Effects of Surrounding Water Table on a Forested Wetland Habitat in East Coast of Virginia

Lane Stokes
*Old Dominion University, stokestl@dukes.jmu.edu*

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EFFECTS OF SURROUNDING WATER TABLE ON A
FORESTED WETLAND HABITAT IN EAST COAST OF VIRGINIA

by

Lane Stokes
B.S. Geology August 2013, James Madison University

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
ENVIRONMENTAL ENGINEERING

OLD DOMINION UNIVERSITY
December 2016

Approved by:
Xixi Wang (Director)
Mujde Erten-Unal (Member)
Hans-Peter Plag (Member)
ABSTRACT

EFFECTS OF SURROUNDING WATER TABLE ON A FORESTED WETLAND HABITAT IN EAST COAST OF VIRGINIA

Thomas Lane Stokes III
Old Dominion University, 2016
Director: Xixi Wang

Exchanges into and out of a wetland, including surface water flow, groundwater flow, and constituents in the flows, usually determine the wetland physicochemical characteristics and biodiversity. To date, of these three exchanges, groundwater flow is the least studied, particularly in the United States of America. In this thesis, field observations were conducted at a forested non-tidal wetland, located on a flat hilltop. The position of the wetland is such that groundwater outflow is the only significant exchange that could be impacted by the surrounding land use. In addition, a spatially variable steady-state model was set up to extrapolate the observations to examine the effects of groundwater flow on the wetland. The model consists of: 1) the stratified unconfined aquifer underlying the wetland; 2) a ditch near the border of the wetland bearing a certain water level (a boundary condition in the model); and 3) recharge from periodic rainfall. The aquifer is relatively thin and where the water table is below the wetland ground surface there is an overall descent of water table toward the ditch. The model was calibrated and validated using the observed data, and then used to predict the distance from the ditch, beyond which the influence of the ditch on the aquifer will become negligible. Herein, the purpose was to determine whether the ditch is hydraulically connected with the wetland. This model can be an effective tool for analyzing groundwater effects on, and assessing the resilience of, the wetland. The results will be useful for protecting the wetland from its surrounding developments.
This thesis is dedicated to God.
ACKNOWLEDGEMENTS

There are many people who enabled this thesis to be produced. Firstly, I would like to thank Tania Alvarez for forthright council which led to my life-changing decision two years ago. Secondly, I would like to thank Dr. Nguyen and Dr. Lasseigne for their committed and transcendent teaching in preparation of my graduate schooling, and Dr. Yoon for introducing me to the department. Also, I would like to thank Dr. Unal for enlightening me with an industry-oriented approach for environmental services. Thirdly, I would like to thank Dr. Wang for the essential engineering instructorship on my core curriculum for groundwater and stormwater. Fourthly, I would like to thank Dr. Schafran for teaching me about water chemistry, a fundamental subject in environmental science. Fifthly, I would like to thank Dr. Plag for his advice about modeling wetland hydrology. Finally, last but not least, I would like to thank my parents for helping to support me for graduate school.
NOMENCLATURE

\[ B, C, D, E \]  Bottom elevations of stratigraphic layers, B, C, D, and E

\[ \bar{B}, \bar{C}, \bar{D}, \bar{E} \]  Thickness of stratigraphic layers, B, D, E, and E

\[ K_i \]  Hydraulic conductivity of specified layer \( i = B, C, D, \) or E

\[ x \]  Distance horizontally from ditch

\[ L \]  Distance from ditch to the edge of the area of influence on the ditch

\[ h \]  Water table elevation at distance “x” from the ditch

\[ h_0 \]  Water table elevation in the ditch

\[ h_L \]  Connected flood threshold elevation

\[ W \]  Recharge rate or (negative) draw rate (units of length, i.e. volume of water per area)

\[ q_L \]  Horizontal groundwater flow rate at the edge of the connected flooded area (units of area per time, i.e. volume of water per time per width of cross section)

\[ FEM \]  Finite Element Method
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I. INTRODUCTION

Wetland groundwater hydrology will be addressed in this study, for being an element of the wetland related to surrounding land-use. Specifically this study will look at how the water table in wetlands is affected by surrounding areas and the effect of recharge/discharge ditches. It will take various approaches to form considerations and then examine them for context and assessment. The visions of county governments, land managers, and environmentalists have necessitated a study.

Most of the field work for study was completed over June, July, and August of 2016. The site studied can be described as a non-contiguous part of the Great Dismal Swamp. The site is a forested non-tidal wetland of the US East Coast; a flat swampy area without major surface flow channels. It is located approximately 20 ft. (6 m) above sea level. At this level, the local creeks are not affected by backwater effects from the regional estuarine shore during storm flooding. Surrounding areas have changing land use, which could affect hydrology and impinge into the wetland. It is unlikely that much groundwater and surface water flow into the wetland, originating from areas out of bound of the forest site, based on the natural position in the landscape, because the site is a high flat area that tends to drain toward surrounding areas. However, its groundwater hydrology could still be affected by changing water levels in surrounding area.

The wetland vegetation is sensitive to changes in water table. Long term rise in water table would result in stress on existing trees (Johnson, 1949) and long term drop in water table would eventually cause scarcerening of hydric soils, and both the trees and hydric soils provide ecological habitat. Since rapid long term changes to wetland environments can cause serious
ecological degradation, there is a need for informed monitoring so that feasible means of areal preservation can be implemented, utilizing existing drainage/recharge ditches and maybe other devices. It will be desirable to predict and assess hydrologic modification scenarios, while minimizing and monitoring any stress on biota.

