maximum Tide Elevation (NAVD83, ft) ⁴	Maximum Tide Date
1	Heavy Rain High Wind High Spring Tide	10/26/17	11/13/17	3.72	2.55	10/30/17	27.8	10/30/17	1.51	11/5/17
2	Heavy Rain High Wind	4/12/18	4/30/18	2.58	1.46	4/12/18	29.41	4/16/18	1.56	4/16/18
3	Heavy Rain High Wind	9/1/18	10/25/18	6.08	1.75	9/11/18	29.16	10/12/18	1.49	9/10/18
4	Heavy Rain High Wind Low Lunar Tide	10/26/18	11/05/18	1.70	1.04	10/29/18	28.77	11/3/18	3.54	10/27/18
5	Heavy Rain High Wind Low Lunar Tide	12/20/18	12/30/18	2.23	1.24	12/22/18	29.94	12/22/18	2.25	12/21/2018

¹New Jersey Department of Environmental Protection Division of Water Monitoring and Standards (DWM&S) Rainfall Data Acquisition website (NJDEP-New-Jersey-Department-of-Environmental-Protection-Rainfall.aspx)
²NOAA Tides and Currents, Sandy Hook, NJ - Station ID: 8531680 (<https://tidesandcurrents.noaa.gov/stationhome.html?id=8531680>) - abv MHHW
³Data collection from GWW31 was discontinued on 10/09/2018. This was the nominal end of the data collection period. However, additional funding allowed continued deployment and maintenance of the data collection equipment in the remaining wells to 10/19/2019.
⁴abv MHHW

1. Northeastern Heavy Rain and High Wind Event followed by a High Spring Tide (10/26/2017 to 11/13/2017)

Description The primary forcing condition during this event was 2.55 inches of precipitation on 10/30/2017 followed 27.8 knot winds (Figure 5a). Additional wind speeds up to 20 knots were observed from 11/10/2017 to 11/11/2017. This primary forcing condition occurred during a low lunar tide that was followed later in the event by a high spring tide from 11/12/2017 to 11/12/2017.

Water Level Response During the heavy rain event, all near-shore wells experienced significant increases in groundwater and tide elevations. Water levels in GWW31 and GWW32 frequently peaked above land surface. Water levels in GWW33 and GWW34 did not peak above land surface. However, the highest tide elevations rose slightly above land surface suggesting some overtopping from the sea. GWW30 also exhibited a significant increase in water level during the heavy rain event. Water levels in GWW31 and GWW32 were highly responsive to tidal forcing during the spring tide. Both groundwater and sea water elevations exceeded land surface elevations suggesting that overtopping had occurred. GWW33 and GWW34 were also responsive but did not peak above the land surface elevation. Water levels in GWW30 experienced a slight increase during this period with some damped oscillations synched to diurnal tides.

Specific Conductance Response During the precipitation event, the Specific conductance increased rapidly in GWW32, GWW33 and GWW34 followed by a rapid decrease. GWW31 exhibited increases and decreases in specific conductance throughout this period though not necessarily in-sync with the weather event or tides. Specific conductance levels for GWW31 were generally high with an average of approximately 36,000 $\mu\text{S}/\text{cm}$. Specific conductance levels in GWW32 increased by approximately 2500 $\mu\text{S}/\text{cm}$ and remained high for the duration of the spring tide before dropping back to its initial concentration. Specific conductance readings in GWW33 increased intermittently during highest of high tides by approximately 1500 $\mu\text{S}/\text{cm}$ before dropping. Specific conductance levels in GWW34 were responsive to tidal fluctuations but did not show appreciable increases during highest of high tides (the overall specific conductance actually decreased).

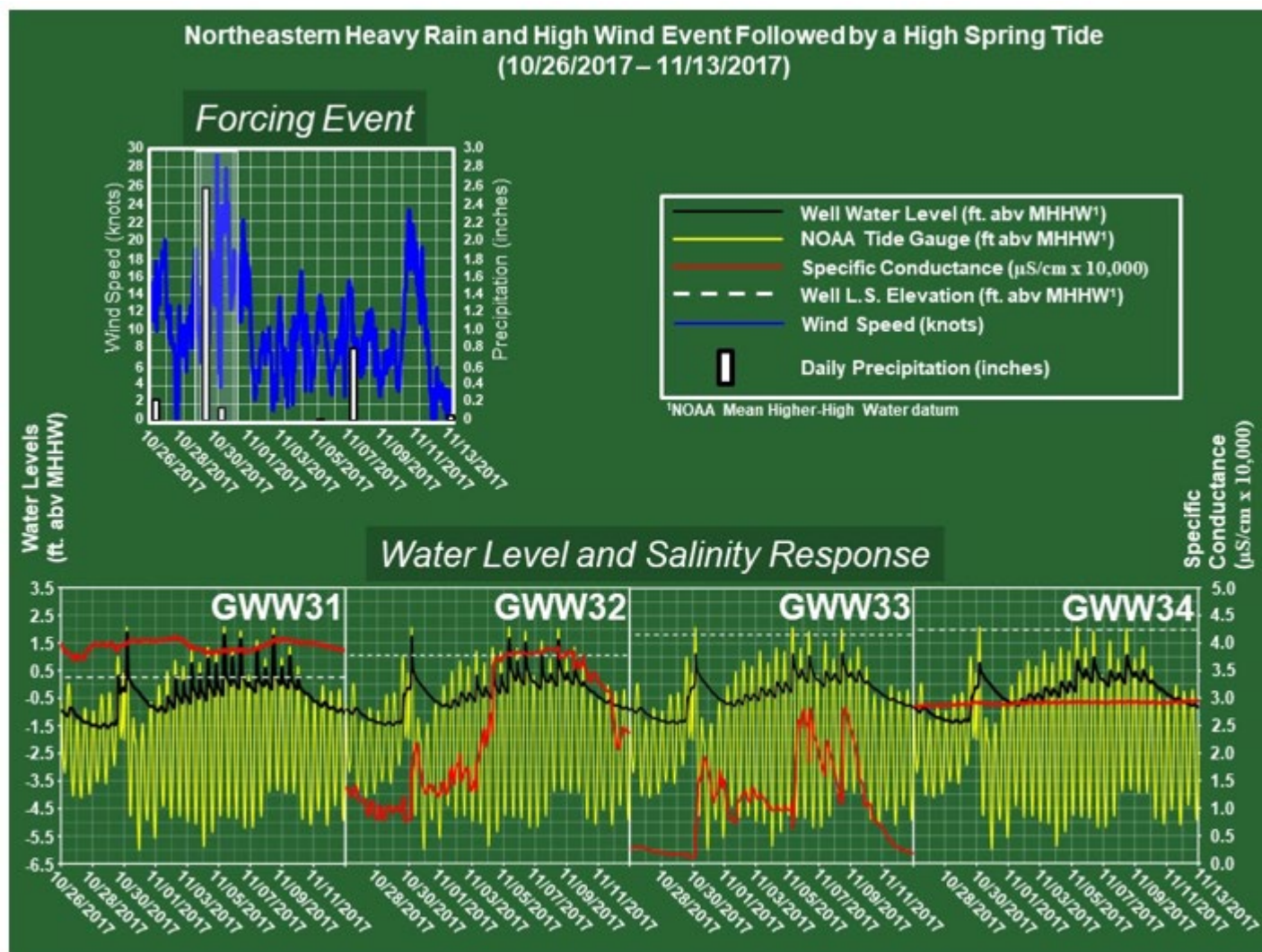


Figure 5a. Shoredward wells groundwater, and seawater levels, specific conductance and forcing events - Sandy Hook Study Area.



