Aquifer Salinization from Storm Overwash

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ABSTRACT


Overwash processes are not only an agent of change to the morphology of barrier islands; they are also a source of instantaneous saltwater intrusion to coastal aquifers. Hatteras Island, North Carolina, USA is particularly susceptible to overwash processes because of its geography and the frequency with which tropical and extra-tropical storms strike the area. Hurricane Emily inundated the island in 1993 with saline water from Pamlico Sound. The floodwaters recharged the Buxton Woods Aquifer, raising salinity levels from approximately 40 mg/L prior to flooding to nearly 280 mg/L within several weeks of flooding. By 1997, chloride levels still had not returned to pre-storm levels.

One-dimensional analytical solutions of the advection-dispersion equation are used to simulate chloride transport within the aquifer utilizing a pulse source implemented with linear superposition. These simulations are matched with chloride breakthrough curves. Initial simulations show that a pulse duration of five days provides the best fit to the data. Simulation of chloride breakthrough at two streamline locations demonstrates that higher gradients advect chloride further into the aquifer, causing higher chloride concentrations and increasing the duration of contamination. The Cape Hatteras region historically is susceptible to several hurricanes in a single season. In order to analyze the effect of multiple overwash events on water quality, predictive simulations show the effect of two overwash events separated by several time lags between storms. Simulations indicate that higher gradients and short time lags between overwash events result in chloride MCL violations that persist for more than four months.

ADDITIONAL INDEX WORDS: Hurricanes, Hurricane Emily, North Carolina, Hatteras Island, saltwater intrusion, storm surge, overwash, barrier island, groundwater modeling, analytical solution, coastal aquifers.

INTRODUCTION

Water quality in coastal aquifers can be threatened not only by upwelling and saltwater intrusion, but also by overwash and storm surge during severe storms. These processes cause flooding that recharges water-table aquifers with saline water. For example, in August and September, 1993, sound-side flooding during Hurricane Emily inundated Hatteras Island, North Carolina (USA) with salt water from Pamlico Sound, a large estuary on the north side of the island (Figure 1). Flooding was most severe in the vicinity of the island’s wellfield that exploits a shallow aquifer for drinking water. A large quantity of the floodwater eventually recharged the shallow Buxton Woods Aquifer (BWA), raising salinity and increasing treatment costs. Chloride levels in the BWA increased from approximately 40 mg/L prior to flooding to nearly 280 mg/L within several weeks of flooding. Chloride levels did not fall below 100 mg/L until March, 1994, and still had not reached pre-flooding concentrations by January, 1997.

The Cape Hatteras Region

Hatteras Island, North Carolina, is the largest island of the Outer Banks, a barrier-island chain that separates the Atlantic Ocean from Pamlico Sound, a 3100 km² estuary (Figure 1). The Cape Hatteras portion of the island lies where the island shifts from a southerly trend to a west-southwesterly trend. It is also at this point that the island widens from less than 1 km in width to over 3 km in width. The “reversed-L” shape of the island acts as a dam during winter extratropical storms (“Nor’easters”) and hurricanes. Northerly winds produced by these storms cross as much as 70 km of open water in the sound, which, coupled with storm surge formed by these intense low-pressure systems, produces a rise in Pamlico Sound of as much as three m (Figure 2). The salinity of Pamlico Sound is approximately 60% that of seawater.

The Buxton Woods Aquifer

The Buxton Woods Aquifer (BWA) has historically been the sole source of freshwater to residents of southern Hatteras Island. Although water pumped from the freshwater aquifer is now supplemented by several moderately-saline deep wells (~70 m in depth), which have chloride levels of approximately 11,000 mg/L and require reverse-osmosis treatment, the shallow groundwater of the BWA continues to satisfy a substantial portion of the island’s freshwater demand. Heath (1988, 1990), Anderson (1999), and Anderson et al. (2000) combine to provide a detailed hydrogeologic framework of the BWA. In general, the aquifer consists of two permeable units, each approximately 10 m in thickness, that are separated by
a semi-confining layer of variable thickness. A silty to clayey sand underlying the lower aquifer unit acts as a semi-confining layer. Burkett (1996) performed a 72-hour pumping test at the center of the island (noted with a * in Figure 3) and determined the bulk aquifer properties shown in Table 1. These parameters, plus average hydraulic gradients for two transects of the island that are derived from Anderson (1999) and Morgan et al. (1994), are used in subsequent analytical simulations.