There is a need for understanding of processes affecting wetlands, and the nature of their vulnerability. Impacts from groundwater, such as from reduced recharge from urban impermeable surfaces and stormwater infrastructure and unconfined aquifer pumping, is often revealed in wetland delineations, along with impacts from surface water discharge and quality of the water. Improved knowledge of hydrologic processes may assist in wetland mitigation projects, investigation of effects of change to recharging water in surrounding areas due to development on the health of the ecosystem, and understanding the effectiveness of prospective solutions.

It is a prevailing question how valuable natural ecosystems can be recognized in the economy. History has proved ecosystem valuation is complicated for both socialism and capitalism. Under Code of Virginia § 10.1-1011 subsection B, permanent conservation easements can provide economic benefit to the land owner based on monetary compensation equal to the difference of the property market value before the new easement and the property market value with the new easement, instead of a compromise of conservation value (determined by consensus) and the prevailing market value difference. This currently is the best available option for protecting valuable environmental resources, because the existing market, being mostly individualistic, currently does not represent the environmental and other “common good” values except those of the stock market and limited philanthropic organizations. However, using the market value instead of the specific values in conservation incentivizes stewardship of the
land to maximize the market value of the land before the transaction, which may be at the
degradation of the common-good resources sought by the government unified with the people.
This study looks at the extent of the effect which hydrologic modifications can actually have on
the land.
II. LITERATURE REVIEWED

In 2006 the Center for Watershed Protection conducted a literature review on different impacts of urbanization on wetland quality, for the ultimate objective to assist the US EPA in wetland management. This guide extensively reviewed scientific literature within the US, but studies conducted in other countries were not considered. It was actually stated in the review that “While the link between decreased groundwater recharge in the contributing drainage area and diminished wetland quality seems tempting, there is simply not enough scientific evidence to determine whether [the link] actually exists.” (CWP, 2006). Sites where recharge in the surrounding areas has an effect in the site hydrology, and especially where this same water discharges to the wetland surface upward from the ground, need to be researched in order to better understand forested non-tidal wetlands of the US East Coast (CWP, 2006). The review did highlight some studies in which an effect on ecologically important streams had been found from reduced baseflow dry weather (CWP, 2006), with a clear observation of environmental degradation (Klein, 1979; Saravanapavan, 2002; Simmons and Reynolds, 1982). More recently Spieran (2010) examined two such wetlands in the riparian zone of streams in Virginia. These wetlands were observed to have water that originated from upland areas both as overland flow recharging into the wetland and groundwater flow discharging from the ground in the wetland, and they were shown to have groundwater hydrology and chemistry (Nitrogen) that interacted with the surface biology.

In the UK and Europe, fens and their groundwater dependency have long been recognized and a less recent study showed how a particular fen is sensitive to small changes in the supporting hydrology (Gilvear, 1993). More recently, in 2013, historic climate and well data
over the course of change in land development were analyzed by (Carol, 2013) in a flow model to look at the effects of groundwater exploitation from surrounding areas on groundwater inflow to wetlands. It was determined that the wetland water balance was affected by groundwater inflow and outflow changes. Wetlands may have a negative feedback mechanism to maintain water levels close to a level needed for health of the wetland. Because the hydrology naturally fluctuates, a change in groundwater levels may make wetlands more vulnerable to drought and stress events, risking change to the forest type over time. A study by Zurek (2014), using methods of groundwater chemical and radioisotope analysis together with geophysical mapping flow modeling, traced flows between aquifers to confirm the dependence of groundwater in a wetland on another aquifer recently planned for supplying wells for water utility. It was suggested that some but not all wetlands can be categorized as groundwater dependent ecosystems. It was also suggested that natural patterns of fluctuation are important to groundwater dependent ecosystems.
III. STUDY SITE

Observations and Background

The study site was an old-growth forested wetland site at Shoulders Hill Road, Suffolk, Virginia. This forested land is near horizontal, and higher in most places and lower in some places than the surrounding land. The wetland is at the head of three different creeks which drain northwest, southwest, and northeast. The original surface drainage basin and groundwater basin contributing to the wetland does not extend very much outside of the wetland itself. The limited surface and groundwater drainage from the horizontal ground is responsible for its wetland hydrology.

The surrounding non-wetlands have a gentle slope up from the numerous creeks in the region, permitting surface drainage to creeks and the mound of draining groundwater to remain sufficiently lower than the ground surface. The water table of adjacent land may have been altered by development and stormwater infrastructure. This region has a thin unconfined aquifer, which keeps the effects of groundwater fairly local.

The forested land has microtopographic roughness on a typical scale of about 1 – 2 ft. (0.3 – 0.7 m) vertical by ~10 ft. (~3 m) horizontal. The wetland has a system of original ditches, mostly along the perimeter of the site, which existed when the forest grew up from secondary succession after 60+ years ago from the present time (2016), before which the site was used as a tree farm. Of the three separate creek-head systems within the site, in the two western ones the creek was at some point modified from the natural flow pattern, by land disturbance from historic logging and/or by the ditches that were put in, so that the creek becomes a channelized ditch upstream to the property, which connects up with a perimeter ditch but is cut off from what
would have been the natural overland tributary channels, which now flow along a different route. The northeastern creek remains more natural and grades from connected flooded areas into a stream channel where the flood water fully covers the land. Vegetation and habitat were observed to correspond with the prevailing hydrologic conditions on the site, with mermaid-weed in the submerged areas, ferns in the higher areas, and southern cane in the transition areas. Most of the area in the wetland is, much of the time, flooded up to a level at which there is just barely any surface flow by a network of connected puddles.
Data Collected

Figure 1 Satellite Image
A series of uncased, 10 ft. (3 m) deep auger boreholes were made every 25 ft. (7.5 m) in a straight line into the wetland forest, perpendicular to the northwestern creek after the point where it becomes channelized as a ditch that runs along the perimeter of, just inside the forest, adjacent to meadow land extending 400 feet (122 m) up to single family homes with grass lawns.

