Hydrogeologic Investigation of a Covered Karst Terrain

Joseph Peter Honings

Louisiana State University and Agricultural and Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_dissertations

Part of the Geology Commons, Geophysics and Seismology Commons, Hydrology Commons, Speleology Commons, and the Water Resource Management Commons

Recommended Citation
https://digitalcommons.lsu.edu/gradschool_dissertations/5994

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Doctoral Dissertations by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
HYDROGEOLOGIC INVESTIGATION OF A COVERED KARST TERRAIN

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Geology & Geophysics

by

Joseph Peter Honings
B.S., University of Iowa, 2013
M.S., Illinois State University, 2018
December 2022
This dissertation is dedicated to my fiancée Emily, my parents, and my extended family. Your unconditional love and encouragement have been vital to me along this journey.
ACKNOWLEDGEMENTS

Thank you to Dr. Carol Wicks, my advisor, for her unwavering support during my time at LSU and amidst a global pandemic. I have learned so much from her just as a scientist, but as a human being. Thank you to my committee members, Drs. Steven Brantley, Karen Luttrell, Frank Tsai, and Eric Peterson, and Dean’s Representative Y. Jun Xu. Thank you to the LSU Department of Geology & Geophysics for the opportunity to pursue my PhD with funding as a teaching assistant. Thank you to the Jones Center at Ichauway for funding, research support, and allowing me to conduct my research amidst such beauty in nature. Thank you to the Geological Society of America, Houston Energy LLP, and Chevron Corporation for scholarship support. Thank you to Robert Ritger and Andrew Webb for help with data collection. Thank you to the ISU Department of Geography, Geology, and the Environment. My experience in the Hydrogeology MS program and Dr. Peterson’s karst hydrogeology class prepared me for undertaking this PhD program. I am grateful that you accepted me amidst what was a scary career shift for me. I will always remember my time back home in Central Illinois and ISU fondly. Thank you to my first employer and my coworkers who helped my professional development in the environmental consulting industry. Thank you to the University of Iowa Department of Earth and Environmental Sciences. I found my purpose as a student in the Environmental Science program that laid the foundation for where I am today. Thanks to Wayne Fett, Caleb Recker, Dr. Adam S. Ward, Dr. Frank Weirich, Dr. Marian Muste, Eric Mueggenberg, Dr. Wondy Seyoum, Dr. Eric Peterson, Dr. Dave Malone, and Paul Meister. Your mentorship has been invaluable to my growth and aspirations a person and geologist. To Dr. Robert “Skip” Nelson, conversations with you in a West Texas diner about life and geology are wisdom I hope to impart on anyone someday. To my classmates, I am thankful for the friendships that I’ve developed over the years at the different stops along the way.
TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................................................ iv

CHAPTER 1. INTRODUCTION ................................................................................................................................. 1
  Dissertation Outline ............................................................................................................................................... 3

CHAPTER 2. KARST GEOMORPHOLOGY OF THE DOUGHERTY PLAIN ............................................................ 5
  Karst Evolution of the United States Coastal Plain .......................................................................................... 6
  Expectations in GPR Imagery at Study Area ................................................................................................. 12

CHAPTER 3. SURFACE GEOPHYSICAL TECHNIQUES ......................................................................................... 15
  Electrical Resistivity Tomography .................................................................................................................. 15
  Ground-Penetrating Radar ............................................................................................................................... 19
  Expectations in GPR Imagery at Study Area ................................................................................................. 22
  Data Collection ................................................................................................................................................ 23
  Data Processing ............................................................................................................................................... 23
  Three-dimensional Visualization ..................................................................................................................... 26
  Interpretation ................................................................................................................................................... 26
  Select Images from the Turkey Woods Draw Feature .................................................................................... 27

CHAPTER 4. GEOPHYSICAL INVESTIGATION AT THE JONES CENTER ............................................................... 30
  Regional Water Resource Sustainability ........................................................................................................ 30
  Numerical Modeling for Improved Sustainability ......................................................................................... 32
  Study Area ...................................................................................................................................................... 34
  Methods ......................................................................................................................................................... 36
  Results & Interpretation ................................................................................................................................. 48
  Discussion ...................................................................................................................................................... 66

CHAPTER 5. FIELD GUIDE TO THE GEOLOGY AND GEOMORPHOLOGY OF THE JONES CENTER AT ICHAUWAY ........................................................................................................................................ 71
  Introduction .................................................................................................................................................... 71
  Stop 1. The Woodruff House and Historic Circle ......................................................................................... 74
  Stop 2. The Paleo-Course of the Ichawaynochaway Creek ........................................................................... 80
  Stop 3. The Sandy Sinkholes of the Turkey Woods ....................................................................................... 83
  Stop 4. The Turkey Woods Draw .................................................................................................................. 87
  Stop 5. Rhexia Pond (Wetland 53) ................................................................................................................ 89
  Stop 6. Balden Pond and Richardson Flat Concealed Feature ..................................................................... 91
  Stop 7. South of Ichauway Bridge near the Baseball Field: The Cover Sediments ........................................ 97
  Stop 8. The Swimming Hole: The Upper Floridan Aquifer ......................................................................... 99
  Summary ....................................................................................................................................................... 102

CHAPTER 6. SUMMARY ....................................................................................................................................... 104

APPENDIX A. ADDITIONAL GPR IMAGERY ......................................................................................................... 109
  The Turkey Woods Draw and Vicinity ......................................................................................................... 109
ABSTRACT

Increasing demand for water for agricultural use within the Dougherty Plain of the Southeastern United States has depleted surface water bodies. In karstic landscapes, such as the Dougherty Plain in southwest Georgia where the linkages between surface and ground waters are close, there is a need to understand the physical characteristics of the subsurface that allow these close linkages. Having a better understanding of the subsurface characteristics will aid numerical modeling efforts that underpin policy decisions and economic analyses. Two common features on this karstic landscape are draws and geographically isolated wetlands. Using LiDAR, aerial imagery, and ground-penetrating radar, this study investigates the subsurface characteristics of a draw and a series of geographically isolated wetlands. GPR reflections indicative of karst features are laterally-continuous and connect the landscape to nearby Ichawaynochaway Creek. The identification of the size and scale of the laterally continuous karstic features will guide the implementation of groundwater models used to determine irrigation and forest restoration programs while minimizing the impacts of water use on surface streams and the ecosystems.
CHAPTER 1. INTRODUCTION

Globally, over-extraction of groundwater resources has reduced baseflow and elevations of surface waters (de Graaf et al., 2019; Döll et al., 2012), which is detrimental to aquatic ecosystems (Golladay et al., 2004; Hynes, 1983; Peters et al., 2008; Sophocleous, 2002; Tetzlaff et al., 2007), and has led to disputes over groundwater resources (Gleeson et al., 2010). Over-extraction is expected to continue and worsen as demand increases and climate change continues (Wada, 2016; Wada et al., 2010).