The BWA and other coastal aquifers of North Carolina have been the focus of several papers. Kimrey (1960) presents an early study of the BWA which shows elevated chloride levels at shallow depths within the aquifer. Harris and Wilder (1964) and Harris (1967) obtained similar results for the BWA and also suggest that aquifer heterogeneities contribute to this phenomenon. Wilder et al. (1978) conducted a study of the water resources of northeastern North Carolina, including the Cape Hatteras region. Winner (1978) presents a study of the Cape Lookout, North Carolina region which suggests that overwash processes are a likely occurrence on the low-lying barrier islands and that weeks to months would be required to sufficiently flush the saline water from the freshwater lens. Mew (1999) demonstrated that chloride levels at shallow depths within the BWA on the north side of the island approach the chloride maximum contaminant level (MCL), which is the legal limit for chloride in drinking water. All of these studies suggest that overwash processes play a significant role in controlling the groundwater quality within the surficial aquifers of North Carolina’s barrier islands.

Coastal Aquifers

Studies of coastal aquifers have mostly been confined to the development of the freshwater-saltwater interface. Many studies focus on methods of evaluating the freshwater-saltwater interface in various unconfined settings (Vacher, 1988; Cheng et al., 1998; Taylor and Person, 1998; Barker, 1999), while others focus on specific coastal settings such as mainland aquifers, carbonate banks, volcanic islands, atolls, and islands of glacial origin (Wallis et al., 1991; Underwood et al., 1992; Vacher and Wallis, 1992; Griggs and Peterson, 1993; Robinson and Gallagher, 1999; Person et al., 2000). Barrier islands have received less focus than the other island types, but several reports present case studies of specific barrier islands (Collins and Easley, 1999; Anderson et al., 2000; Corbett et al., 2000). Some recent work has focused on the effect that tidal processes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Bulk Aquifer Value</th>
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<tbody>
<tr>
<td>Horizontal hydraulic conductivity, $K_h$</td>
<td>m/d</td>
<td>21.2</td>
</tr>
<tr>
<td>Vertical hydraulic conductivity, $K_v$</td>
<td>m/d</td>
<td>5.6</td>
</tr>
<tr>
<td>Aquifer thickness, $b$</td>
<td>m</td>
<td>24.5</td>
</tr>
</tbody>
</table>
have on mixing zone development and near-shore water-table elevations (Nielsen, 1990; Turner et al., 1997; Ataie-Ashtiani et al., 1999; Li et al., 2000a; Li et al., 2000b), but these studies do not address the effects of overwash processes on water quality.

**HURRICANE EMILY**

Hurricane Emily formed in the Atlantic Ocean on August 22, 1993. By the time it reached the Cape Hatteras, North Carolina region on August 31, it was a Category 3 hurricane with winds between 178 and 209 km/h and storm surge potential of 2.75 to 3.65 m. The storm tracked to the east of Cape Hatteras, which produced northerly winds that pushed water from Pamlico Sound onto the north side of the island, adding to the storm surge at Cape Hatteras (National Oceanic and Atmospheric Administration, 1993; Figure 2). Some of these waters penetrated more than one km onto the north side of the island (Figure 3).

Damage from the hurricane was extensive. The hurricane destroyed nearly one-third of the Buxton Woods canopy of loblolly pines (Morgan, 1996). Water quality also declined. Figure 4 shows bulk chloride levels in the Frisco Wellfield immediately following the storm. Also shown in the figure (solid line) is the chloride MCL of 250 mg/L. Within three weeks of the storm, chloride levels in the pumped groundwater were in violation; periodic violations of the chloride standard continued for nearly two months. These chloride data represent bulk chloride levels within the BWA and are used as calibration data for the analytical simulations discussed in this paper.

