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EFFECT OF FLOODING ON WATER-TABLE ELEVATION AND SALINITY IN A COASTAL OLD FIELD

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ABSTRACT

Water-levels and salinity were measured in seven shallow (ca. 2 m deep) wells installed at distances proximal, medial, and distal to the source of tidal flooding between 2017 and 2019 in a warm-season grass meadow adjacent to a salt marsh. Water-table fluctuations greater than 10-cm were associated with seawater, precipitation, or a combination of the two. When the field was flooded by tides (> 0.5 m above predicted), groundwater salinity increased; when the field was flooded by precipitation (> 2.5 cm), the salinity of the groundwater decreased. The increased head gradient that accompanied the rise in the water table appeared to be sufficient to allow the freshwater from precipitation to push the salt water down and towards the marsh creek, resulting in a freshening of the groundwater that persisted until the next saltwater flooding event. Thus, the relative frequency between saltwater flooding, salinization, freshwater flooding, and flushing controlled the groundwater salinity. These findings indicate the importance of high-tide events in the process of salinization of the groundwater and the ameliorating effects of rainfall events whose magnitude is sufficient to increase groundwater elevation at least ten centimeters. Further, they contribute to a growing body of evidence in support of the interaction between fresh- and saltwater flooding events to enhance the salinity of groundwater and drive ecosystem transition from uplands to salt marshes.

ADDITIONAL INDEX WORDS:

extreme tides, rainstorms, salt-marsh migration, agriculture, plant community change

INTRODUCTION

Coastal flooding increasingly threatens human infrastructure (Kulp and Strauss, 2017), forests (Kirwan and Gedan, 2019), salt marshes (Campbell *et al.*, 2022), and agricultural lands (Nicholls and Leatherman, 1995), with agricultural land being at the greatest risk (Feng *et al.*, 2018). Efforts to quantify the causes and impacts of coastal flooding on human infrastructure are extensive (Neumann *et al.*, 2015 and citations therein), while others have characterized the individual and combined impacts of sea-level rise, precipitation, extreme tides, storm surge, and river discharge on flooding on salt marshes and forests (Gori, Lin, and Smith, 2020; Kirwan and Gedan, 2019; Lyddon *et al.*, 2023; Wahl *et al.*, 2015). Only a few studies consider the relative importance of coastal flooding mechanisms to agricultural lands (Fagherazzi *et al.*, 2019b and works cited therin; Gedan and Fernández-Pascual, 2019; Gewin, 2018; Schieder, Walters, and Kirwan, 2018), and even fewer studies (e.g, Guimond and Michael, 2021; Hingst *et al.*, 2022; Huizer *et al.*, 2017) have examined changes in groundwater salinity in agricultural settings during flooding events despite over a century of groundwater salinization in coastal communities (Barlow and Reichard, 2010).

In agricultural lands, salinization of groundwater by coastal flooding can occur on both long- and short-time scales (Werner *et al.*, 2013). On long-time scales, interannual and interdecadal increases in sea level influence coastal flooding in agricultural land (Baart *et al.*, 2012; Chen *et al.*, 2000; Hamlington *et al.*, 2020). At shorter-time scales, a variety of event-related mechanisms influence salinization. For example, Hingst *et al*. (2022) found that local hydrology, geomorphology, and geology controlled the timing and mechanism of salinization of upland agricultural lands, and that tides, storms, and event seasonality influenced by sea-level rise, affected salinity levels of the surficial groundwater, even at depths greater than 4m below ground surface (BGS). Additionally, White and Kaplan (2017) found that the magnitude and duration of storm-induced saltwater inundation is strongly driven by storm intensity, wind direction, tide, and local hydrological conditions. Consideration of precipitation-caused flooding on groundwater salinity is rare, but Cantelon *et al.* (2022), Nordio and Fagherazzi (2022), and Tully *et al.* (2019) concluded that precipitation can decrease groundwater salinity for a day or two after which it returns to antecedent levels. The combined effect of short-term meteorological and hydrological (including both tides and storm surge) events, and their importance to salinization of groundwater systems, is relatively unstudied.

Episodic tidal flooding (note that because the specific source of saline, non-precipitation water cannot usually be determined, the term tidal flooding includes water from storm or wind-blown surge as well as astronomical tides), precipitation, or both, has the potential to affect groundwater salinity and therefore the suitability of coastal upland soils for agriculture. In low-elevation, shallow-sloped fields adjoining coastal wetlands, the water table is close to the ground surface; the vadose (unsaturated) zone is thin; and the capacity of the soil to absorb floodwater is low. Water from seemingly small precipitation and tidal events has the potential to infiltrate the soil quickly causing the water table to rise to, or above, the ground surface, thereby stressing the plants. If the flood water is salty, additional stress is applied to upland plants. As upland areas experience more frequent and longer duration flooding from precipitation or from the wetland along the upland-wetland boundary, upland plants will be replaced by freshwater wetland plants or salt marsh plants if the flood water is salty (Brinson, Christian, and Blum, 1995; Fagherazzi *et al.*, 2019a; Wasson, Woolfolk, and Fresquez, 2013). Indeed, in upland fields, the presence of wetland species is a leading indicator of salt marsh migration into areas with shallow water tables and soil salinization (Anisfeld, Cooper, and Kemp, 2017).

As salt-marsh conditions, including marsh plants, migrate inland, agricultural land is lost. There may be attempts to control flooding with man-made structures (levees, dikes, shoreline hardening) (Gittman *et al.*, 2016) to prolong the agricultural productivity of the land (zu Ermgassen *et al.*, 2021). Ultimately, as sea levels continue to rise, measures to preserve agricultural productivity will be overwhelmed and the upland will become intertidal marshes or subtidal sediments.