Karstic and carbonate bedrock regions are approximately 15% of the global ice-free continental surface and host approximately 16.5% of the total global population (Goldscheider et al., 2020). Aquifers in karstic and carbonate bedrock are generally very productive and populations in these regions depend on these aquifers as a source of water (Goldscheider et al., 2008). As global population increases, driving more consumption of water and as climate changes, water resource management and understanding groundwater-surface water interactions in karstic basins will become more critical (Taylor et al., 2013).

Agriculture is a major industry throughout the Southeastern United States, which utilizes surface and ground water for row crops and pasture. These surface and groundwater resources flow across state and county boundaries, and sometimes overlap depending on scale, which has led to arguments over allocation and usage of the water. A recent example is that water resources of the Apalachicola-Chattahoochee-Flint (ACF) River Basin were subject of a Supreme Court case decision between Florida and Georgia (Klein and Sandfort, 2019). Georgia, like other states, has developed a State-wide management plan to conserve water by mid-century, relying on economic model projections (GWPCC, 2017). The ACF River Basin overlaps with the Lower Flint-Ochlockonee (LFO) River Basin in the southeastern United States, and projections for the LFO
watershed indicate that withdrawals will continue to exceed the sustainable yield of the Upper Floridan Aquifer (UFA), the primary groundwater resource in the region. Both the ACF and LFO basins flow through the Dougherty Plain province in southwestern Georgia, where efforts to sustain water while maintaining crop yield persist.

Due to uncertainty of the availability of water resources with climate change and intense human consumption, numerical groundwater models have been successfully utilized to predict water budgets (Alam et al., 2019; Ghazavi and Ebrahimi, 2018). In clastic sediments, the porous media are Darcian and generally easy to characterize, whereas the heterogeneity and unknown flow paths of karst aquifers are difficult to build into the model parameters (Hartmann et al., 2014). The limitation is not in development of the numerical and discretized models (Shoemaker et al., 2008), but in characterizing the nature of the karstic subsurface (Borghi et al., 2016). Karstic flow paths have often been overgeneralized as subsurface pipes (Peterson and Wicks, 2006) or as higher permeability zones embedded within a porous matrix (Wicks and Herman, 1995). More knowledge of the geometry of the subsurface will facilitate refinement of groundwater modeling efforts in the Dougherty Plain and the drainage basins it lies within.

The Dougherty Plain of the Southeastern United States Coastal Plain is littered with hundreds of wetlands, of which are commonly referred to as geographically-isolated wetlands (GIWs). GIWs are completely surrounded by uplands at the local scale (Tiner, 2003), though this does not mean functional isolation hydrologically, ecologically, or physiochemically (Mushet et al., 2015; Tiner, 2003). The genesis of these wetlands is ponding within karstic depressions and sinkholes (Hicks et al., 1987; Kirkman et al., 2012). The surficial hydrology of these wetlands in the Dougherty Plain has been described as spill-and-fill behaviour by means of overland flow after high-precipitation events (Deemy and Rasmussen, 2017). Hydrologic movement in GIWs is
difficult to observe in nature because these surficial connections are infrequent, of short duration, or the hydrologic connection is via subsurface and groundwater pathways (Mushet et al., 2015). It has been assumed that minimal connectivity exists with groundwater because the sediments underlying the wetlands are relatively impervious (Kirkman et al., 2012). Conceptualization of the connection from the ponds to the subsurface flow system would provide great insight into the region’s water sustainability efforts.

**Dissertation Outline**

Chapter 2 of this dissertation describes the fundamental concepts of karst topography formation and processes as it relates to limestone rocks. The geologic evolution of the Dougherty Plain spanning from deposition of the carbonate bedrock in the Eocene period to present processes are summarized. Karst topography produces unique landforms and features, of which are based on the aquifer recharge mechanisms and dominant porosity of the limestone. The generalized covered karst stratigraphy of the Jones Center at Ichauway served as the basis for predicting the patterns in karst features prevalent through the region. Sinkholes and enlarged fissures are expected features in the Dougherty Plain, and their geometry and materials are depicted in conceptual diagrams. The sediments, water saturation, and presence of air in cavities will determine the reflections observed in GPR data based on the velocity in which the radar waves propagate through them. These velocities are included in the conceptual diagrams to provide a basis for how the GPR data were ultimately interpreted, described in Chapter 3.

Chapter 3 of this dissertation will describe the fundamentals of the shallow subsurface geophysical methods utilized in this research, electrical resistivity tomography (ERT) and ground-penetrating radar (GPR). The expectations in geophysical imagery based on the geology of the Dougherty Plain are described. The survey design and processing for both ERT and GPR is also
explained, as well as how each method succeeded or failed.

Chapter 4 of this dissertation provides a background of contemporary water resource issues in the Dougherty Plain and greater area, as well as local efforts to conserve water in these watersheds. Numerical groundwater modeling projects have been used for decades to assist with and inform these conservation efforts. Because irrigation in this densely agricultural region is expected to increase by mid-century, refinement of these modeling parameters and conceptualization of the linkage of recharge areas to discharge areas is needed. To understand the landscape, ground-penetrating radar (GPR) was utilized to characterize the karst features and drainage in the Dougherty Plain. Findings from the GPR data provide refined information to the numerical groundwater models for improved predictions. Additionally, knowledge of the groundwater flow paths inform land management and policy decisions, as well as guidance for the optimal location of future, sustainable irrigation systems.

Chapter 5 is a Field Guide to the hydrogeology of the Jones Center at Ichauway. The guide serves as an interactive, educational program for non-geologists that visit the property. It covers fundamental geologic concepts that are manifested in outcroppings, sinkholes, and wetlands and relates these spots to the overall karst drainage of the Jones Center and greater Dougherty Plain. The conceptualization of the drainage will help researchers at the Jones Center understand the hydrologic pathways and apply the new knowledge to ongoing and future projects. Chapter 6 will serve as a summary for the dissertation.
CHAPTER 2. KARST GEOMORPHOLOGY OF THE DOUGHERTY PLAIN

Karst topography is a landscape derived from the chemical solution of soluble bedrock as the dominant geomorphic agent. Typically, the bedrock is carbonate in nature, limestone or dolomite. The landscape itself is characterized by depressional features, disrupted surface drainage, caves, and other underground drainage systems. The closed depressional features include dolines (individual sinkholes), uvalas (coalescing sinkholes), and poljes (a series of dolines and uvalas) (White, 1988).