The soil was logged at each of the boreholes. The sequence and thickness of different soil layers were generally uniform except for the top layer which varied from place to place. When later compared with the elevation survey data for the ground surface, the logged soil layers were found to match up, within the accuracy tolerance of the data, to show horizontal stratigraphy. Below these layers in the upper 10 feet (3 m) is a low-permeability, gray silty clay soil of an unknown thickness more than 3 ft. (1 m). It is known to exist on the other side of the wetland at several test holes, as do the other layers, and is assumed to prevail throughout all the area that could influence the water table near the ditch at the data site as an effective confining layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Color</th>
<th>Composition</th>
<th>Thickness (in)</th>
<th>Elev. of bottom (in)</th>
<th>Permeability (in/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>Connected Puddles</td>
<td>-</td>
<td>227</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>Brown</td>
<td>Organic Loam</td>
<td>29</td>
<td>198</td>
<td>48</td>
</tr>
<tr>
<td>C</td>
<td>Grey-Brown</td>
<td>Clayey Loam</td>
<td>24</td>
<td>174</td>
<td>7.2</td>
</tr>
<tr>
<td>D</td>
<td>Orange</td>
<td>Clayey sand</td>
<td>12</td>
<td>162</td>
<td>48</td>
</tr>
<tr>
<td>E</td>
<td>Brown</td>
<td>Sandy Clay</td>
<td>24</td>
<td>138</td>
<td>7.2</td>
</tr>
</tbody>
</table>
The elevation was determined with land surveying techniques. The datum was marked on a tree at a point estimated to be about 20 ft. (6 m) above sea level. A straight line (string) was extended to each of the wells, a level device similar to a bubble level was placed at the midpoint of each of the distances, and the ground surface level relative to the datum was determined by measuring the height of the horizontal string/datum above each of the well heads, within an inch or two (a few centimeters) of accuracy depending on the distance (the extent to which the level device was sensitive).

**Figure 2 Level Device**
A dam was installed in the ditch several hundred feet downstream of the wells to provide a water source to raise the water table, since the ditch had become dry for some time prior to the study period, as it is typical in the summer months. The water level was kept just high enough to cover the bottom of the ditch after the groundwater table equilibrated. Figure 5 shows the change in water table after the installation of the dam. Two weeks later, after the water table had stabilized after the hydraulic modification, two measurements were made (14 July and 17 July). These measurements were taken at neither after heavy rain nor a long dry period (see Appendix A. Precipitation). The field data were converted to elevations (Table 2). The two measurements show the water table curving downward approaching the ditch.
Figure 5 Water Table during Hydraulic Modification
<table>
<thead>
<tr>
<th>Datum to Ground Surface (inches)</th>
<th>-72</th>
<th>-18</th>
<th>-24</th>
<th>-14</th>
<th>-10</th>
<th>-12</th>
<th>-7.5</th>
<th>-13</th>
</tr>
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<tbody>
<tr>
<td>Datum Elevation = ~20 ft (WGS-1984)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal distance from ditch (inches)</td>
<td>0</td>
<td>300</td>
<td>600</td>
<td>900</td>
<td>1200</td>
<td>1500</td>
<td>1800</td>
<td>2100</td>
</tr>
<tr>
<td>27-Jun-16</td>
<td>-1.5</td>
<td>46.5</td>
<td>33.5</td>
<td>34</td>
<td>29.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-Jun-16</td>
<td>Rain, 0.38 in</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29-Jun-16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30-Jun-16</td>
<td>-9.5</td>
<td>40.5</td>
<td>30</td>
<td>30.5</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-Jul-16</td>
<td>Rain, 0.13 in</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-Jul-16</td>
<td>-3.5</td>
<td>38</td>
<td>25.5</td>
<td>24</td>
<td>18.5</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>14-Jul-16</td>
<td>Measurement 1</td>
<td>-2.5</td>
<td>36</td>
<td>23.5</td>
<td>21.5</td>
<td>14.5</td>
<td>11.5</td>
<td>16.5</td>
</tr>
<tr>
<td>17-Jul-16</td>
<td>Measurement 2</td>
<td>-2</td>
<td>40.5</td>
<td>27.5</td>
<td>27</td>
<td>21.5</td>
<td>17</td>
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<table>
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<tr>
<th>Ground Surface Elevation</th>
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<th>222</th>
<th>216</th>
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<th>230</th>
<th>228</th>
<th>232.5</th>
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</tr>
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<tbody>
<tr>
<td>Horizontal distance from ditch</td>
<td>0</td>
<td>300</td>
<td>600</td>
<td>900</td>
<td>1200</td>
<td>1500</td>
<td>1800</td>
<td>2100</td>
</tr>
<tr>
<td>27-Jun-16</td>
<td>169.5</td>
<td>175.5</td>
<td>182.5</td>
<td>192</td>
<td>200.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-Jun-16</td>
<td>Rain, 0.38 in</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29-Jun-16</td>
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<td></td>
<td></td>
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<tr>
<td>30-Jun-16</td>
<td>177.5</td>
<td>181.5</td>
<td>186</td>
<td>195.5</td>
<td>203</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-Jul-16</td>
<td>Rain, 0.13 in</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-Jul-16</td>
<td>171.5</td>
<td>184</td>
<td>190.5</td>
<td>202</td>
<td>211.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-Jul-16</td>
<td>Measurement 1</td>
<td>170.5</td>
<td>186</td>
<td>192.5</td>
<td>204.5</td>
<td>215.5</td>
<td>216.5</td>
<td>216</td>
</tr>
<tr>
<td>17-Jul-16</td>
<td>Measurement 2</td>
<td>170</td>
<td>181.5</td>
<td>188.5</td>
<td>199</td>
<td>208.5</td>
<td>211</td>
<td>210.5</td>
</tr>
</tbody>
</table>
A follow-up visit to the site was made on 12-August-2016, about a month after the well water data collection and after the dam had been taken down. By this time the ditch had become dry again and all of the areas that were flooded in the previous month had also become dry, except for ponded water in one small particularly low area. To investigate the extent of the connected flood area, the area where the water table rests above the ground high enough that puddles connect. Water higher than this level can flow on the ground, and this is periodically a normal condition. The leaves remained darkened on the ground in the places where the water table had been above ground since last fall season. The dark leaves represent the maximum extent of the connected flood area. The extent of darkened leaves was mapped by recursively walking in sweeps back and forth from the ditch to the far end of the forest, across all areas in the forest directly west or southwest of the section of ditch by which the well data were
collected. A transition boundary existing a few hundred feet from the ditch was observed, which fairly quickly transitioned from a dense network of darkened leaves around non-darkened leaves, to mostly non-darkened leaves with small, isolated patches of darkened leaves. This boundary was delineated and its distance to the ditch was measured, shown in Figure 6. All areas on the side of the boundary away from the ditch indicated connected flood areas except for a roughly oval shaped area 200 ft. x 300 ft. (61 m x 91 m) across, dominated by fern vegetation, and having appeared like it may have been slightly higher elevation, and an 80 ft. (24 m) fringe into the north edge of the forest. Figure 6 shows the minimum distance, with its yearly fluctuations, of the area of influence from the ditch.
Figure 7 Darkened Leaves
IV. INTERPRETATIONS