Figure 5b. GWW31 - Zoom View



Figure 5c. GWW34 - Zoom View

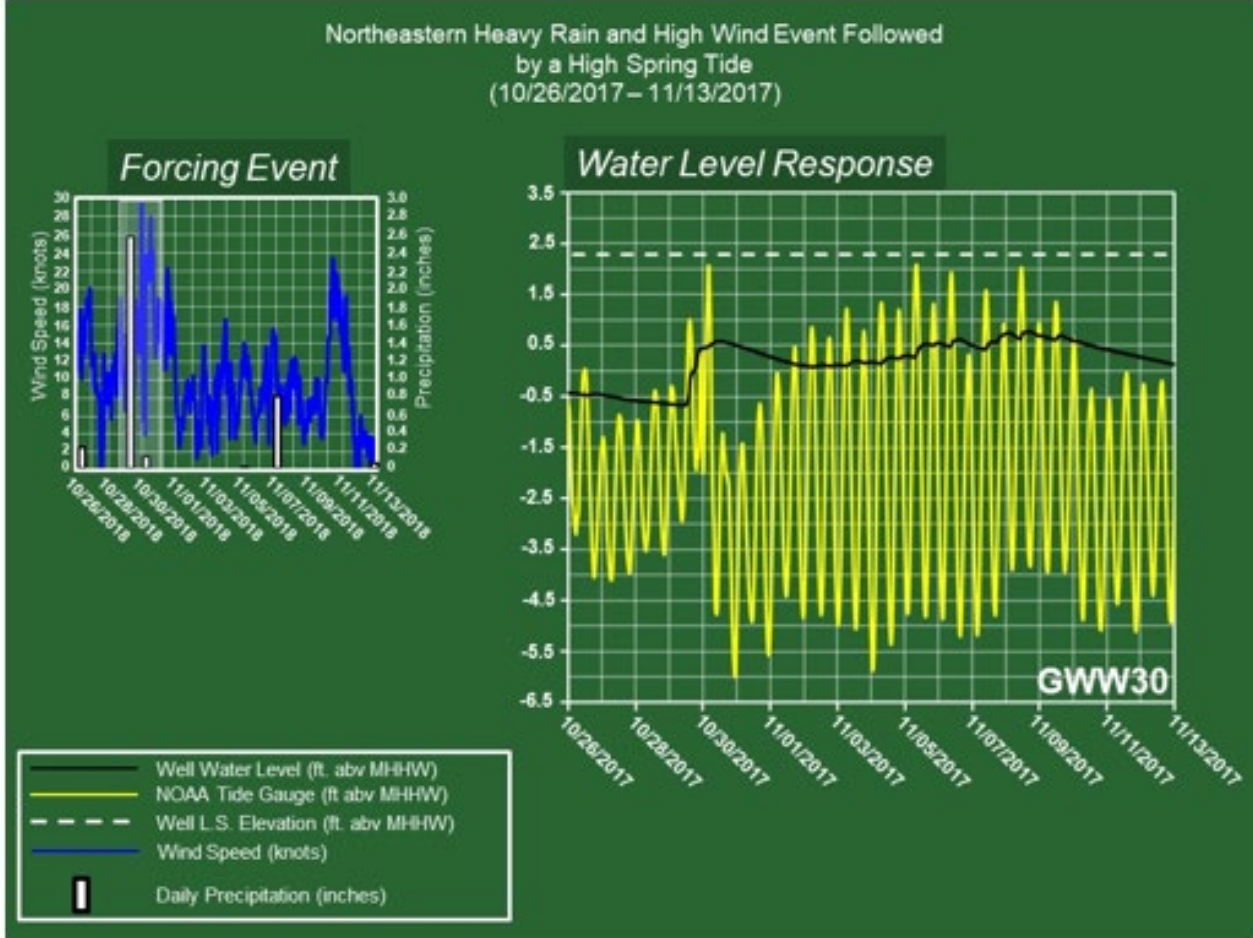


Figure 6. Inland well (GWW30) groundwater, and seawater levels and forcing events - Sandy Hook Study Area.

2. Heavy Rain and High Wind Event (04/12/2018 to 04/30/2018)

Description Event 2 (Heavy Rain and High Wind) occurred during a low lunar tide with two consecutive forcing conditions. The first condition was heavy precipitation (1.96 inches) and high (~25 knot) winds from 04/15/2018 to 04/16/2018. The second event on 4/20/2018 had maximum wind speed of approximately 28 knots on 4/20/2018.

Water Level Response During the first forcing event, all near-shore wells experienced significant increases in water level. Water levels in GWW31 and GWW32 were highly responsive to tidal forcing with peak levels exceeding the land surface elevation suggestion that overtopping had occurred. GWW33 and GWW34 were also responsive though not on the same scale as GWW31 and GWW32; water levels did not peak above the land surface elevation during tidal forcing. Tidal forcing was not observed in GWW30.

Specific Conductance Response Specific conductance in GWW31 and GWW32 increased and remained elevated for approximately 13 days after the primary event. The specific conductance in GWW31 increased by approximately 2500 $\mu\text{S}/\text{cm}$ from 34,500 $\mu\text{S}/\text{cm}$ to 37,000 $\mu\text{S}/\text{cm}$ and the specific conductance in GWW32 increased by approximately 15,000 $\mu\text{S}/\text{cm}$ from 20,000 $\mu\text{S}/\text{cm}$ to 35,000 $\mu\text{S}/\text{cm}$. Specific conductance in GWW33 rapidly increased by approximately 35,000 $\mu\text{S}/\text{cm}$ from 5,000 $\mu\text{S}/\text{cm}$ to 40,000 $\mu\text{S}/\text{cm}$ and then decreased rapidly (~4 days) to the initial level of 5,000. Specific conductance in GWW34 exhibited two approximate 10,000 $\mu\text{S}/\text{cm}$ spikes concurrent to tidal fluctuations.