In areas like the Mid-Atlantic coast of the United States, where accelerated rates of sea-level rise are higher than the global average (Sallenger, Doran, and Howd, 2012), loss of upland ecosystems, especially farmland, is happening rapidly (Campbell *et al.*, 2022; Reed *et al.*, 2008; Sallenger, Doran, and Howd, 2012). For example, an estimated 192 ha of farmland are converted to salt marsh annually in Accomack and Northampton Counties, Virginia where the present study was conducted (Titus *et al.*, 2010) at a cost of \$1.8 to \$2.3 million annually (2012 dollars) (Accomack-Northampton Planning District Commission, 2012). This region has gently sloping topography, rapid rates of sea-level rise, and increasing occurrences of coastal storms and high tides that will accelerate marsh migration into uplands (Fagherazzi *et al.*, 2019b). Thus, this region offers an opportunity to examine how accelerated event-driven coastal flooding can impact water-table elevation and patterns of salinization of environmental changes that lead to inland marsh migration into agricultural land.

The present paper examines coastal flooding that introduces salt water from above the water table when land is inundated with salt water that infiltrates into soils and percolates to the water table in the unconfined aquifer. Salinization is differentiated from salinization by coastal saltwater intrusion in confined aquifers (Water Resources Mission Area, 2019) that typically impacts the groundwater system below the water table, especially the confined aquifers as a result of rising sea levels, increased pumping and withdrawal, and decreased aquifer recharge. Natural saltwater intrusion occurs on timescales of months to millennia, while salinization due to surficial flooding occurs on timescales of hours to days (Barlow and Reichard, 2010). Additionally, the study examined the interaction between flooding from offshore sources *vs.* flooding from precipitation to help understand any mitigating effect the precipitation-derived flooding might have on salinization by tidal flooding (tidal flooding is defined here to include storm surge). The paper focuses on high precipitation and extreme tide events that cause a rise in water-table elevation and salinity of groundwater at the study site where the agriculture field's plant community appears to be transitioning from old-field plants to salt-marsh vegetation.

METHODS

This section provides a description of the field site used, and the techniques whereby water-table elevations and salinities were obtained. These data were then combined with existing data from additional sources to describe changes in water-table elevations and salinities associated with extreme flooding events such as storms. An index to a complete data set providing details of physical (including climatology, geology, and hydrology) and biological characteristics has been provided by the Virginia Coast Reserve Long-Term Ecological Research Site (VCRLTER, 2023).

Study Area

The study was carried out on the Delmarva Peninsula at the Nature Conservancy's Brownsville Preserve (located at 37.472318°N, 75.827455°W) which is near Nassawadox, Virginia (Figure 1). The Delmarva Peninsula extends from Delaware Bay southward along the seaside coast of Maryland to the mouth of the Chesapeake Bay in Virginia; it is bordered on the west by the Chesapeake Bay and on the east by the Atlantic Ocean. This area of the Mid-Atlantic coast has experienced high rates of sea-level rise of 5.52 mm yr^{-1} between 1978-2021 (NOAA, 2022) based on the tide gauge at Wachapreague, VA (Station ID: 8631044, 37.60833333°N/ 75.68500000°W). The Delmarva Peninsula experiences a semidiurnal tidal cycle and precipitation is generally evenly distributed throughout the year, but is often punctuated by hurricanes and nor'easters (National Weather Service, 2022) that can cause coastal flooding. The entire area consists of relict beach faces that date back 125,000 years that are bordered by salt marshes (VCRLTER, 2023). The site studied is approximately 16.5 km from the Atlantic Ocean (see Figure 1).

The study site is an abandoned agricultural field owned by The Nature Conservancy that is separated from a tidal creek and surrounding salt marsh by a failed dike system. Other nearby agricultural fields have begun to transition to salt marsh (Flester and Blum, 2020; Kastler and Wiberg, 1996). Long-term (> 20 years) groundwater salinity measurements (Brinson and Stasavich, 2015a; Brinson and Stasavich, 2015b) and plant species biomass measures (Christian, 2014) indicate that salinization of upland groundwater precedes the shift in plant community from old-field vegetation to high salt-marsh plants.

The field is flat with little topographic relief except for an irrigation pond built in the middle of the field (Figure 1). Excluding that pond and its mounded sides, and some depressions near Well 1 associated with the dike construction, elevations range from 0.65 m above mean sea level (AMSL) at the edge of the field near the marsh to 1.37 m AMSL near the road that provides a southern boundary of the field (Figure 1). The gentle slope across the field from Well 1 to the road is approximately 0.9%. The entire field comprises a single soil, Munden sandy loam, 0 to 2 percent slope (Soil Survey Staff, 2022). During boring for well installation confirmed that the soil (through the entire depth of the well bore) was, indeed homogeneous across the field with respect to texture, structure, and horizonization. Survey points for experimental plots (*viz.,* near Wells 3 and 7) where plant community composition was monitored as part of a separate study are included on this map and were used to draw contour lines shown in Figure 1. The current plant community composition of the study site comprises a variety of dune grasses, high-marsh native species, and old-field plant species. The predominant high-marsh species in the field included *Distichlis spicata, Spartina patens*, and *Iva frutescens* (Table 1).