Groundwater flow modifications affect the extent of hydrologically defined wetland habitat. The effects of water level in adjacent land of natural land cover types, being different from urban drainage infrastructure and ground surfaces that conduce less infiltration, can be imitated using recharge/discharge ditches. Groundwater flow effects across the borders of a wetland can have significant effect for the hydrogeological habitat of the wetland. Groundwater discharges to the ground surface in wetlands have an added benefit of supplying mineral nutrients to the surface biota, especially if the water moving through the mineral sediment contained chelating agents infiltrated from organic soil. Water table depth below ground surface, or degree of flooding in the microtopography, also plays a key role in sustaining the wetland habitat. Hydrology is even among the three features used to define a wetland in wetland delineation studies, along with vegetation type and soils. Also, the land cover, in turn, keeps the water table at a preferable level with a negative feedback loop, whereby evapotranspiration is greater as the water level is closer to the surface.

Recharge is represented by percolation and is equal to the amount of infiltrated water not absorbed by the vegetation root mat in the rain events before it reaches the water table. It is assumed to have a uniform rate across the ground area where water table is mostly below the root mat. Since permeability and thus also infiltration rate is high, the only places where there would be expected runoff are the places away from the ditch where the water table is above the ground surface at a threshold level for connected flooding in the microtopography (“connected flood threshold”). Some expected complications with this assumption of uniform recharge are that 1) the water that would infiltrate would be expected to run to the low areas in the rough
ground surface, causing roughness to the water level data curve; and 2) some evapotranspiration would be expected to draw directly from the water table (over the full time instead of rain event portion of the time), in the high water table areas and in lower water table areas drawing from the water table via capillary action. Because #2 above would be variable depending on water table depth below ground surface, at distances away from the ditch influence this type of evapotranspiration would be non-uniform. Although the root mat is only 6 inches (15 cm) deep and is above the water table in all but one point of the data points, this would have much more effect where the capillary fringe becomes nearer to the surface.
V. MODELS

Preliminary Formulation of the Unconfined Aquifer

A modified version of the ellipse equation was drawn up to represent a stratified aquifer with unconfined hydrology, steady-state, unidirectional flow to a linear ditch with a uniform recharge/draw over the land surface. The assumptions and limitations for this preliminary formulation of the unconfined aquifer are as follows:

1. The groundwater has laminar flow properties.
2. The identified strata are horizontal, uniform thickness, homogenous, and extend throughout the area of influence to the groundwater at the measurement locations.
3. From the underlying Yorktown Confining unit, recharge/discharge is negligible.
4. Recharge from the surface is constant within the area of influence of the ditch.
5. Outside the area of influence the water table elevation $h$ is kept constant by a balance of increase from precipitation and threshold decrease from a combination of runoff by a network of connected puddles, evaporation, and transpiration from the shallow root mat at the surface.
6. The hydraulic gradient $q_L$ outside the area of influence is level with the ground surface.
7. The Dupuit assumptions for each of the strata, which are that a) the velocity of the flow is proportionate to the tangent of the hydraulic gradient instead of the sine as defined by Darcy’s law and b) the flow is horizontal and uniform within each layer in the cross section.
8. The vertical hydraulic gradient at any section in the saturated zone of the unconfined aquifer is negligible. The shallowness of the horizontal hydraulic gradient and the overall...
thinness of the unconfined aquifer are characteristics that indicate this is a reasonable assumption. Further evidence was that a test at this location with two holes next to each other, one extending 3 feet (1 m) deep, just a few inches (<1 dm) below the water table and the other extending 7 feet (2 m) deep, the full column of the unconfined aquifer, showed equal water levels in the holes. It was also confirmed by a simulation with the finite element model described in this article. The assumption might be violated with small effect if there is not aerially uniform recharge or draw. This assumption is likely invalid for many wetlands, especially ones with deep unconfined aquifers with semi-confining layers; however, in this case it is believed to be valid.

