Groundwater Inundation and Wastewater Treatment in the Coastal Plain of Georgia

Ben Hodges
ABSTRACT

Sea level rise as a function of climate change is projected to have profound impacts on coastal environments, and groundwater inundation is expected to follow. In this study, Bryan County, Georgia (USA) was evaluated using ground penetrating radar to determine future impacts of groundwater inundation to onsite wastewater treatment systems (OWTS). Also known as septic fields, OWTSs were mapped using handheld GPS units. These locations were then compared to groundwater projections of 0.2, 0.5, and 1.0-m heights above the seasonal high-water table. OWTS depths were modeled at 0.45 and 0.9 m, based on similar studies in North Carolina (Manda et al., 2015). These conditions create an environment where OWTSs will be a danger to water resources in the area. Modeling shows OWTS groundwater inundation ranging from 99% in Upper Bryan County to 100% in Lower Bryan County at seasonal high-water tables and 1 m of groundwater rise.

INDEX WORDS: Sea Level Rise, Groundwater Inundation, Onsite Wastewater Treatment Systems, Groundwater Modeling, Septic Systems, Ground Penetrating Radar
GROUNDWATER INUNDATION AND WASTEWATER TREATMENT IN THE COASTAL PLAIN OF GEORGIA

by

BEN HODGES

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in the College of Arts and Sciences Georgia State University 2019
DEDICATION

I would like to dedicate this work to my parents, Karen and John Hodges who helped raise me with an awe of science and gave me the means to make this possible. My lovely wife, Clara, who has put up with me and given insight and practical advice throughout, a scientist in her own right. And, finally to Richard Cowan, for pushing me to play in the big leagues.
ACKNOWLEDGEMENTS

I would like to thank the Carl Vinson Institute of Government (CVIOG) at the University of Georgia for providing the data necessary for comparison to our modeled surfaces, as well as the logistical support from the Center for Research and Education at Wormsloe (CREW). I would like to thank Albert “Scoot” Killingsworth, IV and Tim Herold for their contributions to data collection in the field. I would also like to thank my fellow employees at Golder Associates, James Jones for input on geographic information systems and hydrogeologic modeling, Chris Bryant for input and assistance with the selection of ground penetrating radar systems, and Charles Naidoo for input regarding wastewater treatment systems.
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LIST OF ABBREVIATIONS

GPR-Ground Penetrating Radar
GPS-Global Positioning System
OSWTs- On Site Wastewater Treatment Systems
m-meter
ft-foot
SLWT- Seasonal Low Water Table
SHWT- Seasonal High Water Table
1 INTRODUCTION

1.1 Research Framework

The coastal regions of the U.S. are among the nation’s most economically productive and ecologically diverse areas. Based on 2010 U.S. Census data, coastal counties account for 39% of the nation’s population and include many of the largest cities and fastest growing counties (Wilson and Fischetti, 2010). Climate change and sea level rise are significant concerns to the coast of Georgia and to the population and infrastructure (Nicholls and Cazenave, 2010). Projections show sea-level rise ranging from 0.2 to more than 1 meter by the end of the century (Jevrejeva et al, 2012). Adverse effects of sea level rise include marine inundation of the surficial aquifer and salt water intrusion into freshwater groundwater resources (Cooper et al., 2013). However, increases in water table elevation and subsequent groundwater inundation are also major concerns that are less understood. This occurs in coastal areas where groundwater tables rise to land surface and cause flooding that is not associated with the overflow of streams. This rise in groundwater is caused as gradients in freshwater resources decrease. As sea levels rise, rivers and streams will face higher base gradients that will cause them to back up and groundwater discharge to streams will decrease proportionally.
Sea Level Rise does not occur uniformly across the globe (NOAA, 2017). Based on sea level rise projections published by the United States National Oceanic and Atmospheric Administration, sea levels will actually rise faster in the Georgia Bight than global mean sea level projections. Based on these projections, by 2100 the coast of Georgia will see more than a quarter of a meter more sea level rise than the global average in a one meter sea level rise projection. (See Figure 2)
Figure 2: NOAA Sea Level Rise Projections of the Georgia Bight versus Global Sea Level Rise Projections (NOAA, 2017).