**Overwash Processes**

Studies of overwash processes in the literature have focused mostly on the effect of saline waters on backbarrier saltmarsh ecosystems and the effect of overwash on barrier island sedimentation. For example, Salinas et al. (1986) describes the effect of submergence on the barrier islands of the Gulf Coast of Louisiana, including the effect of overwash on saltmarsh communities. Guillen et al. (1994) present a case study of an overwash event in the Mediterranean coast of Spain. Stone et al. (1997) analyze hurricane-induced overwash processes in coastal Louisiana, including predictive simulations of wave height in response to barrier-island reductions. Courtemanche et al. (1999) study the colonization of overwash sands by several saltmarsh plants, including Spartina patens and Spartina alterniflora. Morgan et al. (1994) and Morgan (1996) present analyses of the impact of overwash waters on interdunal wetland water levels in the Cape Hatteras region, noting the rapid rise in water levels with the arrival of the storm. The studies of Morgan et al. (1994) and Morgan (1996), however, do not address aquifer salinization.

**ANALYTICAL MODELING**

One-dimensional analytical solutions of the advection-dispersion equation are used to simulate chloride transport within the BWA. The simulations reflect transport along streamlines that originate as aquifer recharge, which in this case comprises the infiltrating waters of Pamlico Sound. The following simulations use the bulk chloride values measured with water pumped by the Frisco Wellfield as calibration data for the duration of the chloride pulse. Although chloride levels in Pamlico Sound in the vicinity of Cape Hatteras vary from 17,000 to 19,000 mg/L depending on location within the estuary and the time of year (Wilder et al., 1978; Giese et al., 1979), water samples collected by Mew et al. (1993) indicate chloride levels of approximately 12,000 mg/L in ponded surface water near the Frisco Wellfield. This lower chloride value, which is used as the source concentration in the following simulations, may be a product of the diluting effects of the precipitation (~17 cm) that fell during the storm (Morgan et al., 1994).

**Pulse Source Analytical Solution**

The analytical solution for a pulse source of duration $t_p$ as calculated by linear superposition is

$$C(x, t) = \frac{C_0}{2} \left[ \text{erfc} \frac{x - v_s t}{\sqrt{4D_s t}} - \text{erfc} \frac{x - v_s(t - t_p)}{\sqrt{4D_s (t - t_p)}} \right] \quad (1)$$

where $C_0$ is the concentration of the sound water [mg/L], $x$ is the distance along the streamline [m], $v_s$ is the average linear velocity [m/d], and $D_s$ is the hydrodynamic dispersion [m$^2$/d]. The pulse source duration is the length of time that the overwash waters recharge the aquifer; once the overwash waters subside, the chloride source is removed. This is simulated in equation (1) through the use of linear superposition, which considers the pulse source to be the difference between two continuous source simulations that are separated in time by the length of the pulse, $t_p$. The complementary error function, $\text{erfc}$, that is also used in equation (1) is common in analytical solutions of solute transport because it reflects the Gaussian distribution that is typical of solute transport processes involving dispersion. This pulse-source solution of equation (1) is used in the following simulations: (1) the calibration of chloride transport along Transect 1 using data derived from the Frisco Wellfield; and (2) the simulation of chlo-

![Figure 4. Chloride breakthrough at the Frisco Wellfield.](image-url)
ride transport along Transect 2 to determine the degree of impact at a proposed wellfield site. Table 2 indicates the simulation parameters \((C_o, v, D)\) that are used in the calibrated simulations of transport along the two transects.

It is important to note that these simulations utilize parameters that are constant throughout the simulations, which will be a source of error at late times. Another source of error is the variable density of the groundwater, which is disregarded in these simulations. Although the source concentration does not vary through the length of the pulse source, the average linear velocity along the streamline and the resulting hydrodynamic dispersion would certainly vary considerably over time, especially as water levels, and thus gradients, decrease with the passing of the storm. The decrease in the water-table gradient and the average linear velocity is not as significant as it would be at other times of the year, however, because the hurricane occurred at the beginning of the high recharge season. Seven years of water-level data from the Cape Hatteras region show that water levels begin to rise in the autumn as recharge rates rise in response to reduced evapotranspiration rates (Anderson, 1999). Thus, the water-table gradient would be expected to be high throughout the duration of the simulations.

