BARRIER ISLAND GROUNDWATER

Rachel Housego, Woods Hole Oceanographic Institution, rhousego@whoi.edu
Britt Raubenheimer, Woods Hole Oceanographic Institution, britt@whoi.edu
Steve Elgar, Woods Hole Oceanographic Institution, elgar@whoi.edu
Levi Gorrell, Woods Hole Oceanographic Institution, lgorrell@whoi.edu
Heidi Wadman, U.S. Army Engineer Research & Development Center, Heidi.M.Wadman@usace.army.mil
Jesse McNinch, U.S. Army Engineer Research & Development Center, Jesse.McNinch@usace.army.mil
Kate Brodie, U.S. Army Engineer Research & Development Center, Katherine.L.Brodie@usace.army.mil

INTRODUCTION

Storms can have long-term impacts on the groundwater flows and subsurface salinity structure in coastal aquifers. Previous studies have shown that tides, wave driven infiltration, and storm surge elevate the groundwater level within the beach (Nielsen 1999, Cartwright 2004). The resulting bulge of high groundwater propagates inland, and may cause flooding up to several days after a storm has passed (Gallien 2016). In addition, waves, tides, and storm surge force saltwater to infiltrate into the aquifer above the fresher terrestrial groundwater, and storm-driven pulses of salinity may persist for months (Robinson et al. 2014). Here, observations of groundwater heads and salinities collected continuously for three years are used to examine the effects of ocean storms, wind-driven fluctuations in sound water levels, and morphological changes on a barrier island aquifer.

FIELD OBSERVATIONS

Groundwater heads and salinities in the surface aquifer have been measured every 10 min since Oct 2014 at 8 locations spanning the 550-m-wide, sandy barrier island near Duck, NC, USA (Figure 1, solid circles).

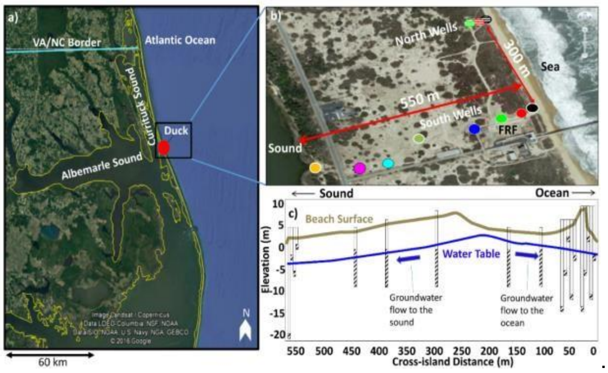

Figure 1: a) Google Earth image of the North Carolina Outer Banks, USA with the study site indicated by the red circle. The land border is highlighted in yellow. b) Aerial view of the groundwater wells (colored circles) and c) schematic of the cross-shore profile of the beach surface (tan curve), water table surface during calm conditions (blue curve, not to scale), and groundwater wells (black rectangles, cross-hatching represents screened sections) versus cross-island distance. Wells in clusters near the ocean and sound are separated by 3 m along-shore.

Ocean wave heights measured in 26-m water depth ranged from 0.2 to 5.5 m (during Hurricanes Joaquin, Hermine, and Matthew) (Figure 2). Ocean tidal fluctuations (mean range about 1 m) and storm surge (up to about 1 m) were measured in 6-m water depth. Tidal effects are negligible in the sound, but winds drove 1-2 m fluctuations in the sound water level. Low sound water levels typically occur during the winter months and are coincident with high ocean water levels driven by winter storms. Ocean salinity ranged from 24-34 PSU, whereas salinity in the sound typically was 2-3 PSU. Nearshore ocean bathymetry was surveyed monthly from the base of the dune to approximately 950 m offshore, and terrestrial lidars measure dune topography and runup hourly. The dune face eroded landward 17 m since the wells were installed.

DISCUSSION

At the beginning of the observational period (Oct 2014) and during periods of small ocean waves (Figure 2a), the groundwater was stably stratified behind the dune (Figure 2b is for x=5 m, black circle in Figure 1b). Following storms, the upper saline plume (USP), a subsurface circulation cell of high-density water created by wave- and tide-driven infiltration, was observed behind the dune face (Figure 2b, red-yellow contours outlined with magenta), and extended up to 33 m inland of the maximum wave runup location. The magnitude of the USP observed behind the dune increased as the dune eroded during Hurricane Joaquin (Figure 2).