There are several issues of concern that occur due to groundwater inundation including loss of habitable dry land, chronic and repetitive flooding, geomorphological variation due to changes in stream drainage, creation of wetlands, and persistently saturated soils (Nicholls, 1995). In a state like Georgia, where agriculture dominates the economy, these effects are especially concerning. The occurrence of these phenomena will not be severe in the short term or as overwhelming as many natural disasters but will require engineering and policy decisions to be made far in advance. These decisions will be costly and will require significant political will and investment. Approximately 60% of the world’s population live within 150 km of the coastline and these mitigation strategies will be necessary (Nicholls, 1995).

Areas such as the Georgia Barrier Islands and Coastal Plain may not be overwhelmed by forecasted sea level rise, but when combined with the loss of habitat from coastal inundation the effects of groundwater inundation become severe (Rotzoll and Fletcher, 2013). The surficial
water table in Georgia’s coast is shallow enough that even moderate groundwater level rise could lead to inundation of low-lying areas. This impact could affect more than just septic waste disposal systems. Development near the coast is often marked by the use of underground utilities in higher income areas. Roads, bridges, cemeteries, and train lines would be impacted, as well as other types of developments such as golf and outdoor resorts.

Onsite wastewater treatment systems (OWTS), also known as septic systems, are used for the disposal of wastewater (Hanchar, 1991; Humphrey et al., 2012; Graham and Polizzotto, 2013). Traditionally these systems consist of a tank, a distribution box, and a piped drainfield (Manda et al., 2015). These are installed in the surficial lithologic unit above the surficial aquifer in the vadose zone, such that they are a considerable distance from the water table. This allows the system to operate in ideal (aerobic) conditions and protects local groundwater from site contamination (Manda et al., 2015).

As much as 25% of the population of the United States use onsite wastewater treatment systems for removal of domestic and commercial wastes (Conn et al, 2006). When septic fields are not allowed the necessary distance above water sources, the aerobic bacteria that are used to break down the pathogens in the sewage are not able to perform their function. As bacteria are limited to a reduced vadose (unsaturated) zone or when sewage enters ground or surface waters, dissolved oxygen is depleted by the bacteria and anoxic zones occur. This can lead to impacts in wetlands, streams, and local ecosystems (Minnesota Pollution Control Agency, 2009).

There are also major concerns regarding the spread of disease that are associated with poor disposal of sewage. Poor wastewater treatment is a cause of disease all over the world, and strong correlations have been shown in diarrheal diseases (Levy et al, 2016). Flooding of septic systems poses an issue in the spread of bacteria in multiple pathways. Groundwater quality is
affected as microbes in the limited vadose zone are unable to fully biodegrade wastes. Pathogens can then be transferred through tidal or conductive groundwater forces to shallow irrigation wells used for agriculture or to surface water bodies. As groundwater continues to rise or during flood events, the wastes that are no longer able to be removed from homes and commercial buildings will back up and spread. In many cases, there may not be alternative means of waste removal. Common pathogens detected in wastewater include E. Coli, N. Meningitidis, S. dysenteriae, and V. cholerae (Cai and Zhang, 2013)

These systems are not limited to biological wastes, and the threats that they pose to groundwater and nearby surface water bodies are considerable. Waste streams that reach septic fields are not limited to excrement. Excrement wastes are known as black water and include refuse from toilets. Often these include discarded antidepressants, steroids, stimulants, and other pharmaceutical compounds (Conn et al, 2006). Waste streams also include what is known as grey water. Grey water is any water that is collected from runoff drains, sinks, showers, washing machines, appliances, and other commercial equipment. These can include disinfectants, antimicrobial agents, and metal chelating agents such as ammonia and various phenolic substances (Conn et al, 2006)

The Georgia Rules of the Department of Public Health do not have a required depth for OSWTs, only stating that “A minimum earth cover of six inches (0.15m) over the tank is recommended” (Environmental Health Onsite Manual, 2016). However, best practices in the industry generally require drain field depth to range from 0.45m to 0.9m below grade. In nearby North Carolina, state regulations mandate that drain field trenches must be installed no deeper than 0.9 m below ground surface. In Florida, it is required that “The water table elevation at the
wettest season of the year is at least 24 inches (0.6m) below the bottom surface of the
drainfield.” (State of Florida, Department of Health, Chapter 64E-6).