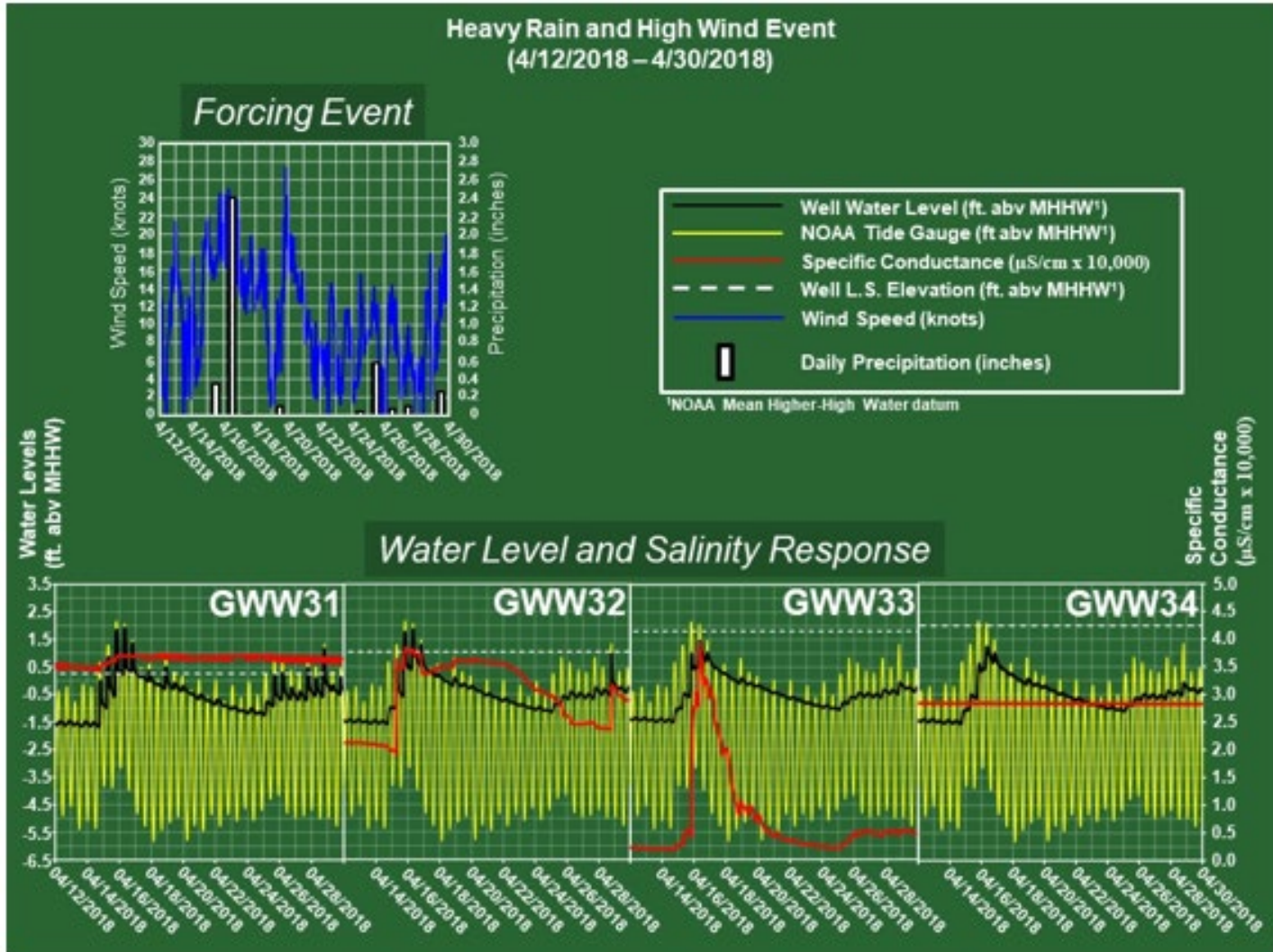


Figure 7a. Shoredward wells groundwater, and seawater levels, specific conductance and forcing events - Sandy Hook Study Area.

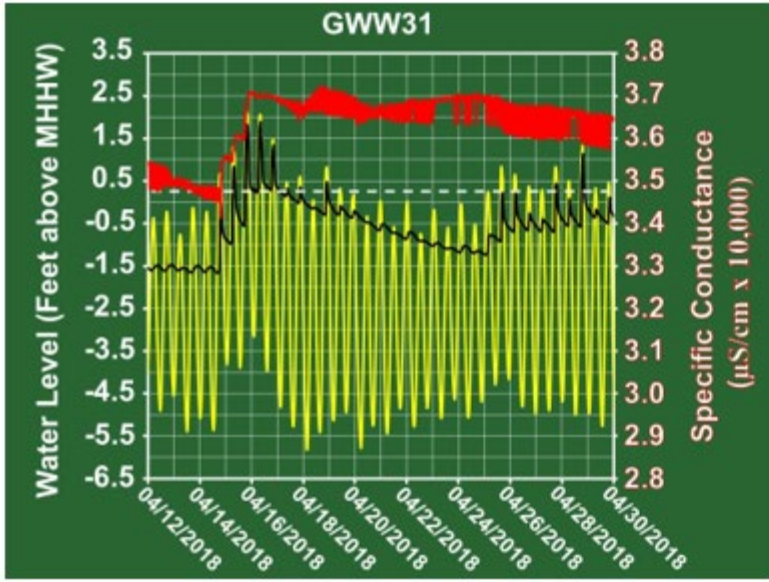


Figure 7b. GWW31 - Zoom View



Figure 7c. GWW34 - Zoom View

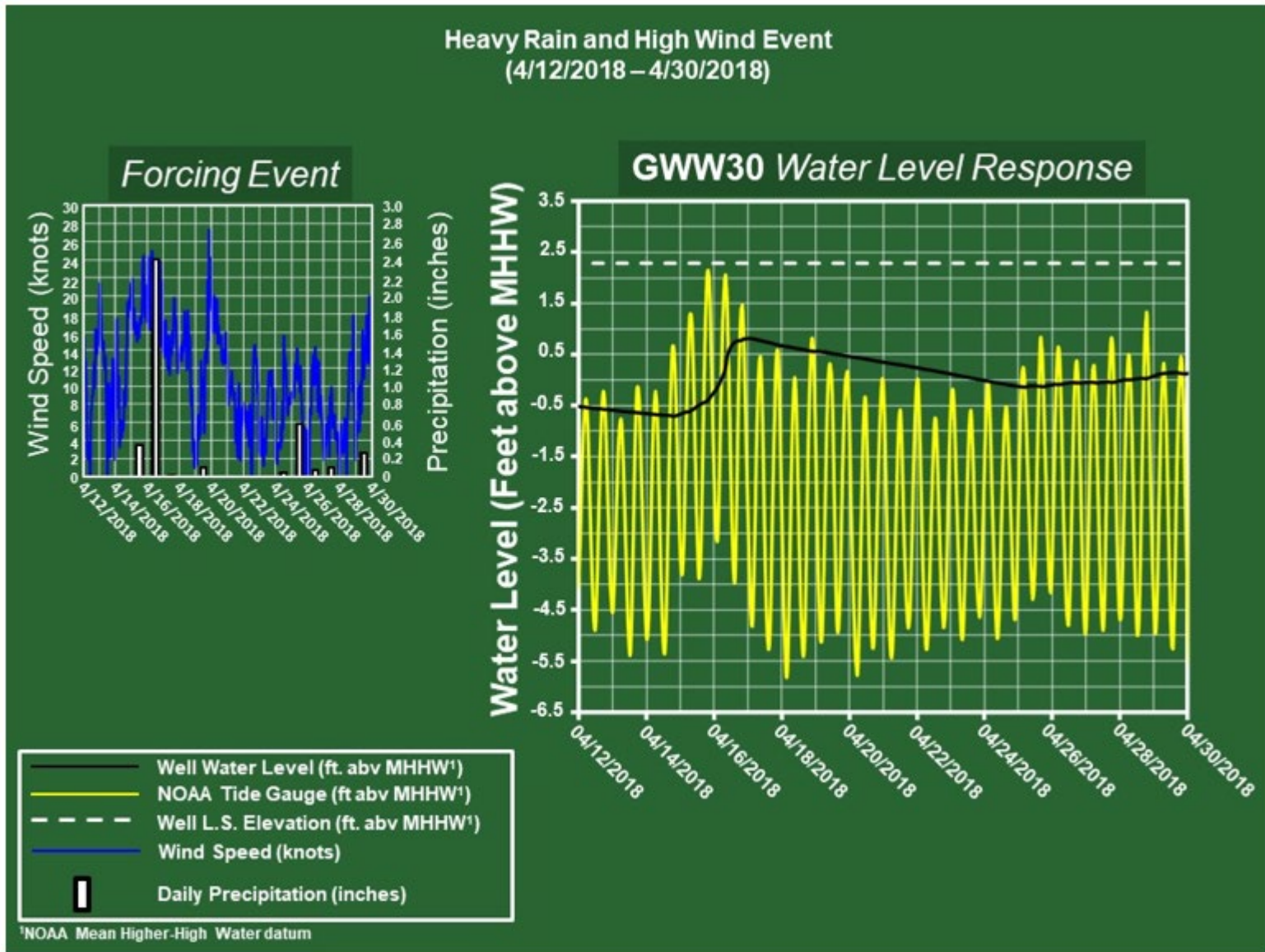


Figure 8. Inland well (GWW30) groundwater, and seawater levels and forcing events - Sandy Hook Study Area.

3. High Precipitation Events (9/01/2018 to 10/25/2018)

Description This event was characterized by three significant precipitation events. The first precipitation event occurred on 9/10/2018 with approximately 1.7 inches of rain and 20 knot winds. Less rainfall was observed in the two subsequent events from 9/25/2018 to 9/28/2018 and 10/10/2018 to 10/11/2018 with 0.5 and 0.9 inches of precipitation respectively. High winds were recorded from 10/10/2018 to 10/28/2018 with the highest windspeed exceeding 29 knots on 10/11/2018 and several high winds above 25 knots over the remainder of the period. The three events were bundled into a single event because of the length of the specific conductance response in GWW32 and, to a lesser extent, GWW33 over this period.