**Derivation of the Governing Equations**

Let the saturated thickness of any given layer i be denoted as \( z_i \), which can be determined as:

\[
\begin{align*}
  if & \quad i + \bar{i} < h, \quad z_i = \bar{i} \\
  if & \quad i < h < i + \bar{i}, \quad z_i = h - i \\
  if & \quad h < i, \quad z_i = 0
\end{align*}
\]  
\[ (V-1) \]

\[ z_i(h) = \frac{1}{2}|h - i| - \frac{1}{2}|h - i - \bar{i}| + \frac{1}{2}\bar{i} \]  
\[ (V-2) \]

The integral of \( z_i(h) \) with respect to \( h \) is as follows:

\[
\begin{align*}
  if & \quad i + \bar{i} < h, \quad \int_{i+\bar{i}}^{h} z_i(h') \cdot dh' = \bar{i} \cdot (h - i - \bar{i}) \\
  if & \quad i < h < i + \bar{i}, \quad \int_{i}^{h} z_i(h') \cdot dh' = \frac{(h-i)^2}{2} \\
  if & \quad h < i, \quad \int_{i}^{h} z_i(h') \cdot dh' = 0
\end{align*}
\]  
\[ (V-3) \]

\[
\int_{i}^{h} z_i(h') \cdot dh' = \left(\frac{1}{2} + \frac{1}{2}\frac{h-i}{|h-i|}\right) \cdot \left(\frac{(h-i)^2}{2}\right) + \left(\frac{1}{2} + \frac{1}{2}\frac{h-i-\bar{i}}{|h-i-\bar{i}|}\right) \cdot \left(\frac{\bar{i}^2}{2} - \frac{(h-i)^2}{2} + \bar{i} \cdot (h - i - \bar{i})\right)
\]  
\[ (V-4) \]
At a given location \(x\) between 0 and \(L\):

\[
q_x = W \cdot (L - x) + q_L = \frac{dh}{dx} \cdot \sum_{i=B,C,D,E} K_i \cdot z_i (h(x))
\]  

(V-5)

Integrate both sides with respect to \(x\) from 0 to \(L\), and one can get:

\[
\int_{x_0}^{x} (W \cdot (L - x') + q_L) \cdot dx' = \int_{0}^{x} \left( \frac{dh(x')}{dx'} \cdot \sum_{i=B,C,D,E} K_i \cdot z_i (h(x')) \right) \cdot dx'
\]  

(V-6)

\[
\int_{x_0}^{x} (-W \cdot x' + (W \cdot L + q_L)) \cdot dx' = \int_{h_0}^{h} \left( \sum_{i=B,C,D,E} K_i \cdot \left( h_i \cdot z_i (h') \cdot dh' \right) \right) = "F(h)"
\]  

(V-7)

\[
\frac{1}{2} W \cdot x^2 + (W \cdot L + q_L) \cdot x = \sum_{i=B,C,D,E} K_i \cdot \left( h_i \cdot \left( \int_{h_0}^{h} z_i (h') \cdot dh' \right) \right)
\]  

(V-8)

The equation (V-9, 10) is written for \(x(h)\) because it was more practical to use Excel Solver than to isolate \(h(x)\) as a function. For simplicity it is written in two parts, below:

\[
x(h) = \frac{W \cdot L + q_L}{W} - \sqrt{\left(\frac{W \cdot L + q_L}{W}\right)^2 - \frac{2}{W} \cdot F(h)} \quad \text{for} \quad |x| \leq L
\]  

(V-9)

\[
F(h) = \sum_{i=B,C,D,E} \left\{ \frac{1}{2} \cdot \left[ \frac{h_i - L}{|h_i - L|} \cdot \left( \frac{(h_i - L)^2}{2} \right) + \left( \frac{1}{2} + \frac{h_i - L}{|h_i - L|} \cdot \left( \frac{L^2}{2} \cdot \left( h_i - L \right)^2 + \bar{i} \cdot (h_i - L) \right) \right) \right] \right\}
\]  

(V-10)

In the case of this wetland, the hydraulic gradient \(q_L\) outside the area of influence, which is level with the ground surface, is horizontal. To find the area of influence of the ditch,

\[
\begin{cases}
  x = L \\
  q_L = 0
\end{cases}
\]  

(V-11)
\[
L = x(h_L) = \frac{W \cdot L + (q_L = 0)}{W} \pm \sqrt{\left(\frac{W \cdot L + (q_L = 0)}{W}\right)^2 - \frac{2}{W} \cdot F(h_L)} 
\]  

(V-12)

\[
L = L \pm \sqrt{L^2 - \frac{2}{W} \cdot F(h_L)}
\]  

(V-13)

\[
0 = \sqrt{L^2 - \frac{2}{W} \cdot F(h_L)}
\]  

(V-14)

\[
L = \sqrt{\frac{2}{W} \cdot F(h_L)}
\]  

(V-15)

**Finite Element Model**

A second method was developed in addition, because of its broader applicability to similar situations allowing fewer assumptions, such as if a vertical hydraulic gradient exists, or if \(W\) is a variable function. The assumptions are as follows:

1. The groundwater has laminar flow properties.
2. The identified strata are horizontal, uniform thickness, homogenous, and extend throughout the area of influence to the groundwater at the measurement locations.
3. From the underlying Yorktown Confining unit, recharge/discharge is negligible.
4. Each horizontal distance segment \(\Delta x\) is short enough that the hydraulic gradient within \(\Delta x\) is essentially a straight line.
5. The model is run with enough iterations that the value of \(h\) converges to a stable value.
Method

The two dimensional flow in the cross section is predicted with a finite element analysis using with cell head values governed by mass balance and Darcy’s law.