1.2 Research Objectives

The objectives of this research are to (1) create a model of the seasonal high-water table
heights anticipated under a range of future scenarios and evaluate their impacts at projected
groundwater levels to OWTS, and (2) to use this research to extrapolate other possible
infrastructure and development impacts that will occur due to groundwater inundation.

1.3 Study Area

Bryan County is located in coastal Georgia near the center of the Georgia Bight and
southwest of Savannah. Bryan County’s largest population centers include Richmond Hill and
Pembroke. The county is bisected by Fort Stewart, a US Army base that splits the county and
research areas into what are referred to in the results as Upper and Lower Bryan County Study
Areas. As of the 2010 census, Bryan County was home to 30,233 people and as of 2017 the
county had registered 37,060 people (https://www.census.gov). Bryan county has a total area of
1,180 square km of which 47 square kilometers (4%) is water (https://www.census.gov). Fort
Stewart is almost as large as the surrounding county at 1,100 square kilometers and completely
separates the county into two parts. In order to reach Upper Bryan County from Lower Bryan
County on public roads, one must leave the county.

1.4 Geology

The dunes and swales of the lower Coastal Plain of Georgia were first described in a
formal manner and mapped by LaForge and Cook (1925). In 1950, MacNeil completed a
regional study and descriptions of the coastal stratigraphic units. In this report, MacNeil
recognized distinct paleoshoreline terraces occurring between modern sea level and
approximately 29-30 meters above MSL. These included the Wicomico, ~29-30 m (~98 ft); Penholoway, ~23 m (~75 ft); Talbot, ~12-14 m (~39-46 ft); Pamlico, ~8 m (~26 ft); Princess Anne, ~4.5 m (~14 ft); and Silver Bluff, ~1.5 m (~5 ft). The upper elevation limit of Quaternary sea level in Georgia is considered to be the coastal sediments attributed to the Wicomico Terrace or paleoshoreline position. The lowest and easternmost of these shorelines being the Silver Bluff.

The Lower Bryan County Study Area and Wormsloe are situated in the Princess Anne and Pamlico shoreline deposits and the Upper Bryan County Study Area is located in the Penholoway and Wicomico terraces (Figure 3).
Figure 3: Locations of Paleoshoreline Terraces of the Georgia Bight (Modified from Hoyt).
1.5 Topography

A digital elevation model (DEM; vertical accuracy=0.25m and spatial resolution=6.1m) derived from Light Detection and Ranging (LiDAR) data (Bryan County GIS) clearly displays the Holocene/Pliocene age dune ridges and swales of Lower Bryan County and to a lesser extent Upper Bryan County (Figure 3). Like many intercoastal areas, the landscape is dominated by shore parallel ridges with the smallest ridges and least elevation variance in the northwestern study (Upper Bryan). Lower Bryan varies from 0m along the intercoastal river areas to 16m in dune ridges. Upper Bryan elevations range from 4m to 49m as you move inland. In Upper Bryan County, the Ogeechee River lies on a gradient of approximately 4.9 x 10^{-4} m/m and 5.1 x 10^{-5} m/m in Lower Bryan.
1.6 Climate

Bryan County is located in a subtropical zone with high humidity, temperatures, and precipitation. The average temperature ranges from 9.4 to 27.2 degrees Celsius, and average yearly rainfall is 129.5cm. (http://bryancountyga.org/about-us/living-here/statistics-demographics). Rainfall is fairly consistent throughout the year in Bryan (Figure 3) though discharge increases during winter months due to lower evapotranspiration (Figure 4). In Lower Bryan County, River Gauge Height can vary up to nearly two meters. The gauge cited in the
figures below is 7.8 miles from the marine water boundary in the marsh just south of Montgomery, GA. (Figure 5) (http://nwis.waterdata.usgs.gov/)

Figure 5: Daily Precipitation in Lower Bryan County, GA (http://nwis.waterdata.usgs.gov/)
Figure 6: Daily Discharge at the Ogeechee River in Lower Bryan Study Area (Negative values are functional of incoming tidal flows) (http://nwis.waterdata.usgs.gov/)

Figure 7: Daily Gage Height Variation in Lower Bryan Study Area (Negative values are below daily average) (http://nwis.waterdata.usgs.gov/)
2 EXPERIMENT