Speleogenesis is the process in which soluble bedrock is dissolved by acidic groundwater. The global equation for the weathering of limestone is as follows:

\[ \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \]

The traditional model for karst dissolution is the combination of atmospheric carbon dioxide (CO\(_2\)) with water (H\(_2\)O) to produce acidic rainwater, carbonic acid (H\(_2\)CO\(_3\)). When the acidic rainwater falls on the landscape and infiltrates into the host limestone, the chemically-aggressive water dissolves the calcium carbonate (CaCO\(_3\)) bedrock, producing calcium (Ca\(^{2+}\)) and bicarbonate (HCO\(_3^-\)) ions in solution. As this process continues over time, cavities develop in the bedrock, often along joint or fracture systems (White, 1988).
Figure 1. Conceptual model of speleogenesis. Precipitation mixes with atmospheric carbon dioxide, then with soil and groundwater carbon dioxide through infiltration. The acidic groundwater dissolves the host limestone.

Karst formation is enhanced in zones of mixing waters (Palmer, 1991), especially at the interface where meteoric water that percolates through the soil interface meets the groundwater table. Additionally, the processes are enhanced within secondary porosity of the host limestone, such as joints and fractures. Bedding planes within the limestone are often areas of concentrated karst formation as well (White, 1988).

**Karst Evolution of the United States Coastal Plain**

The Coastal Plain of the Southeastern United States (Figure 2) is a geologic setting formed by the transgressive-regressive fluctuation of sea level from the Late Cretaceous to present day. Several aquifer systems are situated within gently-dipping, Tertiary-aged carbonate and clastic sedimentary sequences, including the Floridan Aquifer (Figure 3, Miller). The Floridan Aquifer itself consists mainly of thick carbonate formations, the Eocene-aged Avon Park and Ocala Limestones, and the Oligocene Suwanee Limestone where thick enough. Generally, the Floridan Aquifer system is thickly-confined at the top and bottom, with some areas thinly-covered or unconfined (Figure 55, Miller). The upper confining unit is the clastic Miocene Hawthorn
Formation. Additionally, it is divided into an upper and lower unit, separated by a middle confining layer. The limestones of the aquifer have been characterized as highly porous, with secondary porosities resulting from epigenic (derived from atmospheric water and surficial processes) karst processes.

Figure 2. From Miller (1990a), depicting the Coastal Plain in the yellow color. The Dougherty Plain is a province within the greater Southeastern United States Coastal Plain.
Denizman and Randazzo (2000) provide a conceptual model that summarizes post-Miocene karst evolution within the carbonates of the Floridan Aquifer. A joint system within the carbonates was formed from uplift of the Ocala platform. As sea level retreated in the late Oligocene, the Suwanee Limestone and older carbonates were subaerially exposed, and dissolution occurred at both the surface and subsurface, primarily along the joints and bedding planes. This dissolution developed an epikarst zone and subsurface conduits. Then, the Hawthorn Group siliciclastics were deposited atop the Ocala platform during a sea level maximum, establishing an aquiclude that stalled the development of karst. The advance of fluvial systems in the Pliocene facilitated the removal of overlying clastic material, and these rivers controlled the groundwater system as their base level and discharge fluctuated. Localized diffuse recharge enhanced the epikarst, while allogenic recharge focused speleogenesis along the contact between the Oligocene
paleokarst and the overlying Hawthorn clastics. Sea level regressed in cycles through the Pleistocene, thus alternating the vadose-phreatic and fresh-salt water mixing interfaces that further enhanced deeper conduits.

Palmer (1991) classified cave patterns and morphology based on the dominant recharge mechanism and dominant porosity (Figure 4). The speleogenetic history of the Floridan aquifer includes the development of joints in the carbonate bedrock, burial by a siliciclastic formation and dissolution at the contact, and sea level fluctuation that altered the positions of vadose-phreatic and fresh-seawater interfaces. Out of the cave patterns summarized and presented by Palmer, it is hypothesized that the “shaft and canyon complex” pattern would be observed in the Floridan Aquifer. This model accounts for diffuse recharge through a clastic system, as well as allogenic waters enhancing dissolution. These allogenic waters would include the rivers that incised the paleo-landscape during the Miocene through the Pleistocene, and perhaps the seawater that mixed at the freshwater interface. Although there is a known joint system in the carbonates, the bedding planes and contacts serve as key points for dissolution in this model, and must be considered.
Figure 4. From Palmer (1991), depicting a summary of cave patterns and their relationship to types of recharge and porosity.

The hypothesis that the “shaft and canyon complex” is the expected cave pattern within the majority of the Floridan Aquifer has several implications for geophysical investigations of the system. This expectation holds true with the localized setting of the Jones Center at Ichauway (the Jones Center), due to the thick, clastic mantle sediments that cover the Ocala Limestone throughout the landscape. The joint system within the limestone from the Ocala uplift is evident in the linear patterns of sinkholes, and is visible in some stream outcrops (Brook and Allison, 1986; Rugel et al., 2019). Diffuse flow through mantle sediments and alloigenic waters from the Ichawaynochaway Creek will have enhanced these fractures, and at alternating depths determined by the paleo-position of the creek or other former surface bodies. Both vadose and phreatic conduits could exist beneath the mantled surface, and geophysical investigations should be aware
of this possibility.

This system has evolved over time and produced a number of sinkholes that litter the landscape of the Jones Center and greater Dougherty Plain. Sinkholes at the Jones Center are typically cover-collapse sinkholes (Figure 5). These sinkholes are formed when a cavity develops in the limestone underground, overlying sediment moves into the void, subsurface flow removes material from the void, and the land surface depresses or collapses altogether. The epikarstic zone in the study area is expected to contain sediment fill in the voids that focuses recharge into the cavities that penetrate to the greatest depth (Palmer, 1991). Sinkhole development is a precursor to the development of vertical shafts that connect to an underlying conduit system below.

Figure 5. Depiction of the formation of a cover collapse sinkhole from Palmer (1991). Dissolution occurs along bedding planes and pre-existing voids, and overlying sediments fill these voids until subsurface flow or cavity enhancement removes material, causing a collapse.
Expectations in GPR Imagery at Study Area

Ground-penetrating radar (GPR) was utilized to investigate karst features at the Jones Center, and is described in further detail in the next chapter and in Appendix A. Dipping reflectors in GPR imagery that are expected at the Jones Center and the greater Dougherty Plain would be related to cavities, touching-vug porosity, erosional surfaces, and sinkhole funnels and similar features. In these images, the epikarst surface is expected to be irregular (not flat), and could contain several point reflectors related to voids and pieces of rock within the overburden matrix.