\[
0 = \Delta x \cdot K_i \cdot \frac{h - h_1}{l} \\
+ \left( \frac{1}{2} \left| \frac{h + h_2}{2} - i \right| - \frac{1}{2} \left| \frac{h + h_2}{2} - i - l \right| + \frac{1}{2} l \right) \cdot K_i \cdot \frac{h_2 - h_1}{\Delta x} \\
+ \Delta x \cdot K_i \text{below} \cdot \frac{h_3 - h_3}{l \text{below}} \\
+ \left( \frac{1}{2} \left| \frac{h + h_4}{2} - i \right| - \frac{1}{2} \left| \frac{h + h_4}{2} - i - l \right| + \frac{1}{2} l \right) \cdot K_i \cdot \frac{h_4 - h_2}{\Delta x} \\
+ \left( \frac{1}{2} \left| \frac{h - i \text{above}}{2} \right| - \frac{1}{2} \left| \frac{h - i \text{above}}{2} - l \right| \right) \cdot W \cdot \Delta x
\]
The hydraulic head at the bottom center of the cell is determined by this equation, (V-17), written in each of the cells in Microsoft Excel. The value of $h$ where it is written on the right hand side of the equation in (V-16) is the previous $h$ value of the cell.

$$h = \left\{ \frac{\Delta x \cdot K_i \cdot h_1}{\bar{i}} \right\}$$

$$+ \left( \frac{1}{2} \left| \frac{h + h_2}{2} - i \right| - \frac{1}{2} \left| \frac{h + h_2}{2} - i - \bar{i} \right| + \frac{1}{2} \bar{i} \right) \cdot \frac{K_i \cdot h_2}{\Delta x}$$

$$+ \frac{\Delta x \cdot K_{i \text{below}} \cdot h_3}{\bar{i} \text{below}}$$
Each stratigraphic layer is represented as one cell thick. The last line of equation (V-17) is a qualifier that 1) the cell value “h” is never written above the runoff threshold maximum “h_L”, because that excess water very quickly runs off elsewhere and 2) if h is below the cell bottom elevation, the cell value h is determined by the cell below it that contains the water table. In the last line “h” is replaced with “h_3” to prevent the cell from reaching a dead end value. For the top
layer, the terms $\frac{\Delta x \cdot K_l \cdot h_1}{t}$ and $\frac{\Delta x \cdot K_l}{t}$ are omitted. For the bottom layer, the terms $\frac{\Delta x \cdot K_{bellow} \cdot h_3}{t_{bellow}}$ and $\frac{\Delta x \cdot K_{bellow}}{t_{bellow}}$ are omitted. Boundary conditions are entered on the sides of the array.

**Data Entry for Study Site**

An elevation of 170 inches was entered for the boundary condition at the ditch water elevation. The elevation of the connected flood threshold was entered as 227 since this is the ground surface of the furthest well location where it was found that a sporadically active natural channel exists, which would be close to level with the connecting flooded areas. The stratigraphic data was entered into the model and preliminary formulation equations (V-9, 10, 15).
VI. RESULTS

Comparison of FEM with other Methods

Figure 9 Water Table in Shoulders Hill Wetland near Border Ditch

A uniform $W$, albeit a poor representation of reality, was assumed in order to compare the FEM with other methods, which require this assumption. The value of $W$ was determined by trial and error until the curves were calibrated to the data. A recharge of 0.0075 in/day was found to make the curves fit, for both the equation (V-9, 10, 15) and the finite element model. The curves are shown above. For comparison, figure 9 also shows the standard ellipse equation for an unconfined aquifer with uniform recharge and homogenous soil, using the composite horizontal conductivity value for the stratified soil and the same $h_0$, $h_L$, $W$. The distance from the ditch, for the water table to reach the connected flood threshold, $L$ was 360 feet (110 m) for the stratified equation (V-9, 10, 15) and 360 ft. ± 10 ft. (110 m ± 3 m) range for the finite
element model. The FEM is a close approximation to the stratified equation (V-9, 10, 15), which is theoretically exact.

Use of an Assumed Non-Uniform W with the FEM

“W” would not be uniform because evapotranspiration would be affected by water table depth. For this reason, W was written as a function of water table depth, for the finite element model to determine “L”. It is commonly known in the east coastal US that the root mat in forested wetlands is very shallow and plate-like and the roots do not extend very far into the shallow water table where conditions are saturated and anoxic. At the same time, evapotranspiration is limited if the root zone is without the presence of a water table (Johnson, 1949). At the site the roots were found to extend 6 inches (15 cm) below the connected flood threshold elevation in the microtopography. It is assumed that the capillary fringe on the water table is about 6 inches (15 cm) also. The rationale for the function of W used, written below, is that where the water table capillary fringe is lower than the bottom of the root mat, the average W is a constant value, for the reasons discussed above in the Interpretations section; if the water table in is above the connected flood threshold, it is written into the FEM cell equations (V-17) that that excess water gets carried away; if the water table just barely below the connected flood threshold, it is assumed that evapotranspiration equals precipitation, since 1) evapotranspiration rates in flooded wetlands in the summer months are typically higher than the corresponding precipitation rate and 2) in the fully flooded areas of this wetland there is no groundwater inflow (ql) to affect the mass balance, nor any groundwater outflow because the gradient is horizontal (in the fully flooded areas). If the water table is between the threshold and 12 inches (30 cm) below the threshold, it is assumed that the linear change of saturated root mat corresponds with proportion of saturated, full-time evaporation versus storm event evapotranspiration.
\[ W(h) = \left( \frac{1}{2} - \frac{1}{2} \cdot \frac{h - (h_L - 12 \text{ in.})}{|h - (h_L - 12 \text{ in.})|} \right) \cdot W_0 \]

\[ + \left( \frac{1}{2} + \frac{1}{2} \cdot \frac{h - (h_L - 12 \text{ in.})}{|h - (h_L - 12 \text{ in.})|} \right) \cdot \left( W_0 + \frac{0 - W_0}{12 \text{ in.}} \cdot (h - (h_L - 12 \text{ in.})) \right) \]

Figure 10 Recharge as Function of Water Table for Simulation

\[ W_0 \] was determined by trial and error until the curve was calibrated to the data. It was found that \( W_0 = 0.01 \text{ in/day} \).
Figure 11 Finite Element Model using W(h)

$L \approx 800 \text{ ft. (244 m)}$
VII. DISCUSSION

The predicted L based on the non-uniform W is consistent with field observations at the time of the measurements although the exact distance was not measured, and it is between the maximum range of fluctuation for the year (data from site visit 12-August-2016).