Note: There is only a partial record for GWW31 during this period. Data collection was discontinued in this well at the end of water year 2017.

Water Level Response The first rain event may also have coincided with a high lunar tide resulting in overtopping that extended as far inland as GWW33. During this event water levels in all near-shore shallow wells peaked above the land surface elevation. Water levels in the GWW30 inland well were below land surface. However, diurnal tides peaked above land surface in GWW30 on 9/9/2018.

Specific Conductance Response Increases in specific conductance in near shore wells coincided with groundwater and seawater levels exceeding land surface elevations. The length of time specific conductance remained at elevated levels depended on the proximity to the shore and, in-turn, the frequency of overtopping. Specific conductance levels in GWW32 exhibited a rapid rise of 6500 $\mu\text{S}/\text{cm}$ to 37500 $\mu\text{S}/\text{cm}$ when tides began exceeding land surface elevations on 9/5/2018. This was followed by a gradual decline followed by rapid increases related to the precipitation and higher wind events around 9/25/2018 and 10/10/2018 respectively. Specific conductance levels in GWW33 exhibited rapid increases and decreases during this period. The highest increase occurred on 9/10/2018 and may have been associated with the combination of the high lunar tide, high precipitation and high winds. Smaller increases were observed around the precipitation events around 9/25/2018 and 10/10/2018 respectively. Specific conductance levels in GWW34 increased slightly around the first precipitation event and then gradually dropped for the remainder of the period.

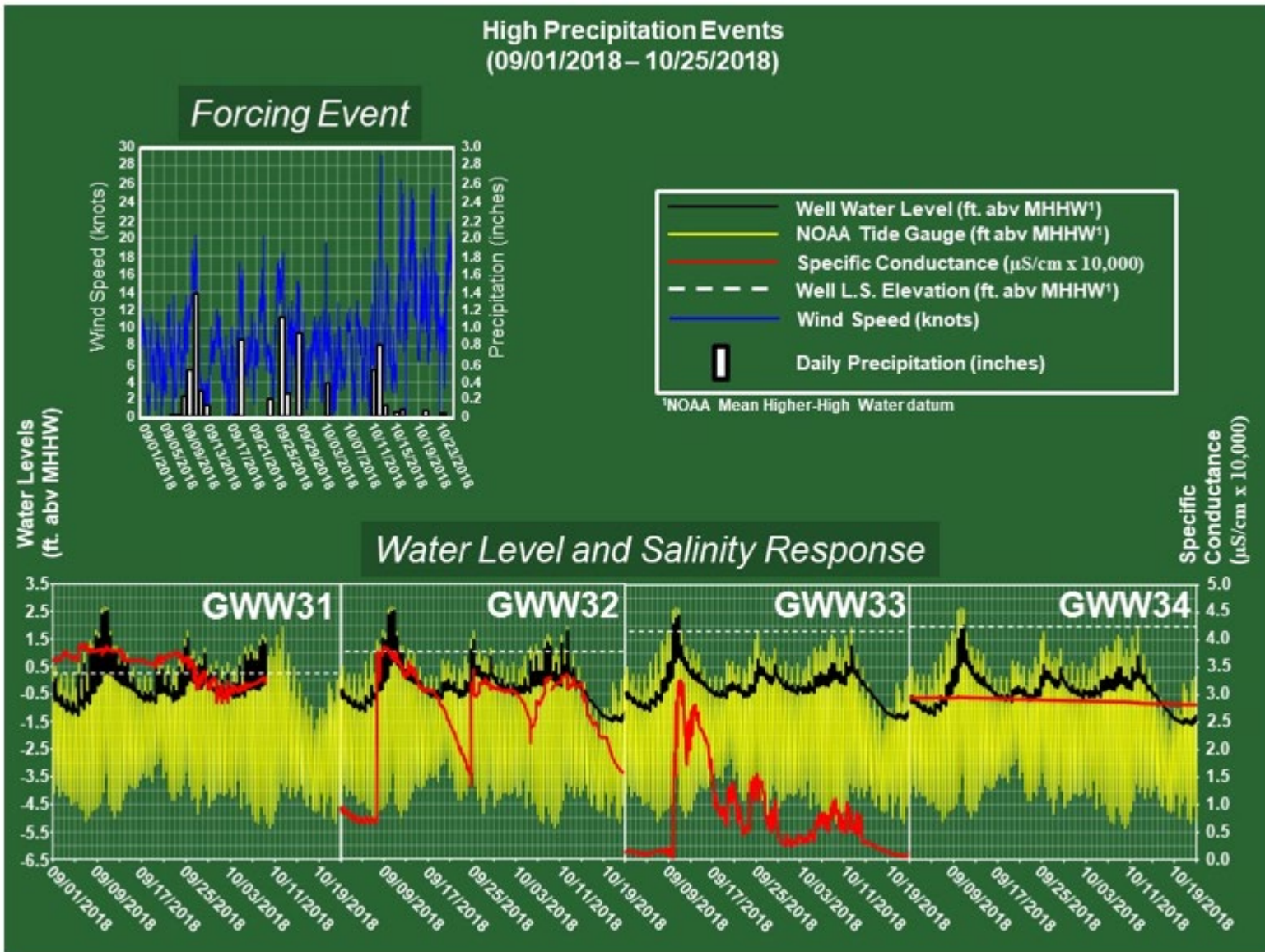


Figure 9a. Shoredward wells groundwater, and seawater levels, specific conductance and forcing events - Sandy Hook Study Area.

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Sandy Hook Storm Events continued