In this research, migration will be utilized to resolve the diffractions related to the karstic features. It is expected that the epikarst surface will be irregular and sometimes sloping in the 2D images. Therefore, migration velocity parameters will be chosen based on the velocity of the diffractions within the karst feature, and not the stratigraphy of soils or epikarst surface. Our goal is to increase the detail around the karst features that cause the lateral velocity variations in the image compared to the bulk. Figure 6 and Figure 7 depict the conceptual models of stratigraphy and heterogeneity associated with karst at the Jones Center.
Water content strongly controls GPR signal propagation in the subsurface (Davis and Annan, 1989). Therefore, if the water table is at higher elevation than a karst feature, the signal attenuation may not reveal the deeper karst feature in the GPR imagery, and velocities will
decrease with water content.
CHAPTER 3. SURFACE GEOPHYSICAL TECHNIQUES

Electrical Resistivity Tomography

Earth materials have different electrical resistivity values determined by lithology and water content (Table 1).

Table 1. Electrical resistivity value ranges for select earth materials. Modified from Akingboye and Ogunyele (2019). References included therein.

<table>
<thead>
<tr>
<th>Common Materials</th>
<th>Cited Resistivity Values (Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>1 – 100</td>
</tr>
<tr>
<td>Sand</td>
<td>10 – 800</td>
</tr>
<tr>
<td>Gravel</td>
<td>600 – 10⁴</td>
</tr>
<tr>
<td>Mudstone</td>
<td>----</td>
</tr>
<tr>
<td>Siltstone</td>
<td>----</td>
</tr>
<tr>
<td>Limestone</td>
<td>80 – 6000</td>
</tr>
<tr>
<td>Shale</td>
<td>20 – 2000</td>
</tr>
<tr>
<td>Sandstone</td>
<td>10 – 5000</td>
</tr>
</tbody>
</table>

Electrical resistivity tomography (ERT) is a non-invasive technique that utilizes electrical currents emitted from surface electrodes to measure the electrical resistivity ($\rho(\Omega m)$) of earth materials in the subsurface. The electrical currents utilized by ERT are not attenuated by water within the subsurface, as which occurs in GPR, which makes ERT a great complement to GPR surveys and a stand-alone sufficient method to image and interpret the subsurface. The theory and
methodology are described in great detail by Akingboye and Ogunyele (2019). Resistivity is defined as follows (Samouëlian et al., 2005):

\[ \rho = R \left( \frac{S}{L} \right) \] \hspace{1cm} (1)

where \( R \) is the electrical resistance (\( \Omega \)), \( L \) is length of a cylinder (m), and \( S \) is the cross-sectional area (\( m^2 \)). The electrical resistance of the cylindrical body \( R \) (\( \Omega \)) is defined by Ohm’s law (Samouëlian et al., 2005):

\[ R = \frac{V}{I} \] \hspace{1cm} (2)

Where \( V \) is the potential (V) and \( I \) is the current (A). Several array configurations of the electrodes may be utilized (Akingboye and Ogunyele, 2019; Samouëlian et al., 2005), including the Wenner and dipole-dipole arrangements. The dipole-dipole configuration uses four stakes as separate pairs, A & B (current electrodes) and M & N (potential electrodes), driven into the ground (Griffiths and Barker, 1993; Zhou et al., 2000). A direct current (DC) is applied into the surface through the current electrodes, and the potential electrode pair measures the potential difference (voltage, \( \Delta V \)) between the two pairs. The voltage is measured by the following equation:

\[ \Delta V = \frac{\rho I}{2\pi} \left[ \frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN} \right] \] \hspace{1cm} (3)

in which \( AM, BM, AN, \) and \( BN \) are the geometrical distance between the electrodes A and M, B and M, A and N, and B and N, respectively (Samouëlian et al., 2005). The current electrodes remain stationary while the potential electrodes are moved laterally in increments of the standard spacing to sample greater depths (Figure 8).
Figure 8. Depiction of the dipole-dipole electrode array. The current (C2 & C1) electrodes remain stationary, separated by a standard spacing "a." The potential (P1 & P2) electrodes are separated by "a," and moved laterally in increments of “a” to sample at greater depths.

The Wenner configuration uses an arrangement of two potential electrodes between the two current electrodes, as depicted in Figure 9. Deeper samples are taken by moving the electrodes in increments of the standard spacing along the survey.

Figure 9. Depiction of the Wenner electrode array. The arrangement is ordered C1-P1-P2-C2, with a standard spacing "a." The electrodes are moved in increments of "a" to sample with greater depth.

The apparent resistivity is measured, and their vertical and lateral distribution is used to produce a pseudo-section of the subsurface. ERT imagery is produced by matching this apparent resistivity pseudo-section to a computer-generated pseudo-section, of which is attained by solving for given earth resistivity structure $\rho(r)$ using the scaled-Laplace equation (Akingboye and
Ogunyele, 2019; Everett, 2013):

\[ \nabla \left( \frac{1}{\rho} \nabla \phi \right) = 0 \]

(5)

The distribution of electric potential is evaluated at locations of the potential electrodes and transformed into a computed apparent resistivity. The models are repeatedly adjusted, with re-computing of apparent resistivity, until there is a match of measured apparent resistivity to a pre-determined acceptable tolerance (Akingboye and Ogunyele, 2019; Everett, 2013). The acquired measured apparent resistivity data must be inverted using computer programs that will produce a 2D resistivity model of the subsurface. The inversion process within the select program is based on smoothness-constrained least-squares from the following equation:

\[ (J^T J + uF)d = J^T g; \text{where } F = f_x f_x^T + f_z f_z^T \]

(6)

in which \(f_x\) and \(f_z\) are horizontal and vertical flatness filters, \(J\) is the matrix of partial derivatives, \(u\) is a damping factor, \(d\) is the model perturbation factor, and \(g\) is the discrepancy vector (Akingboye and Ogunyele, 2019). The algorithm determines resistivities of the subsurface, which is separated into rectangular cells during the modelling process. The resulting measured, calculated, and inversely-modeled resistivities are compared, and Root-Mean-Square (RMS) error is calculated to determine how well the calculated resistivity data match the true resistivity model. If the results are not sufficient, the process is iterated with adjustments of parameters and model settings until an accurate inversion model resistivity section tomograph is produced. The tomographs will be compared against background information obtained from nearby well logs and local geologic publications.

ERT and GPR interpretations of a site will be integrated. If a karst feature is imaged in ERT where the GPR signal has attenuated due to water saturation, it can be deduced that the karst feature is water-filled, or under phreatic conditions. All transects collected will establish the extent
and connectivity of the feature through the landscape.

A total of eleven (11) ERT surveys were completed prior to abandonment of the technique in this research. Both dipole-dipole (8) and Wenner (3) array surveys were completed, with a reoccurring problem being the measurement of some negative apparent resistivity values. Not all measurements in each survey were negative, so the negative measurements are not attributed to incorrect electrode arrangement or user error. The low to negative apparent resistivity measurements are attributed to high moisture in the soils. Additionally, the difference in apparent resistivities between near-surface measurements and deeper measurements ended up being several orders of magnitude, which resulted in high error in the inversions.