Because high velocities have been used in these simulations, two contradictory aspects of the simulations must be noted. First, more mass of the solute per unit time is advected into the aquifer due to high groundwater velocities, thus raising chloride levels considerably after short times. Second, the duration of high chloride concentration will be minimized because the high velocities and dispersion values enable a quicker dilution of solute concentrations. Thus, the simulations that are discussed below are a minimum estimate of chloride breakthrough. See the subsequent sensitivity analyses for the effects of variable groundwater velocity and hydrodynamic dispersion on model output.

### Table 2. Simulation parameters—Transects 1 and 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Bulk Aquifer Value</th>
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<tr>
<td>Source Cl– Concentration, (C_o)</td>
<td>mg/L</td>
<td>12000</td>
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<tr>
<td>Average Linear Velocity, (v)</td>
<td>m/d</td>
<td>0.091</td>
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<tr>
<td>Transect 1</td>
<td></td>
<td>0.170</td>
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<tr>
<td>Transect 2</td>
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<td>4.55</td>
</tr>
<tr>
<td>Hydrodynamic Dispersion, (D)</td>
<td>m²/d</td>
<td>8.85</td>
</tr>
<tr>
<td>Transect 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transect 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Transect 1 Simulations

Figure 5 shows the results of several analytical simulations that use different pulse-source durations. The data comprise the chloride breakthrough curve at the center of mass of the plume for times following the overwash event. The center of mass of the plume was used in calibrating the pulse-source duration because of the uncertainty in the calibration data. Specifically, the data are bulk chloride values obtained from all of the pumping wells that were operating in the wellfield. It is likely that some of the wells detect the breakthrough of the center of mass shortly after the beginning of the overwash event; therefore, rather than picking an arbitrary location along the streamline for the calibration, it was decided that the pulse source calibration should be with the center of mass locations. Subsequent simulations use the calibrated pulse-source duration for calibration of the average wellfield location along the streamline. The left panel of Figure 5 shows simulation results for pulse-source durations of one to six days. As is indicated in the detailed plot shown in the right panel of the figure, the five-day pulse source has a practically identical fit based on a linear least-squares regression \((r^2 = 0.819)\) as does the six-day pulse source \((r^2 = 0.818)\). Although both pulse lengths are equally reasonable, five-day pulses are utilized throughout the rest of the study.

Figure 6 shows breakthrough curves produced by simulations at distances of 25 m, 30 m, and 35 m along the streamline. These locations along the streamline correspond roughly with the position of the screens of the Frisco Wellfield wells. The best fit to the calibration data occurs at a position of \(x = 30\) m along the streamline, where \(r^2 = 0.810\). Deviations from the breakthrough curves at late times suggest that the
dilution that would be expected during higher winter recharge rates is not taken into account by the model.

**Transect 2 Simulations**

Chloride breakthrough curves were also simulated for a streamline parallel to Transect 2. The simulations indicate that the best fit to the breakthrough curve occurs at a distance of 45 m along the streamline; thus, the steeper gradient at Transect 2 advects chloride approximately 15 m further into the aquifer than at Transect 1. This is demonstrated in Figure 7, which compares simulation results for Transects 1 and 2. At a distance of 30 m from the chloride source, chloride concentrations along Transect 2 rise to nearly twice the level that they do in Transect 1. In addition, the peak concentration at 30 m arrives nearly ten days earlier along Transect 2 than it does along Transect 1. Conditions at a position of 45 m along the streamline at Transect 2 are similar to Transect 1 at a position of 30 m.