Well Installation

Well locations were selected based on plant community composition at the time of installation. In 2012, examination of plant species composition found three general community types that changed, in order, with distance from the salt marsh: 1) mostly *D. spicata* and other high marsh plant species, 2) a mix of *D. spicata* and upland grasses, such as switchgrass (*Panicum virgatum*), and 3) mostly switchgrass and other upland grasses (Table 1). Two wells (1 and 2, see Figure 1) were installed in 2013, one (3) in 2014, and four (4 through 7) in 2017 (Figure 1, Table 2). Wells were augered by hand and cased with 2" (5-cm) diameter, 0.01" (0.25 mm) slotted, PVC well screen to a depth of at least two meters. The length of the well screen extended approximately 1 m above the ground surface so that the elevation of the water table could be made in the well, even during flooding events in which the water table was above the ground surface. Once in place, the sand wall of the hole collapsed around the well-screen securing the casing in place. The exact elevation of the top of the well casing (meters AMSL) was determined with high-resolution GPS as part of the topographic survey described below.

Groundwater Measurements

Water level, temperature, salinity, and conductivity were measured occasionally in all wells. Water level was determined with a Solinst Model 101® Water Level Meter and recorded as the distance from the top of the casing for later conversion to elevation above mean sea level. Salinity, temperature, and conductivity (SCT) were measured using a YSI Model 30® handheld SCT meter. Measurements were made three times from June to September of 2017, four times from April to September of 2018, and ten times from May 2019 to January 2020. SCT measurements were taken starting as close to the surface of the water table as possible (*i.e.*, 3 to 5 cm) and every 10 cm thereafter from the top to bottom of the well to obtain an SCT profile of the water column in each well. At each depth stop, the probe was held steady until the reading on the meter stabilized and did not change for at least 15 seconds. That value was taken as exact because repeating the process in a bucket of still water containing varying amounts of salt yielded stable and consistent results. Lowering the probe slowly down the well ensured that the procedure did not mix the water column in the well below the level where a specific reading was made.

Pressure transducers with data loggers (Schlumberger Cera-diver®, Van Essen Instruments) were installed in each of the wells to monitor groundwater elevation and temperature every 12 minutes. Data from the transducers were downloaded periodically. The recording pressure transducers were suspended near the bottom of each well. For data collected prior to July 2017, local barometric pressure provided by the National Oceanic and Atmospheric Administration (NOAA, 2022) was used for barometric compensation. Starting in July 2017, compensation of the groundwater pressure was performed using atmospheric pressure measured with a pressure transducer suspended above the water in Well 7. All elevations, including water-table elevations, used mean sea level (MSL) as the datum. The water-table elevations were used to create well hydrographs for each of the wells.

Meteorological and Tide Data

Daily precipitation data were obtained from the Historical Weather feature of weatherunderground.com (Weather Underground, 2022) for Melfa, VA, 24 km from the study site. Wind speed and wind direction for the high-water events were extracted and are listed for each event in Table 3. Tidal data were obtained from NOAA's Wachapreague tide gauge (NOAA, 2022), because there was no tide gauge in Upshur Creek near the study site. The distance from Wachapreague to the Brownsville site is about 20 km, but the use of the Wachapreague tide data is justified by the strong linear relationship between the tides at Wachapreague and those in Phillips Creek, which is about 1.8 km from Brownsville (Christiansen, 1998).

High-Water Events

Tide and precipitation data were used to identify high-water events that coincided with a rapid rise in the water-table elevation of at least 10 cm at Well 1. If there was no record of tide or precipitation that coincided with instances of a water-table elevation that met the selection criteria, the event was excluded from the analysis. In addition, known weather events were recorded even if the water-table elevation change was less than 10 cm at Well 1. Each high-water event was categorized by the dominant cause of flooding. Events with total precipitation equal to or greater than 2.5 cm were classified as precipitation events. Events with an average difference in measured and predicted tides greater than 0.5 m were classified as tide events. Events with no precipitation were also classified as tide events when the 10-cm water-table event criterion was met, even if the tide was not half a meter above predicted. Events with differences in measured and predicted tides greater than 0.5 m and more than 2.5 cm of precipitation were classified as "combined." Events classified as "combined" included cases of low tide with low precipitation, and high tide with high precipitation when the high-water criterion was met.

RESULTS

The water-table elevation generally followed the ground-surface elevation of the field although the water-table elevation exhibited fluctuations that were correlated with tidal and meteorological conditions over the entire field and over the entire duration of the study (2016-2020). During the study, the minimum and maximum measured water-table elevations at any measurement point within the field were 0.005 m below MSL and 1.78 m AMSL, respectively. Groundwater measurements (including all wells and all sampling times) exhibited a range of salinities from 0 ppt to 33.2 ppt (fresh water and full-strength seawater, respectively) over the observation period. The seven wells fell into three distinct groups (Table 2) that reflected the distance from the nearby salt marsh and also, the zonation of plant community composition. The zones and the well groupings within them were termed proximal, medial, and distal (reflecting the distance from the salt marsh) and comprised Wells 1, 4, and 5; Wells 2 and 3; and Wells 6 and 7, respectively (Figure 1). For this study, data from Wells 1, 3, and 7 were used to illustrate the differences in groundwater observation among the groups. Ground-surface elevation at the wells within each group varied from 0.81 to 0.87 m, 0.92 to 0.96 m, and 0.97 to 1.01 m AMSL for the proximal, medial, and distal groups, respectively (Table 2). In 2017, the plant community composition (Table 1) around the proximal well group was predominantly high-marsh species including *Spartina patens, Distichlis spicata, Borrichia frutescens,* and *Limonium carolinianum*. The distal well group surrounding plant community consisted of upland species commonly found in nearby abandoned agricultural fields (Shiflett, Zinnert, and Young, 2013) including *Panicum virgatum*, *Asclepias incarnata*, and *Setaria parviflora*. The medial group of wells was located in areas where the plant community was comprised of a mixture of the species found in the proximal and distal groups. The dominant species in the medial group were *Distichlis spicata* and *Panicum virgatum*.