2.1 Hydrogeologic Framework

The surficial aquifer in Bryan County is composed of Holocene to Pliocene aged sediments and ranges in thickness from over 67m (220 ft) in the southeastern portion of the county to approximately 43m (140 ft) in the northern portion of the county (Clarke et al., 1999). The aquifer system is in direct contact with the surface and is connected with surface water and tidal streams. The sediments that comprise the surficial aquifer system are dominated by fine to medium quartz sands with minor occurrences of clays and silts. Geoprobe drilling and GPR surveys (160 MHz antenna) at the Wormsloe study area indicate that upper confining clay layer is situated at 20-25 feet below land surface. This clay layer overlies the Upper Floridan Aquifer which is in communication with the surficial aquifer in this area of Southeast Georgia (USGS Scientific Investigations Report 2006-5058). Hydraulic conductivity data obtained via slug testing of shallow wells at the Wormsloe study area yielded values of $1.4 \times 10^{-5}$ cm/sec to $1.6 \times 10^{-4}$ cm/sec ($n=5$) with a mean value of $5.8 \times 10^{-5}$ cm/sec, a value that is representative of a fine sand (Fetter, 2001). In addition, lateral saltwater intrusion has been documented to occur in the shallow aquifer system at limited distances from the intertidal environment (Bush et al., 2016).

2.2 Aquifer Characterization and Groundwater Monitoring

A conceptual hydrogeological model was constructed using data from previous studies of the surficial aquifer system in study areas that are located in near proximity to the subject study area.
Groundwater data was utilized from the Wormsloe State Historic Site in Chatham County, located to the immediate northeast of Bryan County where a monitoring well network collects shallow water level data on a 1-hour frequency or sampling interval. The groundwater data from Wormsloe was used to determine the timing and magnitude of the seasonal high-water table (SHWT) and seasonal low water table (SLWT) conditions.
2.3 Ground Penetrating Radar (GPR)

In Bryan County a MALA GPR system with a Ramac X3M controller was paired with 160 MHz and 450 MHz antennae. These are shielded antennae that incorporate both transmitter and receiver in one unit at a fixed spacing. The controller-antenna system can be used for GPR profiling in either cart or sled mode for the 450 MHz antenna, but required sledding for the 160 MHz antenna. Calibration and configuration were set via the Ramac monitor. The 450 MHz sled
was pulled by hand directly over ground surface and the 160 MHz sled was pushed on a cart in contact with ground surface that took advantage of a wheel odometer to distinguish distance.

One hundred and forty-five (145) locations in Upper and Lower Bryan County were surveyed by a team of Georgia State graduate students and Dr. Brian K. Meyer. Fifty-eight (58) locations were sampled in Lower Bryan County due to difficulty with access in the more coastal region, with the remaining eighty-seven (87) profiles collected in Upper Bryan County.

![Figure 10: MALA GPR System, controller, and 450 MHz antenna](image)

2.4 Data Processing

Processing of the data was performed to remove ambient noise and surface normalization was performed using the LiDAR data to compensate for topography. GPR profile locations were recorded using a Trimble GeoExplorer XH handheld GPS device accurate to within 0.15m. In the Coastal Plain of Georgia, dry sands are optimal for the use of GPR devices. Groundwater increases the dielectric constant and decreases velocity of radar waves. Saltwater saturation
causes a loss of return signal and clay soils attenuate radar until it will not produce viable returns (Daniels, 2004). The water table was identified by the change in velocity associated with the interface of unsaturated and water saturated sands (water table) and compared against the preliminary or conceptual groundwater model.

Figure 11: GPR Pass Taken July 17, 2018 (Orchard Rd Upper Bryan County) As a phase change occurs in radio waves at approximately four feet, from dry sands to saturated sands, the readings from the transmitter appear to become clearer. This is due to increased conductivity in groundwater and lowered wave velocity.
Profiles were calibrated using known groundwater depths at the shallow monitoring wells at the Wormsloe study area. After calibrating the profiles of the antennae to known groundwater depths, a mean value velocity of 508 ft/µs was used to best identify the change or reversal in phase created when waves passed from unsaturated surficial soils to groundwater. This velocity was chosen using the median value of six calibration passes over areas with known groundwater depths and four passes using a hyperbola fit method available in the MALA software. When a continuous layer of attenuated radar was found in the return, it was considered likely to be groundwater. The vertical resolution of the profiles used to estimate the depth of groundwater was approximately 0.15m (6-inches) and were recorded as such.