It was determined that the raw ERT data were not reliable for interpretation due to the presumed erroneous measurements. GPR surveys were less time-consuming and easier to conduct in the field, which allowed for more areal coverage of the target features discussed in this dissertation. Additionally, more information was readily available to interpret from the raw GPR imagery compared to the raw ERT data, which prioritized GPR data collection.

**Ground-Penetrating Radar**

Ground-penetrating radar (GPR) is a surface geophysical technique for high-resolution visualization, and thus characterization, of soil and stratigraphic units (Annan, 2005; Davis and Annan, 1989). In karstic regions, GPR has proven useful to map the depth to bedrock (the depth to top of epikarst), the depth and geometry of sinkholes, and other dissolution features (Carpenter and Ekberg, 2006; Chalikakis et al., 2011; Evans et al., 1994; Kruse, 2014; Kruse et al., 2006; Rodriguez et al., 2014; Vadillo et al., 2012; Van Schoor, 2002). However, the regions examined in these studies did not include sites similar to the covered karst terrain of the Dougherty Plain, within which the signature of collapse and conduit features may appear differently in geophysical
datasets. Thus, more information is needed for understanding the in-filling of sinkholes and conduits, as well as their location and lateral continuity through the covered karst landscape.

GPR utilizes electromagnetic pulses within radar frequency (12.5-1000 MHz) that are emitted into the subsurface by a transmitting antenna. As these waves travel through the ground, they travel through the geologic medium at a velocity (V), and reflect when a new material is encountered due to a difference in dielectric permittivity (K). When the waves reflect to the receiving antenna, these echoes are recorded, and the cross-sectional image is built from them. As the waves travel through the subsurface, the signal attenuates (α). The depth a transmitted pulse will travel depends on several factors, as described in Davis and Annan (1989). The resolution of the GPR is the system’s capability to differentiate between two or more reflections that are similar in travel time. The relationship between range deflection and resolution will depend on the signal attenuation and frequency. The data are displayed as a cross section stacking of the traces.

Figure 10. Generalized diagram of GPR operation. From Nguyen et al. (1998).
Table 2. Dielectric permittivity values for geologic materials present at the Jones Center, and expected reflectance at contact with other materials.

<table>
<thead>
<tr>
<th></th>
<th>K1</th>
<th>Air</th>
<th>Dry Sand</th>
<th>Limestone</th>
<th>Sat. Sand</th>
<th>Silts</th>
<th>Clays</th>
<th>Fresh Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2</td>
<td></td>
<td>1</td>
<td>5</td>
<td>8</td>
<td>25</td>
<td>30</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Air</td>
<td>1</td>
<td>38%</td>
<td>48%</td>
<td>67%</td>
<td>69%</td>
<td>73%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>5</td>
<td>38%</td>
<td>42%</td>
<td>48%</td>
<td>52%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>8</td>
<td>48%</td>
<td>12%</td>
<td>28%</td>
<td>32%</td>
<td>38%</td>
<td>52%</td>
<td></td>
</tr>
<tr>
<td>Sat. Sand</td>
<td>25</td>
<td>67%</td>
<td>38%</td>
<td>28%</td>
<td>5%</td>
<td>12%</td>
<td>28%</td>
<td></td>
</tr>
<tr>
<td>Silts</td>
<td>30</td>
<td>69%</td>
<td>42%</td>
<td>32%</td>
<td>5%</td>
<td>7%</td>
<td>24%</td>
<td></td>
</tr>
<tr>
<td>Clays</td>
<td>40</td>
<td>73%</td>
<td>48%</td>
<td>38%</td>
<td>12%</td>
<td>7%</td>
<td>17%</td>
<td></td>
</tr>
<tr>
<td>Fresh Water</td>
<td>80</td>
<td>80%</td>
<td>60%</td>
<td>52%</td>
<td>28%</td>
<td>24%</td>
<td>17%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Stratigraphic features (top) and karst features (bottom) that are present at the Jones Center with their expected reflection strength.

<table>
<thead>
<tr>
<th>Stratigraphic Features</th>
<th>Reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sand - Limestone</td>
<td>12%</td>
</tr>
<tr>
<td>Wet Sand - Limestone</td>
<td>28%</td>
</tr>
<tr>
<td>Silt seam in sand</td>
<td>42%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Karst Features</th>
<th>Reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-Limestone</td>
<td>48%</td>
</tr>
<tr>
<td>Water-Limestone</td>
<td>52%</td>
</tr>
<tr>
<td>Air-Water</td>
<td>80%</td>
</tr>
<tr>
<td>Clay-Limestone</td>
<td>38%</td>
</tr>
<tr>
<td>Air-Clay</td>
<td>73%</td>
</tr>
<tr>
<td>Sand-Clay</td>
<td>48%</td>
</tr>
<tr>
<td>Limestone-Clay</td>
<td>38%</td>
</tr>
<tr>
<td>Air-Sand</td>
<td>38%</td>
</tr>
</tbody>
</table>

Reflections should occur at contacts between two materials of differing lithologies or water content. The depth, geometry, and strength of the reflections can be correlated to known geologic formations or conceptual karst deformation features. The picking of lithologies are guided by background information obtained from nearby well logs and local geologic publications. Water content strongly controls GPR signal propagation in the subsurface (Davis and Annan, 1989). Therefore, if the water table was at higher elevation than a karst feature, the signal attenuation may
not have revealed the deeper karst feature in the GPR imagery for interpretation.

**Expectations in GPR Imagery at Study Area**

Dipping reflectors that are expected at the Jones Center and the greater Dougherty Plain would be related to cavities, touching-vug porosity, erosional surfaces, and sinkhole funnels and similar features. In these images, the epikarst surface is expected to be irregular (not flat), and could contain several point reflectors related to voids and pieces of rock within the overburden matrix.

In this research, migration will be utilized to resolve the diffractions related to the karstic features. It is expected that the epikarst surface will be irregular and sometimes sloping in the 2D images. Therefore, migration velocity parameters will be chosen based on the velocity of the diffractions within the karst feature, and not the stratigraphy of soils or epikarst surface. Our goal is to increase the detail around the karst features that cause the lateral velocity variations in the image compared to the bulk.

---

**Figure 11.** Conceptual model of the geology of the Jones Center at Ichauway.
Water content strongly controls GPR signal propagation in the subsurface (Davis and Annan, 1989). Therefore, if the water table is at higher elevation than a karst feature, the signal attenuation may not reveal the deeper karst feature in the GPR imagery.

**Data Collection**

Survey lines were oriented perpendicular to the hypothesized karst feature locations based on the patterns described in the literature and observed in topography from the aerial imagery datasets. Parallel transects were completed in an attempt to determine the spatial continuity and overall connectivity of the subsurface feature in the resultant datasets (Figure 12). GPR survey deployment utilized a push cart-mounted common offset with 100 MHz antenna and 1-meter spacing. Measurements were taken at 0.25-meter steps along the traverse as the equipment was pushed forward. Survey locations were limited due to heavy brush, thick surficial sand deposits, and ponding. GPR survey data were examined as cross-sections, and reflections were interpreted as geologic horizons and karst features. Access to ponds off-property was not available.