Groundwater Salinity

Salinity was measured in all 7 wells three times a year during the growing season beginning in 2017. Beginning in September 2019, salinity was measured in each well weekly (Figures 2, 3, and 4). Because the water-table elevation in the wells was not constant with time, the location of salinity measurements for the water-table surface (top) and the mid-point between the top and bottom measurements varied with time, *i.e.*, the distance between measurement points at the bottom, middle, and top of the groundwater depth profile is not the same for each date that salinity was measured.

With exception of a single measurement for Well 3 in May of 2019, water at the bottom of the wells was always more saline than at the water-table surface for all seven wells (data shown for representative wells 1, 3, and 7) and the salinity increased substantially after the summer of 2019 (compare Figures 2, 3, and 4). With increasing distance from the marsh, bottom water salinity decreased, which accounts for the smaller difference between top and bottom water salinity from proximal to medial to distal groups. The largest variation in salinity measurements between the top and the bottom of the well was observed in the proximal group (Figure 2) and the least variation was observed in the distal group (Figure 4). Over time, the mid-point salinity became more like the salinity at the bottom of the well in all three groups. Thus, the groundwater became saltier nearer to the surface and upland plants at this site would, therefore, begin to experience salt stress and, ultimately give way to salt-tolerant marsh plants.

From June, 2017, to July, 2019, tide dominated events events coincided with an increase in groundwater salinity while precipitation dominated events coincided with a decrease in groundwater salinity (examples described below). As water levels fell following both types of events, salinity returned to antecedent conditions. However, in the late summer of 2019, a series of high tide events (Events 31-34, Table 3) following and including a period of relatively low precipitation coincided with higher groundwater salinities that never returned to the levels observed prior to August of 2019 in any part of the well (Figures 2, 3, and 4) during the remainder of the study.

High-Water Events

The largest high tide measured during the study period, 1.99 meters AMSL, was Event 1 (Table 3 and Figure 5) which occurred on January 22-24, 2016, and was associated with a 59-cm rise in the groundwater elevation in Well 1. This event occurred before all the wells were in place and, therefore, was not included in the presented data for salinity, although the measured water level response is included in Figure 5 and Table 3. Water-table elevations often rose after precipitation events in a similar manner to extreme tide events. The most rainfall received during a high-water event (Event 6) was 14.7 cm over 3 days (Table 3 and Figure 5), during which the water-table elevation rose by 21 cm. From 2016 to 2019 there were 38 high-water events (Figure 5) generated by extreme tides, nor'easters, hurricanes, tropical storms, and severe thunderstorms. Wind speeds varied and ranged from 3.1 m s^{-1} to 19.5 m s^{-1}, and wind direction was primarily from the northeast during the events (Table 3).

The number of high-water events increased during the years of the study, and the proportion of the events associated with high tides (either as tide events or combined events) also increased. In 2016, there were six high-water events; three tide, two precipitation, and one "combined" events (Figure 5). In 2017, there were nine high-water events; four tide, three precipitation, and two "combined" (Figure 5). Twelve high-water events were observed in 2018 (Figure 5), of which five were tide dominated, three were precipitation dominated, and four resulted from a combination of both precipitation and tide. In 2019, there were 11 high-water events - seven tide, three precipitation, and one with both tides and precipitation (Figure 5). As seen in Figure 2 through Figure 4, peaks in the water-table elevation coincided with, or lagged slightly behind the observed high tides and precipitation during identified high-water events. As expected, the magnitude of the change in water-table elevation decreased with increasing distance from the tidal creek in each of the cases examined.

High-Water Events: Detailed Examples

Examination of high-water events coinciding with precipitation, high tides, and a combination (both tide and precipitation) at a well representing the proximal (Well 1), medial (Well 3), and distal (Well 7) groups/zones provides insight into the effect of the three types of high-water events.

Precipitation Event: Event #30, July 7-9, 2019

Beginning on July 7 through July 9, 2019, 14 cm of rain fell at the study site (Table 3, Figure 5). This event was the largest rainfall that did not coincide with a tide event or high wind and where salinity data were collected in all three vegetation zones (*i.e.*, Wells 1, 3, and 7). Rain was intermittent with 1.8 cm falling on July 7. A small rise in the water-table elevation (~9 cm) coincided with the July 7 rainfall (Figure 6). Beginning on July 7 and into the morning of July 8, 7.6 cm of rainfall fell, and the water-table elevation rose an additional 23 cm. Finally, a third water-table elevation increase was observed on July 8 when another 4.1 cm of rain fell and the water-table elevation rose by an additional 39 cm. The maximum tide level during this three-day period was 1.04 m AMSL which was 0.42 m above the predicted tide. In Wells 3 and 7, groundwater elevation rose only with the third occurrence of precipitation, likely due to the higher elevation of these wells (*i.e.*, greater storage capacity in the vadose zone).

Combined Event: Event #32, September 5-7, 2019

On September 5-8, 2019, the remnants of Hurricane Dorian passed through the mid-Atlantic region. Precipitation on September 6 totaled 6.35 cm between 7:00 AM and 2:00 PM EST which coincided with a high tide of 1.5 m AMSL, *i.e.*, 0.8 m above the predicted tide. (Table 3, Figure 5). During this time, the water-table elevation in Well 1 rose by 59.5 cm (Figure 7). A similar increase in the water-table elevation was observed in Well 7. In Well 3, the water-table-elevation rose initially by 46.9 cm with the start of precipitation on September 6, and a second rise of 11.9 cm coincided with the following high tide event (Figure 7).