Figure 9b. GWW31 - Zoom View

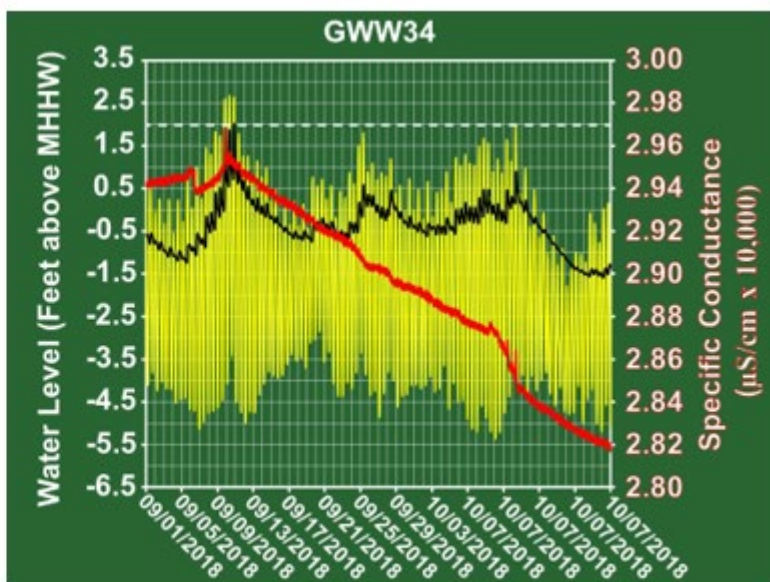


Figure 9c. GWW34 - Zoom View

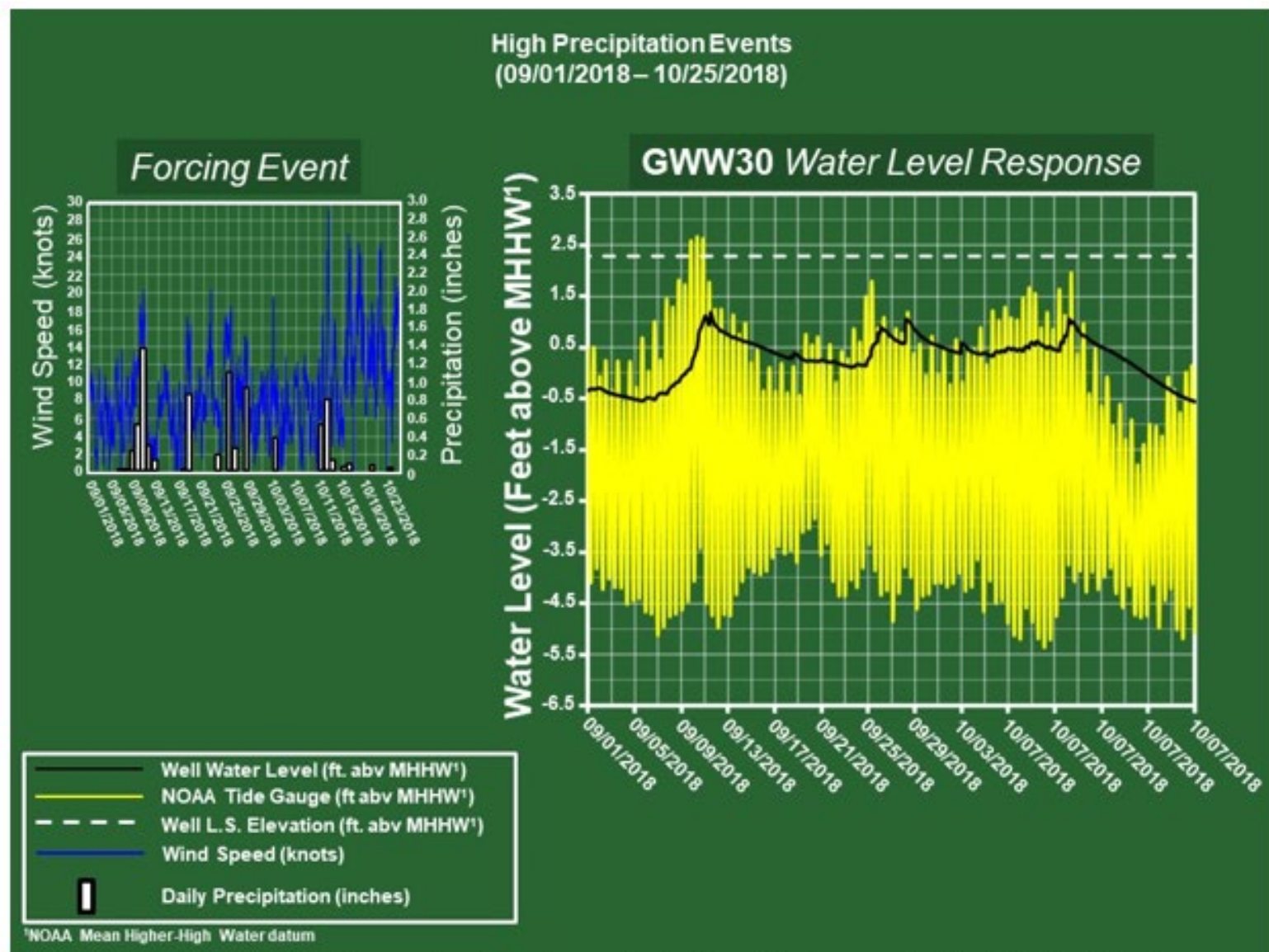


Figure 10. Inland well (GWW30) groundwater, and seawater levels and forcing events - Sandy Hook Study Area.

4. High Precipitation and High Wind Event - Low Lunar Tide (10/26/2018 to 11/05/2018)

Description This period was characterized by a wind and rain event during a low lunar tide. The primary event occurred on 10/27/2018 with approximately 1.1 inches of precipitation and a 26-knot maximum wind speed. Because this occurred during relatively low tides, the spiking of the NOAA Tide Gage water level suggests that it was a response to the forcing event itself and not related to tidal cycles.

Note: GWW31 is not included in this period. Data collection was discontinued in this well at the end of water year 2017.

Water Level Response Groundwater and seawater levels spiked above land surface in both the near-shore and inland wells and then rapidly returned to base levels.

Specific Conductance Response The specific conductance level in GWW32 increased and decreased rapidly with the spike in the tide and groundwater levels. The specific conductance level in GWW33 also appeared to initially spike; however, after the rapid decrease the specific conductance level rapidly increased and remained elevated for the duration of the analysis period. Specific conductance levels in GWW34 rose and fell rapidly with the water level spike.

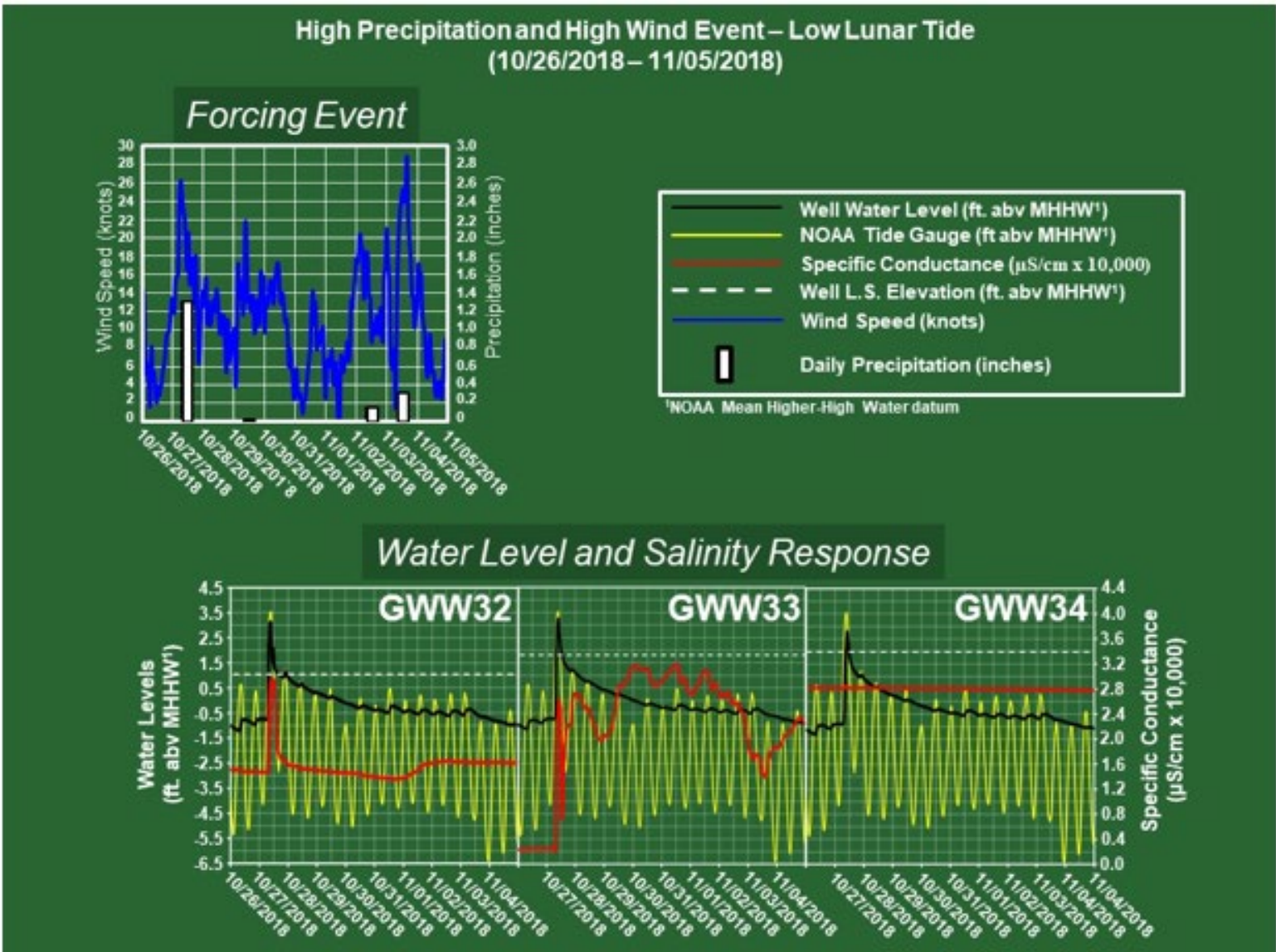


Figure 11a. Shoreward wells groundwater, and seawater levels, specific conductance and forcing events - Sandy Hook Study Area.