### Table 1: GPR Velocity Calculations

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Profile ID</th>
<th>Velocity (ft/us)</th>
<th>Velocity (cm/ns)</th>
<th>Source</th>
</tr>
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<tbody>
<tr>
<td>7/10/2018</td>
<td>MW-01</td>
<td>97</td>
<td>564</td>
<td>17.2</td>
<td>water level measurement (depth calibration)</td>
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<td>7/10/2018</td>
<td>MW-02</td>
<td>99</td>
<td>539</td>
<td>16.4</td>
<td>water level measurement (depth calibration)</td>
</tr>
<tr>
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<td>MW-03</td>
<td>102</td>
<td>538</td>
<td>16.4</td>
<td>water level measurement (depth calibration)</td>
</tr>
<tr>
<td>7/11/2018</td>
<td>Profile</td>
<td>119</td>
<td>434</td>
<td>13.2</td>
<td>hyperbola fit</td>
</tr>
<tr>
<td>7/12/2018</td>
<td>Profile</td>
<td>130</td>
<td>450</td>
<td>13.7</td>
<td>hyperbola fit</td>
</tr>
<tr>
<td>7/16/2018</td>
<td>Profile</td>
<td>145</td>
<td>515</td>
<td>15.7</td>
<td>hyperbola fit</td>
</tr>
<tr>
<td>7/16/2018</td>
<td>Profile</td>
<td>161</td>
<td>418</td>
<td>12.7</td>
<td>hyperbola fit</td>
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<tr>
<td>7/19/2018</td>
<td>MW-01</td>
<td>239</td>
<td>532</td>
<td>16.2</td>
<td>water level measurement (depth calibration)</td>
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<tr>
<td>7/19/2018</td>
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<td>240</td>
<td>490</td>
<td>14.9</td>
<td>water level measurement (depth calibration)</td>
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<tr>
<td>7/19/2018</td>
<td>MW-03</td>
<td>241</td>
<td>501</td>
<td>15.3</td>
<td>water level measurement (depth calibration)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Geometric Mean</th>
<th>Median</th>
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<tr>
<td>Velocity (ft/us)</td>
<td>418</td>
<td>564</td>
<td>498.1</td>
<td>495.8</td>
<td>508.0</td>
</tr>
<tr>
<td>Velocity (cm/ns)</td>
<td>12.7</td>
<td>17.2</td>
<td>15.2</td>
<td>15.1</td>
<td>15.5</td>
</tr>
</tbody>
</table>
The elevation of the water table was calculated at each GPR profile location (n=145) by using the LiDAR surface elevation minus the GPR depth to groundwater \( (GW_{EL} = LAND_{EL} - GW_{Depth}) \). Upon comparison to LiDAR data of Upper and Lower Bryan County, a relationship was determined to exist between surficial groundwater and ground surface that was highly consistent. Using ESRI’s ArcMap 10.4.1, points were created from LiDAR values at the locations mapped where GPR profiles were collected. Groundwater elevations at these locations were then compared to ground surface elevations from LiDAR. In Upper Bryan County the relationship between groundwater elevation and surface elevation indicated a linear relationship with a r-squared value of 0.9996 \( (y = 1.0012x - 4.5616) \). In Lower Bryan County the relationship between groundwater elevation and surface elevation also indicated a linear relationship with a r-squared value of 0.9923 \( (y = 1.0087x - 5.1848) \). Due to these linear relationships, modeling of the water table surface was assumed to strongly follow topography in the area. All surveyed data on groundwater in the research area was collected within eleven days.
Raster surfaces of the water table were then generated to model the seasonal low and seasonal high-water table surface. LiDAR topographic raster values were converted using the slope of the line equation from the topography-water table elevation linear relationship. The relationship between the seasonal low water table (SLWT) and seasonal high-water table (SHWT) were evaluated in the model using long-term groundwater monitoring data from the Wormsloe monitoring well network. Tidal influences were not considered for the model as MW-02 at Wormsloe Historic Site is sufficiently removed from tidal influence and septic locations were assumed to be as well. However, additional tidal influences may affect some locations in Bryan County located near waterways.