**Data Processing**

**Dewow**

A transmitted signal might induce a slowly-decaying low frequency “wow” on the trace which is superimposed on high frequency reflections. The low frequency component does not propagate, but diffuses into the subsurface. Dewow processing removes this low frequency “wow.”

**Two-Way Travel Time Depth Conversion**

Each survey was individually depth-corrected by determining the velocity of the medium for the unconsolidated overburden, achieved by one of two ways. The first method involved the measurement of a shallow, hyperbolic reflector using the velocity calibration tool. The user fits a typical response curve to the hyperbolic reflector in the data, and the velocity is extracted and
applied to the calibration of depth. The second method is a velocity estimation based on the field observations of the soils, i.e. if the ground was mostly sand, the image was calibrated for a velocity of dry sand (0.150 m/ns).

Figure 12. GPR survey lines (green) were generally oriented perpendicular to the alignment of ponds and sinkholes in an attempt to cross the fracture. Parallel transects were completed to determine the lateral continuity of the feature in the subsurface.

**Migration**

Migration of a GPR image concentrates received energy to its source location in the image. It collapses diffractions of dipping reflectors and reconciles them to their true subsurface positions. This is completed to make the GPR section appear similar to the real geologic cross section. The heterogeneity associated with karstic processes around sinkholes, touching-vug porosity, and cavities produce dipping reflectors in the imagery, and their size and shape could be better resolved with migration processing.
In the Ekko_Project V5 software, two (2) migration options are available to the user, F-K (Stolt) migration and Kirchoff migration. The F-K migration uses the entire data set, whereas the Kirchoff migration uses a region around the energy source point, a width in which the user can define.

F-K migration utilizes a synthetic aperture image reconstruction process, in which the data are Fourier-transformed into plane waves at a monochromatic frequency. The waves are individually processed to superimpose the energy at the source point to collapse hyperbolas. In Kirchoff migration, the energy along a hyperbola is summed and placed at its apex, which is the source of the energy.

For both methods, the user specifies a velocity parameter for the migration based on a measured velocity or an estimation based on the geologic materials. The F-K migration uses velocity as the lone input parameter. Kirchoff migration parameters include velocity, a width (meters) of the window for summation along the hyperbolic trajectory, and designation of a target type (All targets, point targets, rod/cylindrical targets, or planar targets). Utilizing a velocity that is too low will not collapse the hyperbola into a point. If a chosen velocity is too high, the data will be over-migrated into a smile shape (concave upwards). It is an iterative process to find the optimal velocity for migration.

After each image was individually depth-corrected using the above methodology, the image was examined for point reflectors that could be measured with the velocity calibration tool. If a velocity could be measured, the image was not rectified for the measurement. Instead, this velocity was used as the input velocity parameter in the chosen migration method (F-K or Kirchoff). If no reflectors were measurable with the tool, velocities respective to the known geologic materials were used. This was an iterative process in which the migrated images were
compared against conceptual geologic models.

Three-dimensional Visualization

Following the processing of GPR data, different methods were utilized with the intent to visualize the data in 3D for each. The first method was an attempt to create a velocity cube within the Ekko Project GPR software, but was unsuccessful because the GPR data were collected as individual lines instead of a collective grid survey. Unsuccessful attempts were made to convert the line data into a grid survey. The second method converted the GPR line files into SEG-Y format using Ekko Project, and imported the SEG-Y files into Petrel software that is commonly used to visualize seismic data. However, due to scaling issues, the data were not successfully visualized despite several troubleshooting techniques. The third attempt to visualize the data in 3D using ArcScene, utilizing the LiDAR DTM as the topographic surface for visualization. Each GPR line was used to create a JPEG image, and each image was attached to a point feature at the location of each survey line in ArcScene. The display settings of the 2D cross section image were adjusted such that the image would “hang” from the point feature in ArcScene. However, there was no way to rectify the image to the end points of the survey, so the image would not rotate with the 3D topography.

The successful 3D visualization method was the conversion of the GPR data into half-meter depth slices using the EkkoProject GPR software. The depth slices are colored, and a color change indicates a change in velocity between slices. These were utilized to visualize the key depths of the higher-porosity zones within the draw and the small gridded survey within the Richardson Flat GIW. Examples are included as figures below.

Interpretation

Reflections at contacts between two materials of differing lithologies or water content were
correlated to known geologic formations or conceptual karst deformation features. The picking of lithologies was guided by background information obtained from nearby well logs and local geologic publications. Water content strongly controls GPR signal propagation in the subsurface (Davis and Annan, 1989). Therefore, if the water table was at higher elevation than a karst feature, the signal attenuation may not have revealed the deeper karst feature in the GPR imagery for interpretation.

Select Images from the Turkey Woods Draw Feature

![GPR Cross Section and Conceptual Model](image-url)

Figure 13. (Top) GPR cross section of a transect between two field-verified sinkholes along the draw. (Bottom) The accompanying conceptual model is an interpretation of geologic materials and karst features.
Figure 14. (Top) GPR cross section of a transect completed between two field-verified sinkholes along the hypothesized subsurface flow path. (Bottom) The accompanying conceptual model with interpretation of geologic materials and karst features.
Figure 15. (Top) GPR cross section of a transect completed adjacent to Ichawaynochaway Creek. (Bottom) The accompanying conceptual model with interpretation of geologic materials and karst features.
CHAPTER 4. GEOPHYSICAL INVESTIGATION AT THE JONES CENTER

Regional Water Resource Sustainability

In the United States, individual states have prioritized water resource management and sustainability. In southern Georgia, water sustainability issues within the Dougherty Plain Province of the United States Coastal Plain (Figure 16) has led to the emergence of surface water-groundwater interactions and resource availability prediction as important topics in contemporary water research in the region. In January 2008, the Georgia Comprehensive State-wide Water Management Plan was conceived, which divided the state into ten regions for development of individual Regional Water Plans to strategize water resources and sustainability through 2050 using economic models. One of these regions is the Lower Flint-Ochlockonee (LFO) in southwest Georgia, which includes portions of the Chattahoochee, Flint, Ochlockonee, and Suwannee river basins of the southeastern United States (GWPCC, 2017), and overlaps with most of the Dougherty Plain. The region is utilized heavily for row crop agriculture and pasture, which rely on irrigation from surface water and groundwater of the Upper Floridan Aquifer (UFA) that underlies the region. As of 2010, the total estimated water usage was 2,505,670 m$^3$, 66% of which was groundwater (1,642,690 m$^3$). Of that 1,642,690 m$^3$, 1,400,450 m$^3$ (86%) was attributed to agricultural use. Estimated withdrawal from the UFA in 2015 was 1,710,820 m$^3$, which exceeds the estimated sustainable yield of 897,045-1,241,480 m$^3$. Projections for 2050 increased the demand to 1,994,695 m$^3$ to the same sustainable yield.
Figure 16. Left: Georgia, USA with locations of the ACF Basin (blue), Dougherty Plain (Green) and the Jones Center at Ichauway (Purple). Right: The Jones Center at Ichauway (purple boundary) surrounded by the Flint River and center-pivot irrigated agricultural fields.