Figure 11b. GWW31 - Zoom View

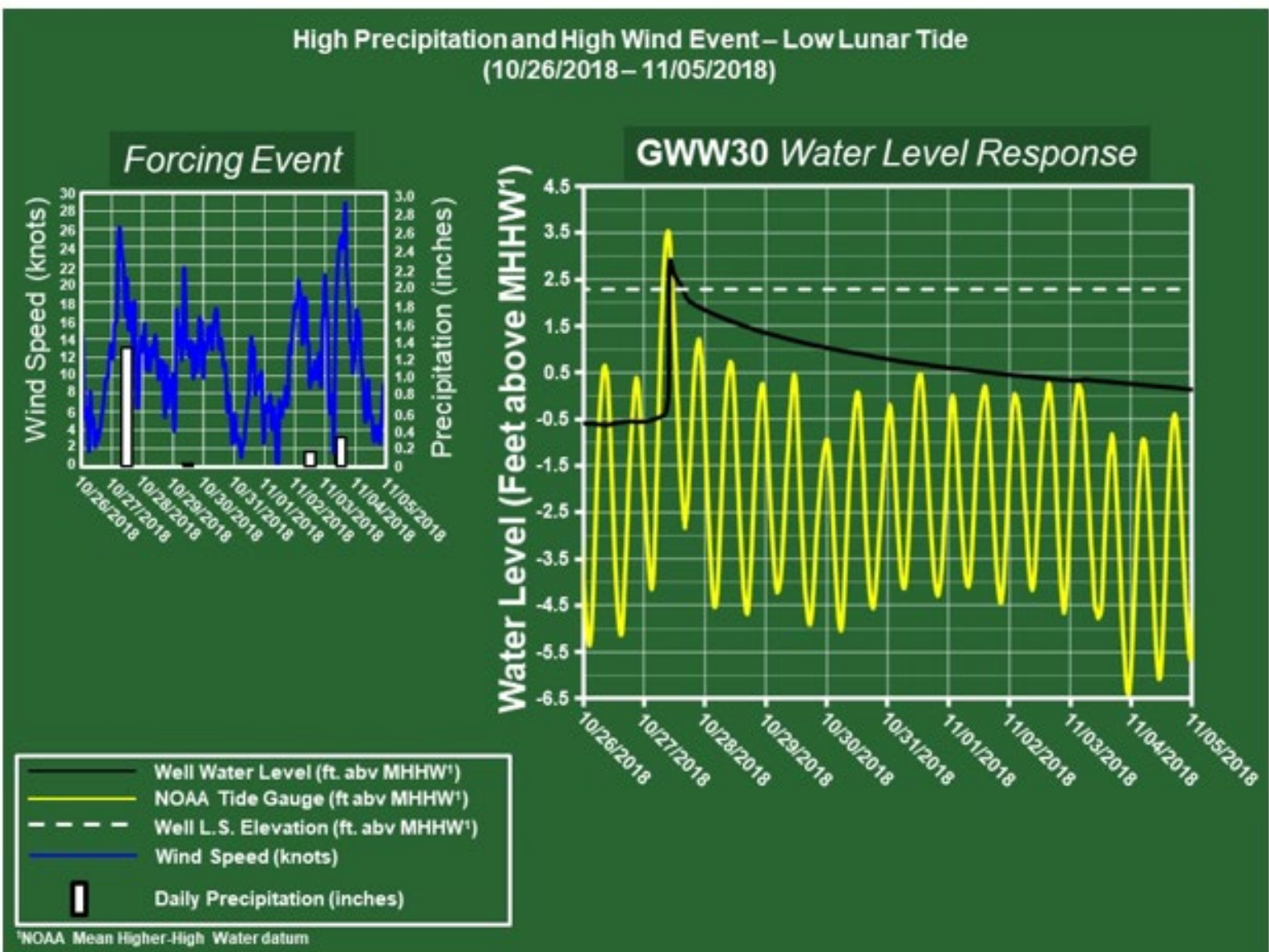


Figure 12. Inland well (GWW30) groundwater, and seawater levels and forcing events - Sandy Hook Study Area.

5. High Precipitation and High Wind Event - Low Lunar Tide (12/20/2018 to 12/30/2018)

Description This period was characterized two rain events and frequent high winds during a low lunar tide. The first event occurred on 12/21/2018 with approximately 1.5 inches of precipitation and a 23-knot maximum wind speed. This event was followed by a high wind event on 12/22/2018 exceeding 30 knots and a high wind event of 22 knots from 12/24/2018 to 12/25/2018. The second event occurred on 12/28/2018 with approximately 0.5 inches of precipitation and a 22-knot maximum wind speed. This event was also followed by a high wind event on 12/30/2018 with a maximum wind speed of 22 knots. Sea levels were elevated during this period with sustained diurnal tides.

Water Level Response Water levels in the near-shore wells experienced rapid increases during the first precipitation event. Diurnal fluctuations corresponding to the tides were also observed. Water levels in GWW32 peaked above land surface with diurnal tides during the high winds from 12/21/2018 to 12/23/2018. Water levels in GWW33 and GWW34 did not exceed land surface elevations; diurnal fluctuations were damped when compared to GWW32 due to the greater distance from the shoreline. Sea levels peaked slightly above land surface elevations of GWW33 and GWW34 when wind speeds were at a maximum on 12/22/2018 and 12/23/2018.

Water levels in GWW30 increased slightly during the first precipitation and wind event on 12/21/2018 but did not exceed the land surface elevation. Slight increases were also observed during the wind event on 12/24/2018 and the second precipitation event on 12/29/2018.

Specific Conductance Response Specific conductance levels in GWW32 and GWW33 increased significantly in response to the first precipitation event and remained elevated for most of the analysis period. The specific conductance in GWW32 also increased in response to elevated wind speeds on 12/24/2018.

Over the 10-day period GWW33 experienced a gradual but significant increase of 20,000 µS/cm and followed by a gradual decrease to the base level. This initial increase/decrease was slightly shifted from the diurnal tide. GWW34 experienced a slight decrease in specific conductance levels during the first precipitation event and remained depressed for the full analysis period.