Some potential causes of error were identified. These could be corrected by the incorporation of some tools. Surface channels may have a significant effect on L. Surface flow networks could be modeled with the use of microtopographic elevation maps if accessible through LiDAR or detailed survey drawings. Spatial variability in the connected flood threshold elevation may also have a significant effect on L. In sites with large scale topography other than horizontal, a variable \( h_L \) parameter could be used, based on ground surface elevation data.

In the context of unsteady reality for model use, the model theory as it pertains to effects of flow within the aquifer on hydraulic head is simplified as steady state, assuming no major temporal fluctuations in storage. Water table fluctuations between rainstorms do have an effect on the water table curve which may be significant in scenarios with torrential rain events or prolonged intervals between rain events. On the other hand, most longer term water table changes would be too gradual to deviate from steady state behavior at a given time. In actuality there should be a natural fluctuation of L between rain event intervals, an unsteady phenomenon which this steady-state flow model approximates with a single value L.

To assess the accuracy of the non-uniform recharge function \( W(h) \) aspect of the model, consider the parameter \( W_0 \). The percolation through the unsaturated root area \( W_0 \), by the collected data, calibrates at 0.01 in/day. According to Weather Underground at Milteer Acres Station KVASUFFO37, one mile away from the data point locations on the study site, the
average daily precipitation between 14-June and 14-July was 0.2 in/day. Thus, $W_0$ was 5% of the precipitation. This result is reasonable based on the fact that evapotranspiration rates in flooded wetlands in the summer months are typically higher than the corresponding precipitation rate.

*This, however, assumes that the other assumptions about $W$ and the rest of the model are accurate.* A non-uniform $W$ function of ideal accuracy would depend on many factors. 1) During rain events this function would depend on transpiration/soil retention from antecedent moisture content below field capacity. For the duration of the rest of the time, this function would depend on transpiration directly from the water table via saturated flow and via unsaturated capillary action above the water table, evaporation from puddles and moist soil. 2) The actual unsteady fluctuation of the water table from rain intervals may also have an effect on $W$. 3) Another consideration about $W$ is that seepage from head difference between aquifers across the lower confining unit is a factor. 4) The long term steady $W$ equals 0 at the normal water table level, which the wetland is adapted to. The simulation of this study assumed that $W$ was 0 where the water table was at or just below the connected flood threshold. $W$ could be 0 at a water level below this point, but it cannot be 0 above the connected flood threshold. That is, unless there is some outside influence, which leads to 5) There could be intermittent surface flow channels across specific locations. During infiltration events surface channels would have a significant effect on $W$, causing it to vary spatially in addition to its dependence on water table depth. This would be more spatial in sites with less permeable soils, where percolating water may be slowed over the vertical hydraulic gradient and the connected flood water may collect in perches above the water table for periods of time, and for which flood water travels further from its origin before infiltrating. 6) Large scale topography would result in groundwater inflow and
outflow in the areas beyond the influence of the ditch, on hills and slopes not within a depression. W also depends on this. This could easily be solved, though, by referencing $h_L$ to ground elevation data.

*Research implication for management of wetland sites in general:* The fact that the water table in the wells changed when the water level in the ditch was changed and the slope of the water table curve downward toward the ditch demonstrates the principle that the water table is affected by change in hydrologic conditions at the forest border. The fact that the water table is below ditch in summer implies that the water table in the forest is being affected by the adjacent land. The model provides a theoretical basis for quantifying the effect into wetlands from the water table on the often linear border of sites.
VIII. CONCLUSIONS

Outcomes of the Study

A reproducible flow simulation was made using modeling techniques that represent the water balance, microtopography, geology, and boundary conditions from the surrounding area. The model results were consistent with actual field conditions. Field measurements of groundwater flow modifications were demonstrated to change the water table in this site, thereby affecting the extent of hydrologically defined wetland habitat. This model is a simple tool to analyze groundwater effects on wetlands which have minimal surface flow channels, in order to assess a wetland’s vulnerability from surrounding groundwater influences. The hydrologic conditions can be managed to sustain the health of specifically adapted ecological zones within the wetland.

If the model results for this site are viewed as a case study for what the effects may be like in other like wetlands common in the East Coast US, it should be considered that the effects would be further-reaching where a wetland is downhill, and water table changes in adjacent lands would have further reaching effects than in the thin aquifer of this study. In this study, the dry area in the wetland was attributable to the effect from the water table being at 4.5 feet (1.4 m) below ground surface on the border of the site (the water in the ditch), according to the model steady effect, 800 feet (244 m) into the wetland, and more so during the dryer portion of natural water level fluctuations.

Recommendations

For the management of the Shoulders Hill Wetland, the perimeter ditches can be used to maintain a water table elevation that the vegetation is adapted to all the way to the edge of the
forest. The level in the ditch can be kept similar to the water table depth in the rest of the wetland in order to maintain a wetland hydrology throughout the forest. Adjustable weirs along the creeks that have been deepened into a ditch would serve this purpose, while allowing them to still function as active surface flow channels.