The Apalachicola-Chattahoochee-Flint (ACF) River Basin overlaps with the Lower Flint Ochlockonee Basin in the southeastern United States. Disputes over water resources in the ACF have persisted for more than four decades (Ruhl, 2005), and agricultural demand is increasing (Fanning and Trent, 2009; Martin et al., 2013). Adverse effects of over extraction have already been observed in surface streams with diminished baseflow and longer periods of low-flows and no-flows, leading to hypoxic conditions that are detrimental to aquatic life (Golladay and Battle, 2002; Golladay et al., 2004; Hicks and Golladay, 2006; Rugel et al., 2012; Singh et al., 2016). Considerable research has focused on reducing water demands while simultaneously maintaining, or even improving, crop yields, and these practices have been implemented widely (Vellidis et al.,
Numerical Modeling for Improved Sustainability

Numerical groundwater models have been useful in predicting changes in water budgets due to over-extraction and climate change (Alam et al., 2019; Ghazavi and Ebrahimi, 2018). While numerical models have been developed that address the non-laminar flow encountered in karstic aquifers (Shoemaker et al., 2008), describing the subsurface heterogeneities has been proven difficult (Hartmann et al., 2014) as such models require knowledge of the properties of the aquifer at the scale of the discretization. Thus, measurements of karstic features, such as conduits that serve as preferential flowpaths and the irregularity of the epikarstic surface are necessary for characterization of the aquifers and for optimal performance of the numerical models (Hartmann et al., 2014). The limitation is not in development of the numerical and discretized models (Shoemaker et al., 2008), but in our ability to characterize the physical and geometric properties of the subsurface (Borghi et al., 2016). Previous researchers have used oversimplification of conduits as straight pipes embedded within an impermeable bedrock (Peterson and Wicks, 2006) or as high-permeability zones embedded within a porous matrix (Wicks and Herman, 1995) in an attempt to compensate for the lack of data at the scale of the discretization of the numerical model (Hartmann et al., 2014). More recent research has focused on efforts to constrain the ranges of parameters associated with conduits in karst regions (Berglund et al., 2020).

Several modeling studies have focused on water resource conservation in the Dougherty Plain and ACF Basin region under various combinations of irrigation, drought, and projected future consumption. Torak and Painter (2006) completed a geohydrologic study of the lower ACF basin and developed a conceptual model of the system that served as a basis in subsequent conceptual models (Jones et al., 2017; Jones and Torak, 2006; Karki et al., 2021). The conceptual
model includes three layers: the upper semi-confining unit (USCU), the UFA, and the lower confining unit; and included stream-aquifer exchange, irrigation, and other inflows and outflows (Jones and Torak, 2006). Mitra et al. (2016) used the Jones and Torak (2006) model to simulate the 2010-2012 drought with irrigation, Singh et al. (2017) evaluated surface streams and tributaries that were affected by irrigation, as well as applying water sustainability scenarios. Jones et al. (2017) determined that groundwater discharge to wetlands and minor and ephemeral streams was unknown, and that the horizontal hydraulic conductivity of the UFA was a sensitive parameter for predicting discharge to surface waters and model boundaries. Karki et al. (2021) evaluated the impacts of increased irrigation by simulating the scenario identified by the LFO RWP (GWPCC, 2017). They developed a Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012; Srinivasan et al., 1998) model and used the recharge estimates as a specified flux into a two-layered (USCU and UFA) MODFLOW (Harbaugh, 2005) model. The USCU was divided into geohydrologic zones identified by (Torak and Painter, 2006). Their results indicated upland interstream karst was the most sensitive recharge zone to irrigation, which comprises a strong portion of the Lower ACF basin, and roughly half of Baker County, GA. Other sensitive geohydrologic zones included upland instream, interstream karst swamp, and instream karst, all of which are present in Baker County GA as well. Large groundwater level reduction was predicted where the aquifer is thin and close to the land surface, including the Ichawaynochaway Creek watershed. Ongoing modeling efforts in the basin, such as (Barrie et al., 2022) have focused on characterization of small-scale features to inform both local and larger, regional-scale models. Such a model could be used to inform decisions related to forest management and restoration (Brantley et al., 2018).

Because irrigation is expected to increase by mid-century, there is an immediate need to
refine the numerical models of the coupled groundwater-surface water systems, requiring characterization of the subsurface in the UFA and a better understand the groundwater-surface water interactions that link recharge areas to discharge areas (Torak and Painter, 2006). Being able to visualize the spatial distribution of the sediments and karstic features would provide insight into locations of recharge features and thus, groundwater-surface water interactions. Being able to quantify the thickness of sediments (without an intensive coring effort), the irregularly of the epikarstic surface, and location and size of subsurface conduits and recharge features would lead to better constrained numerical models. However, because the Dougherty Plain is approximately 7000-km², there is a need to focus on features that are common, such as draws and geographically-isolated wetlands (GIWs). Thus, the goal of this study was to characterize two draws and a sequence of GIWs that can be used as a template for analogous features on the Dougherty Plain.

Study Area

The 7,000-km² Dougherty Plain (Martin et al., 2013a) of southwestern Georgia is a covered karst region within the Dougherty Plain of the southeastern U.S. Coastal Plain (Figure 16). The Dougherty Plain is part of the greater ACF Basin. This region of Georgia is home to 322,463 people (2010) (Martin et al., 2013a) who use groundwater as a source of domestic water and as a source for irrigating crop lands (Martin et al., 2012; Rugel et al., 2012). The Dougherty Plain is also littered with hundreds of geographically isolated wetlands that are host to unique ecosystems (Cohen et al., 2016; Kirkman et al., 2012) and protecting that ecological diversity and wetland density is important.

The unconsolidated cover consists of white sand and reddish clay, between 0-30 meters (0-100 feet) thick, overlying the Ocala Limestone (Beck, 1986). The karstic Ocala Limestone is the groundwater reservoir (artesian in many locations) that is the primary aquifer (upper Floridian
Aquifer) of the region (Fanning and Trent, 2009). Groundwater recharge to the UFA has been presumed to be from infiltration of precipitation through the mantle material and through subsurface flowpaths associated with sinkholes and fracture systems (Torak and Painter, 2006).