![Figure 6](image-url)

*Figure 6. Simulated chloride breakthrough at three streamline locations at Transect 1.*

![Figure 7](image-url)

*Figure 7. A comparison of simulated chloride breakthrough curves at several locations along Transects 1 and 2.*

### Table 3. Sensitivity analysis parameters—Transect 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Range of Values</th>
</tr>
</thead>
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<tr>
<td>Source Cl⁻ Concentration, ( C_0 )</td>
<td>mg/L</td>
<td>4000–20000</td>
</tr>
<tr>
<td>Average Linear Velocity, ( v_x )</td>
<td>m/d</td>
<td>0.009–0.9</td>
</tr>
<tr>
<td>Hydrodynamic Dispersion, ( D_x )</td>
<td>m²/d</td>
<td>0.5–45.5</td>
</tr>
</tbody>
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### Discussion

The simulated breakthrough curves suggest that future water quality scenarios along Transect 2 are problematic. Although the area appears to be more protected geographically than the highly exposed area near Transect 1 and the existing wellfield (Figure 3), favorable aquifer conditions near Transect 1 (i.e., lower hydraulic gradient) advect less chloride into the aquifer. This suggests that less time will be spent in violation of chloride MCLs with future storms as a result of pumping from the existing Frisco Wellfield. The following section discusses the sensitivity of the simulated breakthrough curves to changes in model parameters in an effort to demonstrate their influence on model output.

**SENSITIVITY ANALYSES**

Sensitivity analyses of the parameters involved in simulating chloride breakthrough were conducted to determine the level of influence that each of these parameters has on model output. Three parameters were varied: average linear velocity within the aquifer \( v_x \), hydrodynamic dispersion \( D_x \), and the source concentration \( C_0 \). Both \( v_x \) and \( D_x \) were varied over two orders of magnitude. A range of two orders of magnitude was impractical for \( C_0 \) because of the smaller range that is possible. Sensitivity parameters are shown in Table 3.

Figure 8 shows the results of the sensitivity analyses at a time of 50 days after the overwash event. The chloride concentrations that are plotted in the figure represent those found at the center of mass of the chloride plume. As is expected, the sensitivity of \( v_x \) and \( D_x \) are inversely proportional. This is reflective of the Peclet number, \( Pe = v_x/D_x \). At high

![Figure 8](image-url)

*Figure 8. Parameter sensitivity analysis results for \( v_x \) (squares), \( D_x \) (triangles), and \( C_0 \) (diamonds).*
Peclet numbers, advective processes dominate and model output is sensitive to \(v_r\) but insensitive to \(D_r\). At low Peclet numbers, the opposite is true: dispersive processes dominate and model output is sensitive to \(D_r\) but insensitive to \(v_r\). Time is also an important constraint in these simulations. The sensitivity of each of these parameters decreases significantly as time increases.

Because of the high degree of sensitivity of the model output to average groundwater velocities, it is important that adequate information is used to estimate this parameter. Also, because of the high degree of sensitivity to average groundwater velocities, the precision of the dispersion estimate is less critical in highly advective systems. Conversely, highly dispersive systems will require less precision in average groundwater velocity estimates. Model output is also directly proportional to the source concentration, \(C_0\). As \(C_0\) increases, the chloride concentration at the center of mass of the plume also increases; as \(C_0\) decreases, the chloride concentration at the center of mass of the plume also decreases.

### PREDICTIVE MODELING—MULTIPLE HURRICANES AND WATER QUALITY

There have been several instances in the past decade when more than one hurricane has hit the coast of North Carolina in a single season. Recent examples include 1996 with Hurricanes Bertha (July 12) and Fran (September 5), and 1999 with Hurricanes Dennis (August 30) and Floyd (September 16) (YOUNG et al., 2000). The time intervals between these historic storms are 55 days in 1996 and 17 days in 1999. Thus, it is a likely scenario that two storms would follow a track like that of Hurricane Emily in a single season, producing similar conditions and threats to water quality within the BWA but raising the threat to water quality.

### Pulse Source Analytical Solution with Second Hurricane

The effects on water quality of a second hurricane that occurs shortly after an initial hurricane can also be calculated with an analytical solution for solute transport with two pulse sources that are simulated using linear superposition. 