GPR measurements coverage varied from 2.0 to 9.6 meters in Lower Bryan County and 5.8 to 47.3 meters in Upper Bryan County. OWST locations ranged from 0.2 to 9.5 meters in Lower Bryan County and 4.3 to 47.9 meters in Upper Bryan County. GPR locations were also
spatially distributed to cover each section of the county as completely as possible, avoiding tight groupings. (See Figure 13)

Figure 13: Locations of Groundwater GPR Survey
Using OWTS data provided by the Carl Vinson Institute of Government (CVIOG) at the University of Georgia, locations of the OWTS and associated metadata were added to the GIS geodatabase. The systems were modeled at assumed depths of 0.45 and 0.9 meters below ground surface based on local regulations and best practices. These assumptions are bracketed by the fact that shallow groundwater as mapped in the area would provide a practical limit to septic field depth. Using these rasters, data was pulled at the locations of the OSWTs, and compared to projected depths of the sanitation systems. Based on groundwater level rise projections in coastal environments (Jevrejeva et al, 2012) these elevations at the OWTS locations were projected using a “bathtub model”. In this model, groundwater level rise projections of 0.2m, 0.5m, and 1m were modeled and compared with current OSWT depths.

Figure 14: Study Area with LiDAR and Mapped Onsite Waste Treatment Systems
3 RESULTS

3.1 Modeled Results

Modeling of the mapped locations of OSWTs showed that the majority of these systems would be inundated by groundwater at the very least during seasonal high groundwater periods in even modest sea level rise scenarios. This amounted to a projected 98% of Upper Bryan County OSWTs and 99% of Lower Bryan County systems at one meter of sea level rise, regardless of drainfield depth. In the nearer term, nearly 80% of Lower Bryan County OWTSs will be inundated at only 0.2m of sea level rise if buried at a depth of 0.9m.

Table 2: Rates of Septic System and Ground Surface Inundation in Seasonal High and Low Water Table Scenarios at 0.2, 0.5, and 1.0m of Sea Level Rise

<table>
<thead>
<tr>
<th>Depth</th>
<th>Upper Bryan</th>
<th>Lower Bryan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seasonal Low</td>
<td>Seasonal Low</td>
</tr>
<tr>
<td>Ground</td>
<td>0.30%</td>
<td>0.54%</td>
</tr>
<tr>
<td>0.45M</td>
<td>0.91%</td>
<td>2.57%</td>
</tr>
<tr>
<td>0.9M</td>
<td>6.54%</td>
<td>66.12%</td>
</tr>
<tr>
<td></td>
<td>0.91%</td>
<td>2.57%</td>
</tr>
<tr>
<td>0.45M</td>
<td>6.54%</td>
<td>66.12%</td>
</tr>
<tr>
<td>0.9M</td>
<td>89.83%</td>
<td>98.03%</td>
</tr>
</tbody>
</table>

Notes:
- M = meters
- Seasonal Low = average seasonal low water table (01 May – 01 August)
- Seasonal High = average seasonal high water table (01 December – 01 February)
- 0.45M = assume OSWTs construction of 0.45 meters below land surface
- 0.9M = assume OSWTs construction of 0.9 meters below land surface

4 DISCUSSION

4.1 Research Limitations

Future research and modeling will be required to determine the region of Bryan County where the relationship of modeled groundwater level rise will cease to be linear and what that
relationship may be. This is because stream gradients in the two portions of the county are variable by an order of magnitude, and that elevation change over distance is not comparable. It is likely that interdune swales in the Pamlico or Princess Anne paleoshorelines may be the last regions of the coast not in immediate communication with streams that are likely to be inundated. These may create future marshes or wetlands, but more modeling and research will be necessary to define those limits. Additionally, due to the simplicity of this model, groundwater adjacent to streams and surface waters is likely closer to ground surface than is modeled, but for the purposes of this research the outcome is a more conservative product. The assumption used in this case is that septic systems are likely not located in areas where groundwater is already near surface.