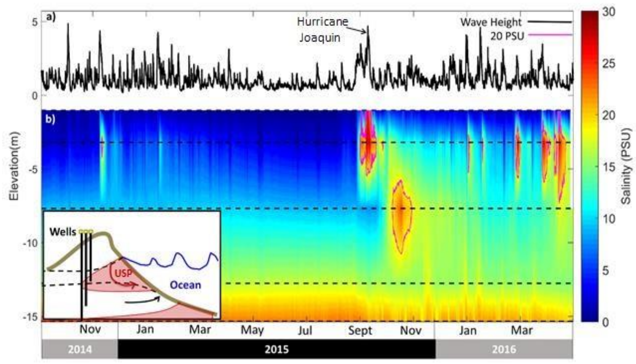

Figure 2: a) Significant wave height (black curve, 26-m water depth) and b) salinity (colors, scale on the right) measured under the dune (black circle in Figure 1b) as a function of depth versus time from Oct 2014 until Apr 2016. Following large wave events, high salinity (red) plumes are observed in the shallow groundwater (elevation 0-10 m). The 20 PSU boundary of the USP is highlighted in magenta. The black dashed lines mark the depths of the sensors. The inset schematic illustrates the salinity (red shaded) structures in the groundwater.

The inland penetration of the USP may have been influenced by the storm induced groundwater bulge under the dune (as well as by the dune erosion). During a nor'easter storm prior to Hurricane Joaquin, the groundwater head near the ocean increased about 0.5 m above pre-storm levels in response to setup, storm surge, and wave infiltration (Figure 3). Hurricane Joaquin increased the groundwater head an additional meter. This bulge of high groundwater propagated up to 160 m inland, with its amplitude decreasing with distance inland (Figure 3).

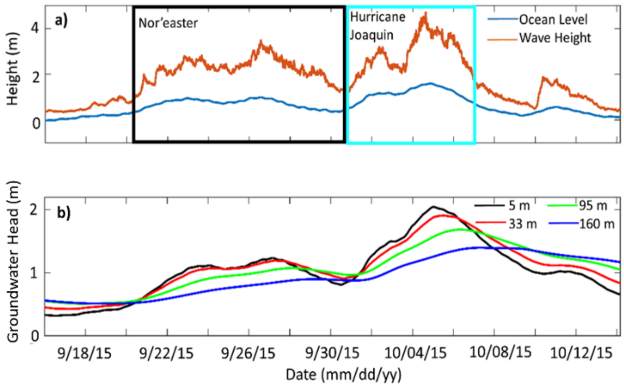

Figure 3: a) Wave height (orange) and 36-hr average ocean water level (blue, including setup and storm surge) and b) 36-hr average freshwater equivalent groundwater head (curves) at x= 5 (black), 33 (red), 95 (green), 160 m (blue) inland from the base of the dune versus time during the Nor'easter (black box, 9/20-9/30/15) and Hurricane Joaquin (cyan box, 10/01-10/07/2015). The colors of the curves correspond with the well locations in Figure 1b, and their distances from the dune are listed in the upper right of Figure 3b.

The storm driven increase in the groundwater level near the ocean during the nor'easter and Hurricane Joaquin reversed the direction of groundwater flow on the ocean-side of the island. Prior to (and following) the storms the inland head levels (Figure 3b, blue and green curves) are higher than the head levels near the ocean (Figure 3b, red and black curves) and groundwater flow is directed toward the ocean. During the storms, the head decreases inland from a maximum in the well closest to the ocean (Figure 3b), creating inland-directed groundwater flow. The inland-directed head gradient and corresponding groundwater flow during storms may explain why the USP extends inland behind the dune face and the location of the maximum runup on the beach.

Feedbacks between the groundwater, ocean water level, and beach morphology, and the effects of storm clusters, dune erosion, and wave-driven setup on groundwater behavior will be discussed.

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