The analytical solution for two pulse sources of sound water of duration \(t_1\) and \(t_2\), with hurricane occurrence times of \(t_{H1}\) and \(t_{H2}\), is

\[
C(x, t) = \frac{C_0}{2} \left[ \text{erfc} \left( \frac{x - v_s t_{H1}}{\sqrt{4D_t t_{H1}}} \right) - \text{erfc} \left( \frac{x - v_s (t_{H1} - t_1)}{\sqrt{4D_t (t_{H1} - t_1)}} \right) 
\]

\[
+ \text{erfc} \left( \frac{x - v_s t_{H2}}{\sqrt{4D_t t_{H2}}} \right) - \text{erfc} \left( \frac{x - v_s (t_{H2} - t_2)}{\sqrt{4D_t (t_{H2} - t_2)}} \right) \right] \tag{2}
\]

In these simulations, the calibrated effects of Hurricane Emily are coupled with a second hurricane of equal duration, \(t_2\), lagged a time \(t_{H1}\) after the first hurricane.

### Multiple Hurricane Simulations

Figure 9 shows breakthrough curves at a position of 30 m along a streamline parallel to Transect 1 for several dual hurricane scenarios. In these simulations, the time of the second hurricane was lagged by values ranging from 7 to 35 days. The figure shows the results of each lagged hurricane simulation in addition to the calibrated single storm simulation that was shown in Figure 6. A one-week lag time between storms shows the most severe effect, with a violation of the chloride MCL for more than 100 days. The effects diminish with increasing lag times as chloride levels within the BWA have a chance to dilute before receiving the second pulse. A lag time of 35 days between storms reduces the duration of the violation by at least three weeks.

Figure 10 compares multiple hurricane breakthrough curves for Transects 1 and 2. The breakthrough curves represent the arrival of chloride along streamlines parallel to the transects at distances of 30 m and 45 m for Transects 1 and 2, respectively. These locations were chosen for comparison because they represent the location of potential groundwater withdrawals along the streamlines. The results in Transect 2 are similar to Transect 1, with two exceptions: the peak chloride levels within Transect 2 are higher than those in Transect 1.
Transect 1, and the chloride MCL is violated for approximately two more weeks along Transect 2 due to higher hydraulic gradients. Along Transect 2, a lag between hurricanes of seven days produces chloride MCL violations for more than four months, while a lag of 35 days produces chloride MCL violations for nearly four months at lower peak values.

**DISCUSSION**

The effect of storm overwash on the water quality of coastal aquifers is a real, yet relatively unstudied, phenomenon. Field data from the Cape Hatteras region of North Carolina show that overwash in the form of storm surge has seriously affected water quality in the Buxton Woods Aquifer. Early studies of the BWA suggest that overwash has been an important factor in the past (HARRIS and WILDER, 1964; HARRIS, 1967), and a study at nearby Cape Lookout, North Carolina suggests that overwash could be a serious water quality threat to low-lying barrier islands (WINNER, 1978). Bulk groundwater chloride levels monitored at the Frisco water treatment plant in 1993–94 demonstrate that chloride levels violated MCL standards for more than one month following the storm, with periodic violations for two months. Analytical simulations presented in this study suggest that the effects of multiple overwash events in succession could raise chloride levels in the Buxton Woods aquifer above the MCL for more than 100 days.

The Cape Hatteras region now supplements its freshwater supply with brackish water pumped from three deep wells. The County of Dare, North Carolina currently mixes the freshwater from the existing Frisco Wellfield with saline waters from the deep wells, and then treats the mixed water with a reverse-osmosis treatment system. Although this makes the overwash process less of a problem for the Cape Hatteras region than it was in 1993, it continues to be a concern for several reasons. First, overwash raises the overall salinity of the influent waters, leading to increased treatment demands, time, and costs. Second, coastal regions in the United States are seeing an increase in water demand as populations in these areas increase. The Cape Hatteras region is transitioning from a seasonal tourist destination to a year-round tourist destination. The increased water demand that these year-round tourists bring to the area means that more water is being pumped from the aquifer, thereby shrinking the freshwater lens and diminishing the aquifer's ability to dilute the saline overwash waters. Finally, with the advent of global warming, rising sea levels and more frequent tropical storm events expected on a warmer Earth suggest that there will be an increased frequency of overwash events, further reducing the aquifer's water quality.

**LITERATURE CITED**


MORRISON, A.S., 1996. Water-Table Response to Large Storm Events in Freshwater Wetlands and Adjacent Uplands of a Barrier Island.
Anderson