It is important to note that in the few locations where groundwater did not follow topography very closely, these were locations were in non-native soil and/or fill material. An example location would be a service station located on the exit ramp from Interstate 16. At this site, water levels were found to be at eighteen feet below ground surface. This location was clearly developed far above grade in order to facilitate an overpass over the interstate. This likely leads to the conclusion that transportation and other infrastructure that are built above grade in the study area will likely not be affected at the same rates that OWSTs will be. Careful attention was paid in the GPR survey to avoid taking readings in roadways or other non-native ground.

4.2 Discussion of Impacts of Research

In addition to complete or seasonal inundation, these systems will no longer be removed from the water table in the way in which they were designed in even the more conservative models. Loss of the required drainage space in the vadose zone and the aerobic conditions that exist therein will disable the system’s ability to break down fecal coliform and other wastes
associated with septic systems. The pathogens released in sewage waste will not only produce a
disease pathway but can quickly affect nearby streams and/or shallow wells used for irrigation.

Considering that the average storage capacity of a fine sand, as was noted in the research
area, is $6.95 \times 10^{-3}$ cubic meters (0.21 ft$^3$) of water (Fetter, 2001), the impending loss of up to
1.5m of groundwater storage capacity will have massive effects on the built infrastructure of the
coast and how its drainage is engineered. Retention ponds, drainage basins, and other hydraulic
systems need to be engineered with long term goals in mind. Stream flashiness and mitigation of
flooding under current groundwater storage conditions will be greatly affected by the loss of the
storage in groundwater.

These levels of seasonal inundation combined with reduced storage in the surficial
aquifer could lead to severe groundwater quality issues. Additionally, the backflows of sewage
and wastewater could pose a danger to commercial and residential structures throughout the
Georgia Coast. The average water level depth in Upper and Lower Bryan County was 1.4m
(4.6ft) and 1.5m (5ft) from ground surface, respectively. Ground water level rise of any
significance will have major impacts on life in the Lower Coastal Plain of Georgia.

In Lower Bryan County alone, UGA mapped 4,114 sites of known onsite wastewater
treatment systems. Often these systems are tightly clustered into communities. (Figure 11)
Unfortunately, these communities are often built very near streams or tidal areas due to
commercial fishing or for the attraction of their natural beauty. This tendency toward tight
grouping, and their proximity to freshwater resources present special dangers. As dry areas and
vadose zone capable of aerobic degradation decrease, concentrations of hazardous chemicals
near sensitive receptors will increase. Also, the dilution that might occur if these conditions were
isolated will not be possible due to the density of septic fields in relatively small areas. A
negative feedback model is created. This could have catastrophic effects on human health and the environment.

Figure 15: Lower Bryan County OWST Density Map
Due the property values of these areas, and in some cases, economic inability to rebuild elsewhere, these communities are unlike to relocate based on groundwater inundation. Defense of shorelines is expensive and may not be viable at all as groundwater inundation occurs. Thankfully, this density also provides opportunities for development of small to mid-size public treatment systems. These systems will face a similar challenge that electrical and other underground utilities will face in the future. The gravity fed drainage systems and lift stations will likely need to be installed and designed based on projections. Dewatering and other engineering difficulties that would be faced under future conditions would make these solutions economically impossible. However, pump design and improvement can be done incrementally as water levels rise. This will only be a first step in an organized retreat.

In many cases, rural areas and isolated properties may never be viable options for addition to public utilities. Our research suggests that regulations should be put into place that require all future installations of septic systems in the lower coastal plain of Georgia to be built above grade. This is the required practice in many states, including nearby Florida, where groundwater resources are vital to the state economy. These regulations generally require septic tanks and drainage fields to be installed above current ground level and then bermed with soils appropriate for proper drainage. This design allows for the necessary drainage required for effective aerobic biodegradation of wastewater prior to reaching groundwater, or limits concentrations of hazardous compounds in wastes to a manageable limit.