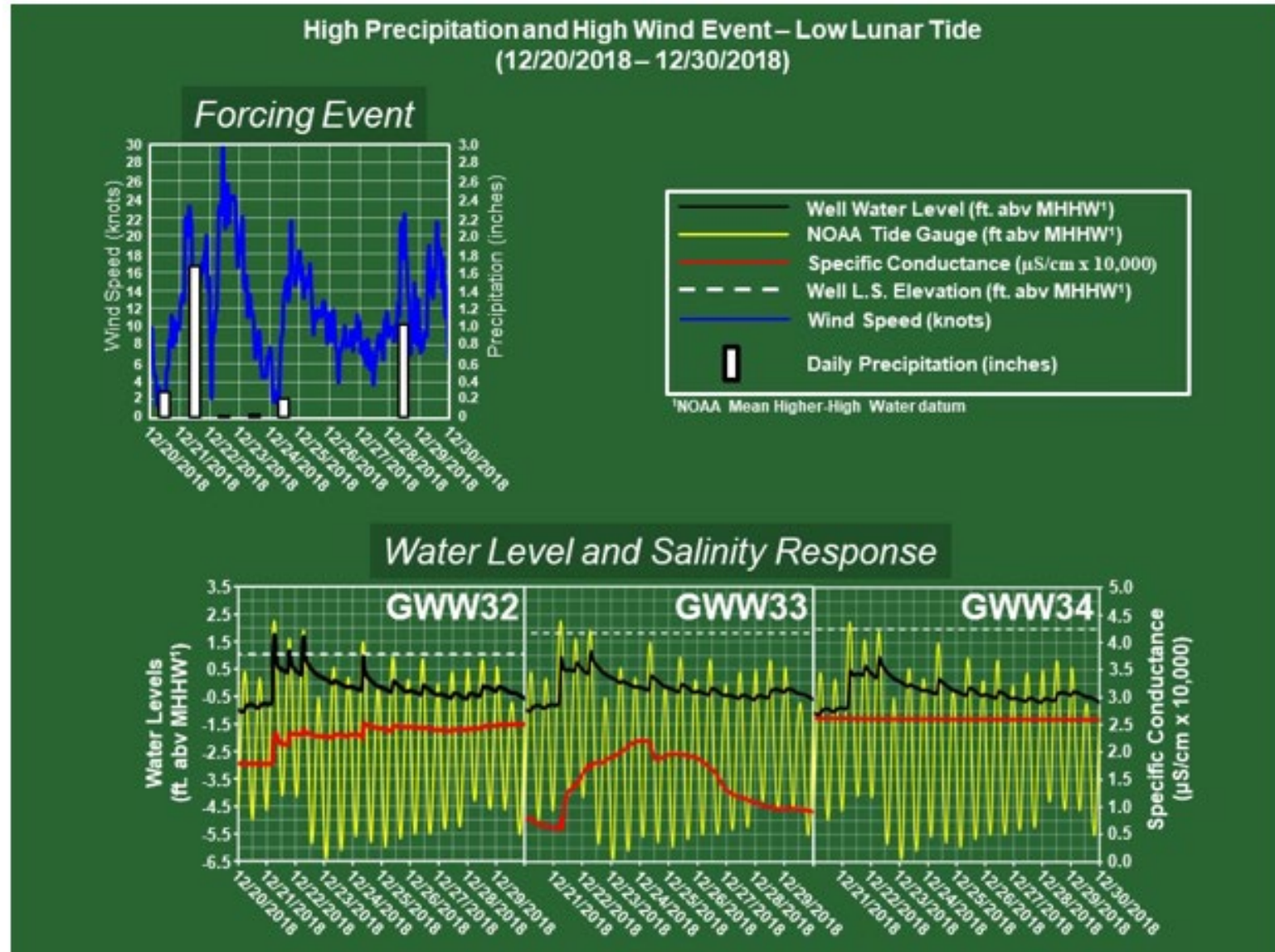


Figure 13a. Shoreward wells groundwater, and seawater levels, specific conductance and forcing events - Sandy Hook Study Area.

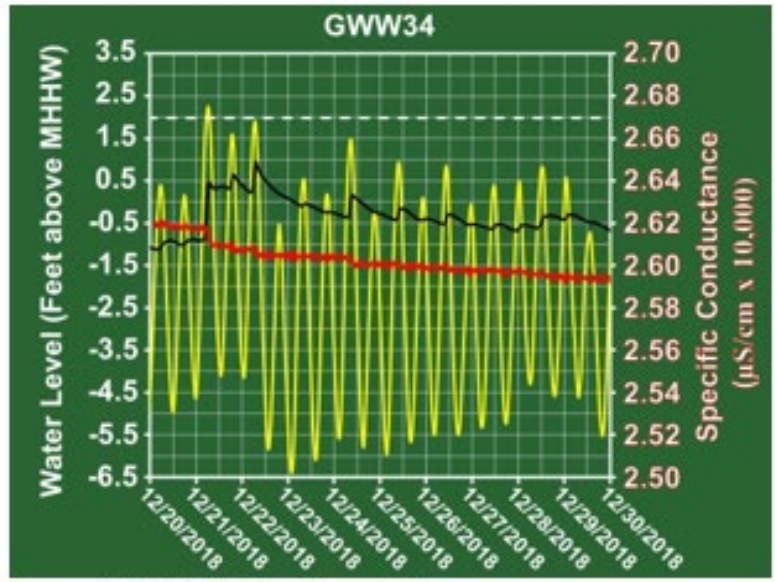


Figure 13b. GWW34 - Zoom View

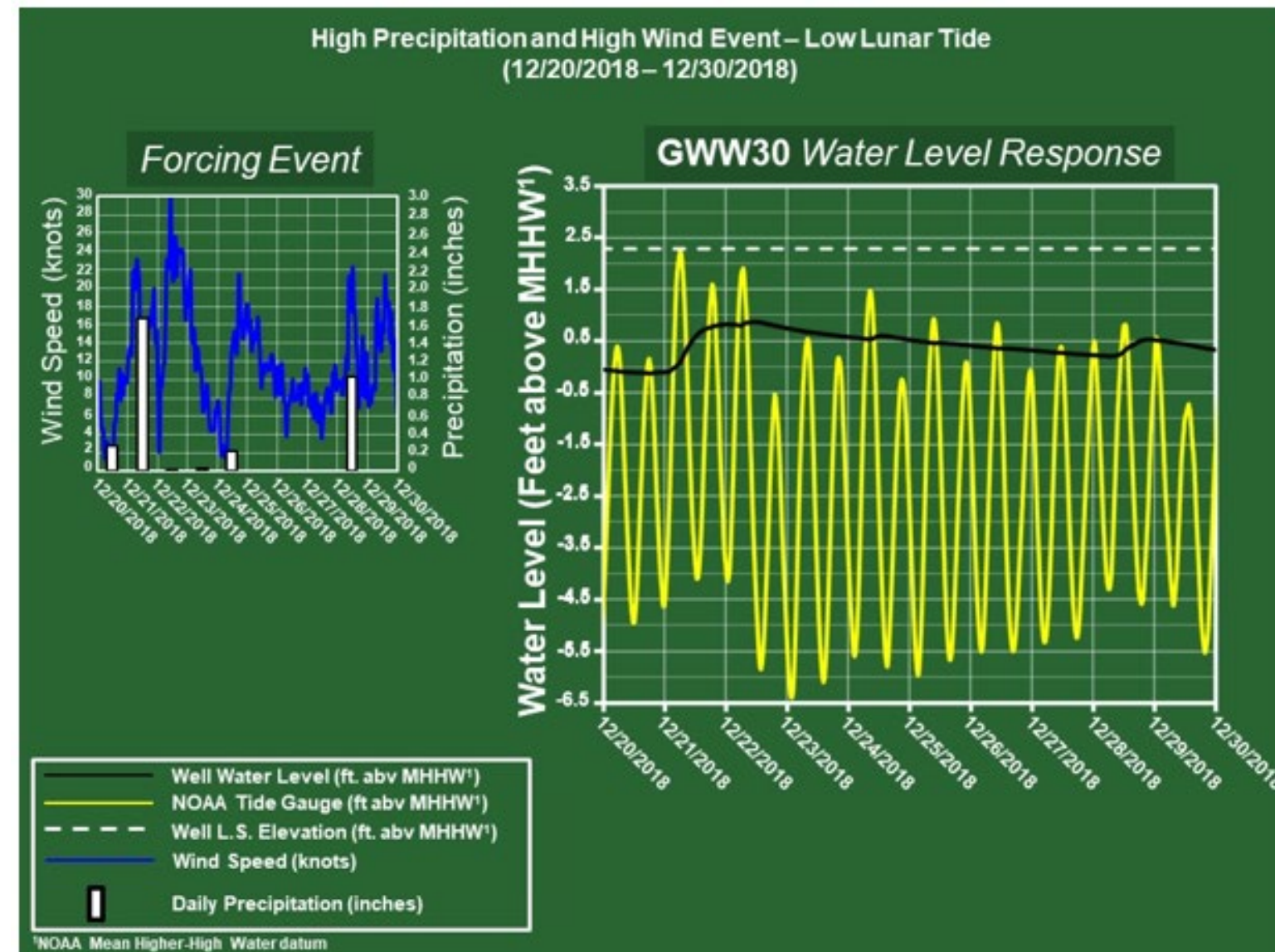


Figure 14. Inland well (GWW30) groundwater, and seawater levels and forcing events - Sandy Hook Study Area.