Tide Event: November 16-19, 2019 Event #38

Beginning on November 16 to November 19, 2019, an extreme tide event was observed with an average difference in measured and observed high tides of 0.68 m AMSL. Over the four-day event, six increases in water-table elevation in Well 1 slightly lagged the six high tides (Figure 8). The six high tides measured were 0.59 m, 0.78 m, 0.70 m, 0.74 m, 0.78 m, and 0.50 m above the predicted tide. The six observed increases in water-table elevation in Well 1 measured 26 cm, 17 cm, 27 cm, 6.4 cm, 25 cm, and 5.7 cm. Only three water-table elevation rises of 6 cm, 9.4 cm, and 10.6 cm were observed in Well 3. These water-table elevation increases occurred following the first recorded high tides on November 16, 17, and 18, 2019. In Well 7, only two water-table elevation increases of 17 cm and 6.7 cm were observed. The Well 7 peaks lagged behind the first recorded high tides by approximately 3 hours on November 17 and 18, 2019.

DISCUSSION

The analysis of groundwater salinity showed a temporal response to freshwater flooding from precipitation and saltwater flooding from extreme tides (Figure 2 through Figure 4) that suggests overland flooding with saline water from nearby tidal creeks is the source of salinity in the groundwater. These results are consistent with the findings of Huizer *et al.* (2017) and others (Cantelon *et al.*, 2022; Hingst *et al.*, 2022; Kearney, Fernandes, and Fagherazzi, 2019; Nordio and Fagherazzi, 2022; Tully *et al.*, 2019) who observed that increases in groundwater salinity coincided with tides and storm surges. As sea-level rises, smaller tides will be required to cause floods, resulting in more frequent flooding of uplands with salt water, leading to salinization of the groundwater (Hingst *et al.*, 2022; Kirwan and Gedan, 2019; Tully *et al.*, 2019). However, salinization of the groundwater may not persist if seawater flooding events are followed or accompanied by freshwater inputs from precipitation. As discussed below, results reported here showed a decrease in groundwater salinity in response to freshwater inputs from precipitation. Previous studies suggest that the response may be a result of dilution during high precipitation events (Cantelon *et al.*, 2022; Tully *et al.*, 2019). The responses in the wells studied here suggest that the increased hydraulic-head gradient that accompanies a rise in the elevation of the (fresh) water table upgradient from the wells enhances groundwater throughflow. The freshwater, in response to that greater head gradient between the water table and the saltwater level in the adjacent marsh creek pushes the salt water down and toward the marsh creek, as observed by Cantelon *et al.* (2022). Taken together, the results indicate the importance of high-tide events in the process of salinization of the groundwater and the ameliorating effects of rainfall events whose magnitude is sufficient to cause the groundwater elevation to rise at least ten centimeters. These findings contribute to a growing body of evidence in support of the interaction between fresh- and saltwater flooding events to enhance the salinity of groundwater and drive ecosystem transition from uplands to salt marshes.

Changes in groundwater salinity were directly related to the type of high-water event. Similar to the reports by others (Fagherazzi *et al.*, 2019b; Kearney, Fernandes, and Fagherazzi, 2019), the results reported here observed that tidal events in the absence of precipitation resulted in an increase in groundwater salinity (Figure 2 through Figure 5). For example, two tide events in August 2019, coincided with large increases in groundwater salinity that persisted until measurements were ended later that year. Alternatively, precipitation events in the absence of saltwater flooding resulted in a decrease in groundwater salinity (Figure 2 through Figure 5). For example, between October 15 – 23, 2019, two precipitation events coincided with a decrease in salinity to pre-event levels that persisted until the next tide flood event. In a nearby forested upland adjacent to a salt marsh, Nordio and Fagherazzi (2022) found no correlation between the change in groundwater salinity and the amount of precipitation that occurred during their study. In that study, rainfall resulted in an instantaneous decrease in groundwater salinity that was attributed to dilution; once the rain stopped, the salinity of the groundwater increased to pre-rainfall levels within a day or two. In this study, groundwater salinity decreased during precipitation events (10-cm increase in water-table elevation) and persisted until the next saltwater flooding event. Perhaps the difference between the studies is due to the difference in the magnitude of the precipitation events examined. Nardio and Fagherazzi (2022) did not observe flooding due to extreme high tides or storm surge, but they examined all occurrences of rainfall regardless of the amount of rainfall or of the groundwater elevation response. The present study includes only precipitation events that caused a substantial increase in the water-table elevation. The increased groundwater elevation increases the hydraulic gradient pushing the saline water downward and towards the salt-marsh creek until the next tidal-flooding event brings in additional saline water and reduces or even reverses the head gradient. Another important difference between the two studies is that Nordio and Fagherazzi (2022) never observed surface flooding by tides or storm surge at their study site, whereas many of the flooding events examined in the present report were caused by extreme high tides or storm surge.

Groundwater salinity changes resulting from the combined impacts of precipitation and tidal events, including storm-surge flooding (*i.e.*, tropical storms, hurricanes, and nor'easters), will vary based on the magnitude of the source of flood waters: freshwater from precipitation or saltwater from high tides and storm surge. When precipitation inputs were greater than saltwater inputs, the salinity in the groundwater decreased; during the five combination events accompanied by both high tides and precipitation (Figure 5), the high precipitation mitigated the impact of the saltwater input from the high tides (Figure 7). A similar response was observed during the remaining three combination events that were sufficient to raise the level of the water table but in which the saline flooding was less extreme (measured tide < 0.5 m above predicted) and precipitation was less (Figure 5), but in which a 10-cm increase in the water table was observed. That the frequency of precipitation plus combination events increased (from 2016 to 2020) may be evidence of increased regional storminess which is in agreement with the predictions of Najjar *et al.* (2000). Understanding the impact of increased storminess on flooding event type will be important to informing predictions of short-term effects of coastal flooding on groundwater salinity, especially when considering the source and salinity of the flood waters.