If this model is used for other sites, it must be used within the limitation that its assumptions are reasonable for the given site. Some adaptations can be made if needed, such as in the previously mentioned notes on accuracy for W and L in the Results section. As presented in this study, the model is designed for wetlands with minimal large scale topography and minimal surface flow channels. This is usually reasonable for wetlands of East Coast US.

**Ideas for Future Research**

Models like this one could benefit from more research for information on evapotranspiration for the W function on the “interface of land cover.” This would involve looking at rain interval patterns, moisture levels, water table depth and fluctuations, along with other background factors for evapotranspiration, and monitoring of the rest of the water balance (precipitation, storage change, groundwater flow, runoff if existent). Hydraulic conditions that affect the health of the wetland ecosystem could be studied at the same time, by using a study wetland surrounded by wilderness.

The chemistry of groundwater inflow to wetlands in the wilderness could be a desirable topic of study. Many wetlands would naturally receive water from surrounding lands. However, urban stormwater often results in degradation to wetlands. If natural water chemistry entering the wetland was reproduced in managed stormwater, and if the groundwater and surface water flow patterns were also reproduced to preserve the natural morphology, then some water from stormwater ponds could be treated and handled to accordingly discharge into the wetland for
benefits to the wetland, water quality and surrounding areas. This could be a subject of future study for caution is needed in implementing such measures. The ability of ditches to counteract effects in the contributing surface drainage basin and groundwater basin was demonstrated in this study; they could also be used as a tool to imitate a natural or evolving land environment.
REFERENCES


APPENDIX A. PRECIPITATION

Figure 12 below is a histogram of inches of precipitation over time (from Weather Underground at Milteer Acres Station KVASUFFO37) marked with solid lines which represent site visits and the red lines represent the beginning and end of the dam influence when the ditch was filled with water.

Figure 12 Precipitation
APPENDIX B. GEOCHEMISTRY OBSERVATION

Areal water chemistry may be affected by the changes of water flow path through the, geologic formations, biological zones, and surrounding interface of land use/cover. As shown in Figure 13, within the bore cores through layer C, there were planar vertical cracks in the stratum which parted easily when handling the cores and were filled with a rust colored accumulation. This likely has to do with the chemistry of water flowing between the organic soil horizon and the sandier underlying layer D.

Figure 13 Fractures with Rust Color
# APPENDIX C. EQUATION COMPUTATIONS

## Table 3 Equation Computations

<table>
<thead>
<tr>
<th>Layer</th>
<th>Color</th>
<th>Composition</th>
<th>Thickness (in)</th>
<th>Elev. of bottom (in)</th>
<th>Permeability (in/d)</th>
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<tr>
<td>A</td>
<td>-</td>
<td>Connected Puddles</td>
<td>-</td>
<td>227</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>Brown</td>
<td>Organic Loam</td>
<td>36</td>
<td>198</td>
<td>48</td>
</tr>
<tr>
<td>C</td>
<td>Grey-Brown</td>
<td>Clayey Loam</td>
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<td>174</td>
<td>7.2</td>
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<td>D</td>
<td>Orange</td>
<td>Clayey Loam</td>
<td>12</td>
<td>162</td>
<td>48</td>
</tr>
<tr>
<td>E</td>
<td>Brown</td>
<td>Sandy Clay</td>
<td>24</td>
<td>138</td>
<td>7.2</td>
</tr>
</tbody>
</table>

h0 = 170 in

hL = 227 in

W = 0.0075 in/day

L = \(4307.0918 \div 26\) in

+/- = -1 (1 or -1)

x = \(4307.0917 \div 4\) in

h = 227 in

q1 = 0 sq in / day

Stratified

Graph h = 170 182.64591 192.88222 201.37347 207.34735 211.848 215.424 218.328

Graph x = 0 300.03042 600.06605 900.10770 1200.15659 1500.21 1800 2100

Set x to 0 300 600 900 1200 1500 1800 2100

Homogenous K= 20.8 L= 4373.52032

h = 170 182.01979 190.78807 197.75379 203.49462 208.311 212.383 215.828

x = 0 300 600 900 1200 1500 1800 2100
## APPENDIX D. FEM Computations

### Table 4 FEM Computations

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<tr>
<th>Uniform W Run</th>
<th>Other Data</th>
<th></th>
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<th>Ave. Precipitation</th>
<th></th>
<th></th>
<th>(Weather Underground)</th>
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<td>in</td>
<td></td>
<td>0.15</td>
<td></td>
<td></td>
<td>0.15 in/day</td>
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<tr>
<td>h1</td>
<td>226</td>
<td>in</td>
<td></td>
<td>0.00</td>
<td></td>
<td></td>
<td>0.00 in/day</td>
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<tr>
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<td>60</td>
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<tr>
<td>L</td>
<td>3</td>
<td>in</td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>3 in/day</td>
</tr>
<tr>
<td>delta x</td>
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<td>in</td>
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</table>

<table>
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<tbody>
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<td>Low h W</td>
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<td></td>
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<tr>
<td>Top h W</td>
<td>0</td>
<td>in/day</td>
<td>Layer</td>
<td>E</td>
<td>D</td>
<td>C</td>
<td>B</td>
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VITA

Lane Stokes is a 2013 JMU alumnus where he majored in Geology and minored in Mathematics. During this project, he was a student at the Old Dominion University Department of Civil and Environmental Engineering, to obtain a master’s in Environmental Engineering. He has assisted in professional environmental consultants’ projects at Stokes Environmental Consultants, where he also assisted in reviewing of documents, propagation of native plant species, taking samples at contaminated sites, detection and closure of decaying underground storage tanks, documenting environmental geology, renovating roads, and stormwater drainage management. Before, he did volunteer work to get experience with different activities, industries, and causes. Now, he values those connections for involvement.