Final Summary

Date ranges selected for analysis had either rainfall greater than 1 in. and/or wind speeds greater than 20 mph and/or significant tidal forcing. The Northeastern heavy Rain and High Wind event (10/26/2017 to 11/13/2017) had the highest precipitation at approximately 2.55 inches and the highest wind speed at 29.35 knots on 10/29/2017. The highest of high diurnal tides occurred during the High Precipitation events (09/01/2018 to 10/25/2018) with a maximum recorded sea level of 2.67 feet abv MHHW on 09/10/2018 at 10:12 AM. The highest groundwater and sea levels were recorded during the High Precipitation and High Wind Event - Low Lunar Tide (10/26/2018 to 11/05/2018) with a maximum sea level of 3.54 ft. on 10/27/2018 at 09:24 AM (table 2):

Well Name	Date	Time	Water Level
GWW30	10/27/2018	1030	2.92
GWW32	10/27/2018	0915	3.12
GWW33	10/27/2018	0945	3.26
GWW34	10/27/2018	0945	2.77

Table 2: Maximum Water Levels During the High Precipitation and High Wind Event - Low Lunar Tide (10/26/2018 to 11/05/2018)

Water Level Response

There were three types of water level response: 1. Short-term fluctuations coupled to diurnal tides, 2. short-term fluctuations coupled to meteorological events (precipitation and wind) and 3. long-term fluctuations coupled to a combination of meteorological events with lunar tides. Tidal fluctuations complicated the determination of relationship of water level fluctuations to either wind or precipitation. For example, were increased water levels with high tides linked to meteorological events or were they linked to naturally occurring tidal fluctuations?

In general, high winds yielded higher groundwater levels but that was not always the case. For example, during the 10/26/2017 to 11/13/2017 event (Northeastern Heavy Rain and High Wind Event Followed by a High Spring Tide) a high wind event (> 30 knots) late on 10/29/2018 resulted in sea and groundwater level spikes in each of the near-shore wells.

However, during a sustained high wind from 10/30/2018 to 11/01/2018 significant increases in either sea or groundwater levels were not observed. Another example is the observed change in water levels in GWW30. During the High Precipitation and High Wind Event at Low Lunar Tide (10/26/2018 to 11/05/2018), the moderate precipitation (~1.1 in.) and high (~26 knot) wind at low tide on 10/27/2018 resulted in sea and groundwater levels spiking above the land surface elevation. However, during a later High Precipitation and High Wind Event at Low Lunar Tide (12/20/2018 to 12/30/2018) the greater precipitation (~1.5 in.) and slightly slower wind speed (~23 knots) resulted in only a mild, longer lasting increase in water levels.

The near shore wells were highly responsive to both tidal (diurnal and lunar) and meteorological forcing. The amplitude of the water level response generally decreased moving inland from the coast. GWW31 was the closest to the shoreline and, therefore, most responsive to any forcing. GWW31 was also constantly inundated by seawater. GWW32 was also frequently inundated during the highest of high tides as well as during high wind and high precipitation events, though not as often as GWW31. GWW33 and GWW34 were the farthest inland from the shore and were only occasionally inundated by seawater. Inundation of GWW33 and GWW34 (sea and groundwater levels >0.5 ft above land surface elevation) occurred during the High Precipitation Events from 09/01/2018 to 10/25/2018 (~ 1.0 to 1.5 ft above land surface) and High Precipitation and High Wind Event to Low Lunar Tide from 10/26/2018 to 11/05/2018 (~3.0 ft abv land surface). Sea levels did reach the land surface elevations of GWW33 and GWW34 for other high precipitation, high wind and high tide events but only slightly and sporadically during the highest of high tides.

GWW30 experienced only a mild increase in groundwater levels in response to high precipitation and/or wind speeds (High Precipitation Events (09/01/2018 to 10/25/2018); Heavy Rain and High Wind Event (4/12/2018 to 4/30/2018)). However, the High Precipitation and High Wind Event at Low Lunar Tide (10/26/2018 to 11/05/2018) did push water levels above land surface on 12/21/2018.

Specific Conductance

Specific conductance levels in the near-shore wells were correlated to the proximity of the well to the shoreline. This was true in both the response to tidal fluctuations and storm events.

GWW31 was nearest to the shoreline and exhibited the highest ambient specific conductance (~30,000 to 40,000 µS/cm), most likely related to constant inundations during high tide and storm events. The effects of specific storm events on the specific conductance in this well was limited. Significant fluctuations were observed during high amplitude tidal cycles where water levels in the well fluctuated significantly. However, fluctuations in specific conductance did not necessarily correlate to water level fluctuations in the well. For example, during the Northeastern Heavy Rain and High Wind Event Followed by a High Spring Tide (10/26/2017 to 11/13/2017) specific conductance levels actually dropped by about 1,000 to 2,000 µS/cm when sea and groundwater levels were highest. In general, the changes in specific conductance to any forcing event was either minimal or not directly correlated in GWW31.

GWW32 was frequently inundated by either storm or high lunar tides. During most of the events, rapid and prolonged increases were observed in the specific conductance. During the Heavy Wind and Rain (4/12/2018 to 4/30/2018) event, for example, the specific conductance increased from ~20,000 µS/cm to ~40,000 µS/cm and remained near or at that level for the duration of the event. The exception was the specific conductance response during the High Precipitation and High Wind Event at Low Lunar Tide (10/26/2018 to 11/05/2018) where the specific conductance level spiked to ~15,000 µS/cm to ~30,000 µS/cm and then rapidly returned to the starting level of ~15,000 µS/cm.

GWW33 was occasionally inundated by either storm surges or high lunar tides. Specific conductance levels increased significantly during the events. However, the time and duration of time of the increases varied between events. For example, during the Heavy Rain and High Wind Event (4/12/2018 to 4/30/2018) the specific conductance increased rapidly from ~2500 µS/cm to ~40,000 µS/cm and then dropped to ~7500 µS/cm in approximately 2 days. Conversely, during the High Precipitation and High Wind Event at Low Lunar Tide (12/20/2018 to 12/30/2018) event, the specific conductance increased gradually from ~7500 µS/cm to ~22,500 µS/cm over 5 days and then gradually declined over 9 days to 10,000 µS/cm.

The specific conductance in GWW33 exhibited an unusual response during The High Precipitation and High Wind Event at Low Lunar Tide (10/26/2018 to 11/05/2018) event. During this period, groundwater levels spiked approximately 1.5 feet above the land surface elevation on 10/27/2018 in response to the high wind, rain, and tide. However, while the water level decreased steadily back to the base level, the specific conductance exhibited a concurrent spike that decreased rapidly, immediately increased again and then remained elevated for the remainder of the event.

Specific conductance levels in GWW34 (the deep well) generally fluctuated with diurnal tides though occasional spikes with storm or tide events were observed (Precipitation and High Wind Event at Low Lunar Tide (10/26/2018 to 11/05/2018); Northeastern Heavy Rain and High Wind Event Followed by a High Spring Tide (10/26/2017 to 11/13/2017)).

Data References

National Oceanic and Atmospheric Administration, Tides and Currents website, Top Ten Highest Water Levels for long-term stations in meters above MHHW (as of 4/2018) https://tidesandcurrents.noaa.gov/es/Top10_form.pdf, accessed on 11/8/2022.