The cycle of flooding, inundation, salinization, and flushing can happen over varying timescales (Cantelon *et al.*, 2022), and an excellent figure showing all the processes at work during the flood events is contained therein. Evidence presented here supports the claim that a persistent shift in groundwater salinity depends on the frequency and duration of flooding from extreme tides relative to the frequency and amount of precipitation. In the short-term, precipitation events in the field at Brownsville can slow the conversion of upland to salt-marsh plant communities. Eventually, as sea-level rises and the hydraulic gradient between upland and mean sea-level decreases, the ability of precipitation events to freshen the groundwater will gradually diminish, and the freshwater - saltwater interface will gradually move inland so that what is currently a fresh groundwater system will become fully salinized.

During the study period, the number of precipitation events remained constant (~3 events per year) while the frequency and magnitude of tide- and storm-surge-caused events increased each year of the study (from five to eight over the period examined). The increase in groundwater salinity at all wells occurring in 2019 (Figure 2 through Figure 4), likely reflects the more closely spaced tidal flooding events with few interspersed precipitation events (Figure 5).

Earlier it was proposed that the transition from agricultural land to salt marsh would be accompanied by decreasing soil drainage, higher water table elevations, decreasing depth to the fresh-salt water interface, and increasing salinities in both the soils and groundwater (Fagherazzi *et al.*, 2019a). Current observations of the water table elevation, groundwater salinity, and plant communities agree with that conceptual model, and the three groups of wells – proximal, medial, and distal – used in this study fall along the gradient hypothesized in that model. A decrease in groundwater salinity and an increase in depth to the fresh-salt water interface was observed along this gradient with increasing distance from the tidal creek. Additionally, the increase of the water table due to the flooding decreased with increased distance from the tidal creeks (compare Figures 6, 7, and 8). The measured groundwater response to tidal events was highest in the proximal wells and decreased with increasing distance from the tidal creek (Figure 8). This is similar to the findings of Anisfeld *et al.* (2017) where tidal flooding variability at higher elevations was driven by individual storm events.

The hydrologic systems of farm fields are heavily influenced by the vertical exchanges of water between the atmosphere, soil, and groundwater (Brinson, Christian, and Blum, 1995), and also by tidal and storm-surge flooding (Fagherazzi *et al.*, 2019a; Fagherazzi *et al.*, 2019b). Infiltration into the soil is controlled by the amount of water reaching the soil surface (precipitation or tidal flooding or storm surge) and by the antecedent moisture content such that wet soils admit and store less water than drier soils. Differing antecedent moisture conditions can yield different groundwater level and salinity responses to flooding events of the same type and magnitude as observed here. Similar flooding depths were achieved whether they were the result of a precipitation or tide event but the timing of water table responses to individual events of similar magnitude varied. The short-term variation in water table elevation response time could be dependent on the antecedent soil moisture conditions. Wetter soils have less storage capacity available for flood waters to infiltrate leading to deeper flood waters above the ground surface than for dry soils experiencing the same level or tidal inundation or precipitation. When the soils were previously dry, *i.e.*, low water table elevation (Figure 6), peaks in water table elevation lagged the event by a greater time than for wetter soils. This lag could also be due in part to a poor hydraulic connection between the surficial soil water and the groundwater. When soils were previously saturated, a smaller event resulted in a much larger peak in water table elevation (Figure 6) that evolved more rapidly than in the drier soils. Antecedent soil-moisture conditions likely also influenced groundwater salinity. Studies have shown that during wetter periods and high antecedent soil moisture conditions can reduce salt water impacts, whereas, drier periods can enhance salt water impacts (Bailey and Jenson, 2014; Cantelon *et al.*, 2022). Future studies should consider antecedent moisture conditions when examining the mechanisms of coastal flooding, saltwater introduction and marsh migration.

At longer temporal scales, evapotranspiration has a significant impact on groundwater levels, increasing in the summer when air temperatures are higher and photosynthesis is occurring (Nordio and Fagherazzi, 2022). Although not presented in this study, daily and seasonal trends related to evapotranspiration in the water-table elevation like those reported by Kearney *et al.* (2019) and Flewelling *et al.* (2013) in coastal systems were observed. The presence of the short-term and long-term evapotranspiration signals has implications for the hydrologic fluxes and the extent of salinization within old fields, especially related to antecedent environmental conditions. High rates of evapotranspiration can lower the water table, especially in periods of prolonged drought, and increase groundwater salinity. No meaningful impact of evapotranspiration on groundwater salinity was seen; however, there is need to explore what impact, if any, evapotranspiration may have over longer time periods, as salinization of groundwater may drive plant community changes.

Inevitably, increases in sea level will result in increased water-table elevations near coastal marshes. When the water table is closer to the ground surface, the water storage capacity of the overlying soil is decreased, and less water is required to inundate the land during precipitation and tide events. A higher frequency of waterlogged soils will result, that will require more time for soils to drain, and place additional physical stressors on the established plant community. The higher water-table elevation observed in the proximal, medial, and distal wells may be a result of the increased frequency of flooding events over the observation period. Six high water events were identified in 2016, nine in 2017, twelve in 2018, and eleven in 2019. Given the accelerating rates of sea-level rise in the region, similar tide and precipitation events would be expected to result in deeper floods over time. Deeper and more frequent flooding may have already increased the groundwater salinity permanently in the proximal locations at the study site. Eventually, the plant community in the distal zone is expected to begin to resemble that of the medial zone, the medial plant community will more closely resemble that of the proximal zone (Table 1) and would consist of a mix of upland and wetland species before eventually mirroring that of the current proximal group that is dominated by the high marsh species *Distichlis spicata* and *Spartina patens*. The pattern of sequential change observed here is consistent with and extends the marsh-transgression model of Brinson *et al.* (1995) beyond its original spatial limits.