There are numerous projection models for sea level rise in the next century. Our models are based on fairly conservative versions of these, and many show greater than 1m of sea level rise by 2100. Similar projections show regional sea level rise will likely be even more prolific than the global average. The rate at which sea level rises, and accordingly groundwater levels
rise, will be the determining factor in how our coastal areas will manage future development, infrastructure, and emergency management. Our research shows that sea level rise alone will not be the only threat to these areas, and that the inland coastal plain will likely be as much affected as near coastal zones.
5 CONCLUSIONS

In discussion of future sea level rise, options for future land use are often limited to three choices, adapt, defend, and retreat. Due the slow-moving nature of sea level rise, combined with population increase and high property values for coastal real estate, these options are sure to be contentious. Government planning does not typically work on these time scales. However, as flood insurance rates and mortgage banks begin to react to continuing research these will have impacts on the built environment in the Georgia Coastal Plain. This creates a scenario where an “organized retreat” will be necessary. Private citizens, local, state, and federal governments will need to be planning in the time range of 30-50 years. These decisions need to be made with an awareness that these impacts will not be limited to surficial inundation and that rising groundwater will likely be just as severe.
REFERENCES


Cai, Lin and Zhang, Tong, 2013. Detecting Human Bacterial Pathogens in Wastewater Treatment Plants by a High-Throughput Shotgun Sequencing Technique. Environmental Science and Technology, 47, 5433-5441


Jevrejeva S, Moore JC, Grinsted A. 2012. Sea level projections to AD2500 with a new

LaForge, L., and Cooke, C.W., 1925. Physical Geology of Georgia, Georgia Geological Survey

Untangling the Impacts of Climate Change on Waterborne Diseases: a Systematic Review of
Relationships Between Diarrheal Diseases and Temperature, Rainfall, Flooding, and
Drought. Environmental Science and Technology, 50, 10, 4905-4922.

Manda AK, Sisco MS, Mallinson DJ, Griffin MT. 2015. Relative role and extent of marine and
groundwater inundation on a dune-dominated barrier island under sea-level rise scenarios.


Minnesota Pollution Control Agency, 2009. Low Dissolved Oxygen in Water: Causes, Impact on


the United States.
Ogeechee River at US 17, near Richmond Hill, GA

https://nwis.waterdata.usgs.gov/nwis/inventory/?site_no=02203536&agency_cd=USGS&am
p; (Accessed: 19th December, 2018)


State of Georgia, Department of Public Health, Environmental Health Section, Manual for On-Site Sewage Management Systems


APPENDICES

Appendix A  Ground Penetrating Radar Profiles
File: DAT_0104.rd7

Soil: 508 ft/µs
Antenna: GX450 HDR (v.0)
File: DAT_0106.rd7
Soil: 508 ft/μs Antenna: GX450 HDR (v.0)
File: DAT_0110.rd7

Soil: 508 ft/μs  Antenna: GX450 HDR (v.0)
File: DAT_0117.rd7
Soil: 508 ft/μs  Antenna: GX450 HDR (v.0)
File: DAT_0123.rd7

Soil: 508 ft/μs           Antenna: GX450 HDR (v.0)
File: DAT_0135.rd7

Soil: 508 ft/μs  
Antenna: GX450 HDR (v.0)
File: DAT_0136.rd7

Soil: 508 ft/μs  Antenna: GX450 HDR (v.0)
File: DAT_0142.rd7

Soil: 508 ft/µs  Antenna: GX450 HDR (v.0)
File: DAT_0149.rd7

Soil: 508 ft/µs  Antenna: GX450 HDR (v.0)
File: DAT_0171.rd7

Soil: 508 ft/μs  Antenna: GX450 HDR (v.0)
File: DAT_0172.rd7

Soil: 508 ft/µs  Antenna: GX450 HDR (v.0)
File: DAT_0174.rd7

Soil: 508 ft/μs    Antenna: GX450 HDR (v.0)
File: DAT_0179.rd7

Soil: 508 ft/μs  Antenna: GX450 HDR (v.0)
File: DAT_0206.rd7
Soil: 508 ft/µs  Antenna: GX450 HDR (v.0)
File: DAT_0207.rd7

Soil: 508 ft/µs  Antenna: GX450 HDR (v.0)
File: DAT_0209.rd7

Soil: 508 ft/μs  Antenna: GX450 HDR (v.0)
File: DAT_0214.rd7

Soil: 508 ft/μs  Antenna: GX450 HDR (v.0)
File: DAT_0219.rd7

Soil: 508 ft/μs

Antenna: GX450 HDR (v.0)
File: DAT_0238.rd7

Soil: 508 ft/μs   Antenna: GX450 HDR (v.0)
File: DAT_0201.rd7
Soil: 545 ft/μs Antenna: GX450 HDR (v.0)