The results reported here provide important insights on the effect of increased saltwater flooding on the salinization of groundwater in abandoned old fields. When soils are saturated for extended periods of time, the resulting conditions can facilitate plant community change from upland to wetland species (Brinson, Christian, and Blum, 1995; Fagherazzi *et al.*, 2019b); even in the absence of further sea-level rise, changes to plant-community composition can be expected (Fagherazzi *et al.*, 2019b; Kearney, Fernandes, and Fagherazzi, 2019; Tully *et al.*, 2019). Wasson *et al.* (2013) found evidence that increased flooding frequency and duration with salt water was driving the landward movement of salt-marsh plant communities. Raposa *et al.* (2017) suggested that soil waterlogging from increased tidal inundation was a primary factor in vegetation shifts from the salt-meadow species *S. patens* to the low-marsh species *S. alterniflora* as predicted by Brinson *et al.* (1995). Increased flooding with saline water over time is a result of increases in the magnitude and frequency of tidal inundation and storm surge. The expected increase in frequency of tide-dominated high-water events due to sea level rise will result in a shallower water table, and, in the absence of precipitation, in a permanent increase in groundwater salinity.

CONCLUSIONS

The work presented herein concludes that changes to the groundwater in areas bordering salt marshes and tidal creeks will promote plant community change from old-field species to those of the salt marsh. Despite the effect of precipitation in retarding permanent salinity increases in shallow groundwater, eventually sea-level rise will result in regular flooding with saline water that will lead to permanent changes in vegetation.

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<u>LIST OF FIGURES</u>

Figure 1. Brownsville field topography and monitoring well locations. Contour units are m above mean sea level. The salt marsh is located at the top (north) of the image outside the contour lines. The area containing the contour lines is the abandoned agricultural field which is bounded by the road on the south side of the contoured area. Across the road (further to the south and to the bottom of the image is another abandoned field that was not part of the present study). The latitude and longitude of each of the wells is included in Table 2. The Proximal Group (close to the marsh) includes Wells 1, 4, and 5. The Medial Group (intermediate in distance from the marsh) includes Wells 2 and 3, and the Distal Group (farthest from the marsh) comprises Wells 6 and 7. Dominant plant species in each of the group areas are presented in Table 1.

Figure 2. Water table elevation and salinity – Proximal Group (Well 1).

Figure 3. Water table elevation and salinity over time in the Medial Group (Well 3).

Figure 4. Water table elevation and salinity over time in the Distal Group (Well 7).

Figure 5. All flooding events in a 4-year period (2016 – 2019). An event was defined as when the pressure transducers measured a10-cm increase in groundwater elevation in a

short period of time at well 1. Events are numbered sequentially from the beginning of the record. Black bars indicate tide events. White bars indicate precipitation events. Gray bars indicate events with both tides and precipitation (combined events). Black and white dots indicate the total precipitation over the duration of the event.

Figure 6. An example of a high-water event associated with precipitation (Event #30). The top panel shows the predicted tide (solid line) and the actual high and low tide evaluated at a stream a short distance from the field under study. The second panel shows the precipitation received during the event, and the bottom three panels show the water table elevation for each of the three example wells representing the portion of the field proximal, medial, and distal from the stream

Figure 7. An example of a high-water event associated with both precipitation and tide Event #32). The panels show information as described in Figure 6.

Figure 8. An example of a high-water event associated with tide (Event # 38). The panels show information as described in Figure 6.

Table 1. Plant community composition surrounding groundwater wells proximal (wells 1, 4, and 5), medial (wells 2 and 3), and distal (wells 6 and 7) to the nearby salt marsh and tidal creek. Species are listed in order of relative abundance based on personal observation. Superscripts indicate species with synonymous names. Scientific names were assigned using the Integrated Taxonomic Information System (U.S.G.S., 2022).

Proximal	**Medial**	**Distal**
Spartina patens (Aiton) Muhl.[1]	*Distichilis spicata* (L.) Greene	*Panicum virgatum* L.
Distichilis spicata (L.) Greene	*Panicum virgatum* L.	*Asclepias incarnata* L.
Aster tenuifolius L.[2]	*Asclepias incarnata* L.	*Setaria parviflora* (Poir.) Kerguélen
Borrichia frutescens (L.) DC	*Kosteletzkya pentacarpos* (L.) Ledeb.	*Distichilis spicata* (L.) Greene
Typha sp. (L.)	*Setaria parviflora* (Poir.) Kerguélen	*Kosteletzkya pentacarpos* (L.) Ledeb.
Limonium carolinianum (Walter) Britton	*Aster pilosus* Willd.	*Iva frutescens* L.
Kosteletzkya pentacarpos (L.) Ledeb.[3]	*Phragmites australis* (Cav.) Trin. ex Steud.	*Cyperus esculentus* L.
	Scirpus sp. (L.)	*Fimbristylis thermalis* S. Watson[4]
	Fimbristylis thermalis S. Watson[4]	
	Juncus roemerianus Scheele	

[1] *Sporobolus pumilus* (Roth) P.M. Peterson & Saarela
[2] *Symphyotrichum tenuifolium* (L.) G.L. Nesom
[3] *Kosteletzkya virginica* (L.) C. Presl ex A. Gray
[4] *Fimbristylis spadicea* (L.) Vahl

Table 2. Characteristics of wells. All pressure transducers were monitored until January 8, 2020. The mean high and low tide for the period of the study (Jan 1, 2016 to Jan 8, 2020, calculated with data from the tide gauge at Wachapreague, VA) were 0.1204 and 0.0304 AMSL, respectively

Well	Well Installation Date	Transducer Installation Date	Group	Plant Community at Well Installation	Location		Ground-Surface Elevation (m AMSL)	Well depth (m below ground surface)	Depth to sensor from top of well casing (m)[a]	Elevation of top of well casing
					Latitude (°N)	Longitude (°W)				
1	7/8/2013	7/9/2013	Proximal	High-marsh species	37.4729	75.82700	0.81652	2.940	2.835	1.889
2	7/8/2013	7/9/2013	Medial	Switch grass and mixed forbs	37.4725	75.82780	0.95461	2.920	2.915/2.816	1.983
3	8/6/2014	8/7/2014	Medial	Switch grass and mixed forbs	37.47271	75.82816	0.92884	2.450	2.328	1.523
4	7/31/2017	9/16/2017	Proximal	High-marsh species	37.47280	75.82923	0.87083	2.554	1.748/0.782	1.375
5	7/31/2017	9/16/2017	Proximal	High-marsh species	37.47273	75.82920	0.85868	2.560	2.318	1.508
6	8/1/2017	9/16/2017	Distal	Old-field species	37.47103	75.82883	1.00280	2.662	2.222	1.823
7	9/16/2017	9/19/2017	Distal	Old-field species	37.47253	75.82553	0.97978	2.740	2.112	1772

[a]Where two depths are indicated, a second transducer was added when the first was destroyed or malfunctioned.

Table 3. Summary of case-study weather events. Source: NOAA Tides and Currents (NOAA, 2022); Weather Underground Historical Data (Weather Underground, 2022).

Event #	Date	Type	Measured Maximum Tide (m)	Predicted Maximum Tide (M)	Tide Differential[a] (m)	Maximum Wind Gust (m/s)	Wind Direction	Precipitation (cm)
1	Jan. 22-24, 2016	Tide	1.986	0.649	0.83	29.7	NE	0
2	Feb. 8-10, 2016	Tide	1.56	0.711	0.69	6.7	NE	0.1
3	Apr. 28 – May 9, 2016	Combined	1.511	0.863	0.44	11.6	NNW	5.8
4	Sep. 19-22, 2016	Precipitation	1.061	0.904	0.17	13.6	ENE	5.1
5	Sep. 29 – Oct. 4, 2016	Tide	1.41	0.715	0.56	13.4	ENE	0.5
6	Oct. 8-10, 2016	Precipitation	1.068	0.405	0.44	24.6	N	14.7
7	Apr. 23-27, 2017	Precipitation	1.237	0.818	0.32	16..7	NE	2.5
8	May 5-8, 2017	Precipitation	0.862	0.525	0.19	11.1	S	4.9
9	May 23-30, 2017	Precipitation	1.313	0.903	0.37	11.6	NE	8.1
10	Jul. 6-8, 2017	Combined	0.838	0.681	0.15	9.7	SW	1.2
11	Jul. 28-30, 2017	Combined	1.21	0.483	0.56	14.1	NE	3.9
12	Sep. 17-21, 2017	Tide	1.498	0.808	0.53	9.5	NE	0
13	Oct. 12-14, 2017	Tide	1.414	0.753	0.66	17.1	NE	0.43

14	Nov. 4-10, 2017	Tide	1.398	0.817	0.39	10.2	NE	0.56
15	Dec. 3-5, 2017	Tide	1.165	0.874	0.29	5.2	NE	0
16	Jan. 4-5, 2018	Combined	0.977	0.779	-0.01	23.5	NNW	1.7
17	Mar. 3-8, 2018	Tide	1.41	0.63	0.65	18.3	W	1.4
18	Mar. 20-22, 2018	Combined	1.368	0.66	0.52	19.1	NE	3.3
19	Jun. 10-13, 2018	Precipitation	1.21	0.747	0.34	17	NE	8.7
20	Jul. 7-16, 2018	Combined	1.16	0.898	0.15	9.1	NE	1.1
21	Jul. 21-26, 2018	Precipitation	1.055	0.614	0.21	11.1	WSW	8.2
22	Aug. 30 – Sep. 2, 2018	Precipitation	0.919	0.659	0.10	3.1	W	3.5
23	September 8-12, 2018	Tide	1.762	0.9	0.51	16.7	NE	0.8
24	Oct. 11-13, 2018	Tide	1.245	0.649	0.38	17.9	SE	0.3
25	Oct. 26-27, 2018	Tide	1.341	0.811	0.47	15.2	E	0
26	Nov. 13-16, 2018	Combined	0.954	0.473	0.52	18.6	ENE	6.4
27	Nov. 25-27, 2018	Tide	1.257	0.78	0.39	14	SSE	0.3
28	Jan. 19-20, 2019	Tide	1.31	0.742	0.40	5.7	NE	1.2
29	Jul. 1-5, 2019	Tide	1.118	0.84	0.25	6.3	N	0

30	Jul. 7-9, 2019	Precipitation	1.035	0.615	0.31	9.1	SW	14
31	Aug. 25-28, 2019	Tide	1.3	0.739	0.45	14.4	NE	0.1
32	Sep. 6-7, 2019	Combined	1.493	0.724	0.61	19.5	NE	6.4
33	Sep. 29-30, 2019	Tide	1.255	0.936	0.45	11.8	NE	0
34	Oct. 8-12, 2019	Tide	1.524	0.662	0.63	15.5	NE	1.2
35	October 15-17, 2019	Precipitation	1.053	0.729	0.21	13.7	S	3.9
36	Oct. 20-23, 2019	Precipitation	1.125	0.656	0.32	10.3	E	12
37	Oct. 27-31, 2019	Tide	1.34	0.952	0.30	9.6	NE	0
38	Nov. 16-19, 2019	Tide	1.403	0.624	0.68	15.8	NE	0.2

[a]Difference between the measured and predicted tide