The study area is the Jones Center at Ichauway, a 117 km² (29,000-acre) property in Baker County, Georgia, (Figure 16) owned by the Robert W. Woodruff Foundation, managed for ecological and conservation research and education, that is situated within the Dougherty Plain. A recent focus of the Jones Center’s water program has been on improving the understanding of the region’s hydrology and connection to the UFA, with the goal of developing optimal sustainability practices for both human consumption and ecological needs. Because of the relatively undisturbed, natural setting, the Jones Center is an ideal study area to investigate groundwater-surface water interactions that link recharge features to discharge features. Specifically, a series of GIWs at the Jones Center and surrounding properties, two draws, a new (2020 collapse) sinkhole, a cluster of sinkholes, and the “Historic Circle” were the subject of this study. For the GIW sequence on the Jones Center property, George Sand Pond, Richardson Flat, and Balden Pond were included, along with Sea Pond and an unnamed pond immediately adjacent to the Jones Center boundary to the east (Figure 17).

The Jones Center is surrounded by central pivot irrigation (Figure 16). Numerous karst collapse features are present at the surface and beneath the cover at the Jones Center and throughout the surrounding landscape. As is typical of covered karst settings, the surface recharge features are connected to discharge features by an unknown network of solution-enlarged fractures and conduits.
Methods

Historical Imagery

A review of historical aerial photographs, maps, topographic maps, and satellite images was completed to assess the history of the GIWs. The years of these images include 1937, 1941, 1948, 1953, 1975, 1993, 1999, 2002, 2006, 2011, and 2018. In each image, wetlands were examined for the degree of ponding, change in size, addition or filling of sinkholes, and if any surface connection to other ponds occurred.

Ground-Penetrating Radar (GPR)

Ground-penetrating radar (GPR) is a surface geophysical technique for high-resolution visualization, and thus characterization, of soil and stratigraphic units (Davis and Annan, 1989; Samouëlian et al., 2005). In karstic regions, GPR has proven useful to map the depth to bedrock (the depth to top of epikarst), the depth and geometry of sinkholes, and other dissolution features (Carpenter and Ekberg, 2006; Chalikakis et al., 2011; Evans et al., 1994; Kruse, 2014; Kruse et al., 2006; Rodriguez et al., 2014; Vadillo et al., 2012; Van Schoor, 2002). However, the regions examined in these studies did not include sites similar to the covered karst terrain of the Dougherty Plain, within which the signature of collapse and conduit features may appear differently in geophysical datasets. Thus, more information is needed for understanding the in-filling of sinkholes and conduits, as well as their location and lateral continuity through the mantled karst landscape (Honings et al., 2022).

Selection of Target Areas for Investigation

Previously, Brook and Allison (1986) mapped fractures within the Dougherty Plain and (Rugel et al., 2019) identified similar fractures in stream bank outcrops of Ichawaynochaway Creek, which flows southward through the Jones Center. Since dissolution is favored along pre-
existing fractures in karst terrains (Palmer, 1991; White, 1988), it is hypothesized that preferential subsurface flow paths (solution-enlarged fractures and conduits) would develop along these patterns within the Jones Center and greater Dougherty Plain.

Aerial photography and 1-meter resolution digital terrain models (DTMs) created from light detection and ranging (LIDAR) datasets of the Jones Center were visualized within an ArcGIS interface (Network, 2022). The Jones Center terrain was examined for patterns in topography that resembled the dominant northeast-southwest and northwest-southeast trends described in the literature, which included depressions, sinkholes, lineaments, or drainage patterns that could represent a surface expression of the karstic deformation in the subsurface. Because the Jones Center is densely-forested, LIDAR imagery provided evidence of features that are otherwise concealed by vegetation in normal aerial imagery.

**Geographically Isolated Wetlands**

A sequence of ponds and sinkholes within those ponds was identified extending several kilometers in a northeast-southwest manner from the George Sand Pond in the west, through Richardson Flat, Balden Pond, Sea Pond, and several unnamed ponds in a sequence eastward (Figure 17). A total of 11 GPR surveys were completed for this study. Nine (9) of the surveys were completed as a small grid over a gauged depression in the southwest corner of Richardson Flat in April of 2017, pictured in Figure 18. Two additional surveys, one through the middle of Richardson Flat and one along a road between Richardson Flat and Balden Pond, were completed in June of 2019. A north-south survey orientation was chosen to cross the hypothesized continuation of the fracture trend in the subsurface.
Figure 17. The George Sand Pond-Richardson Flat-Balden Pond-Sea Pond GIW sequence (West to East), with selected GPR survey lines.
Figure 18. Looking southeast at the gauged depression in the southwest corner of Richardson Flat. A small grid survey was completed in the depression in Spring 2017.

Additionally, a complex of sinkholes was identified in the LiDAR DTM, then field-verified in an area with sandy soils and minimal vegetative cover. The sinkholes are approximately 2.5 meters deep (Figure 19). GPR surveys were completed around the edges and within the sinkholes (Figure 20) in an attempt to interpret their geometry and connection.
Figure 19. GPR unit within the approximately 2.5-meter deep sinkhole complex.

Figure 20. 1-meter LIDAR DTM with location of the compound sinkholes and GPR survey lines.
**Draws**

The Natural Resource Conservation Service (NRCS) defines a “draw” as “a small, natural watercourse cut in unconsolidated materials, generally more open with a broader floor and more gently sloping than an arroyo, ravine, or gulch, and whose present stream channel may appear inadequate to have cut the drainageway that it currently occupies.”

The first draw is located west of Ichawaynochaway Creek (Figure 22) where a linear pattern of sinkholes matches the orientation of a prominent regional fracture described by (Brook and Allison, 1986; Rugel et al., 2019). This location is within a paleo-channel of Ichawaynochaway Creek, and only contains water during flood conditions. There are no steep sides, and the surface is sandy and vegetated (Figure 21). South of the feature is a series of sand deposits related to other paleo-positions of the creek. Immediately northwest of the feature is a gently-sloping bluff (greenish color in Figure 22) that contains cobble- to boulder-sized clasts of Ocala Limestone and chert as float or embedded in the soil. It is assumed that Ocala Limestone is in-place beneath the soil cover. The approximate length of the draw is 850 meters.
Figure 21. Looking northeast and up-valley, near sinkholes within the draw feature near Ichawaynochaway Creek.
Figure 22. One-meter resolution LiDAR DTM with GPR surveys collected in the draw containing the lineament of sinkholes.

The second draw feature is a depressional pattern, colloquially referred to as the “Lark Drain,” that continues southwest from an agricultural field immediately east of the property, westward through the property, and into the east bank of Ichawaynochaway Creek (Figure 23). The depression is inconspicuous in the field and in most aerial imagery, but is evident in the 2019 LiDAR DTM. There is no evidence of this depression serving as a surficial water body, and it is heavily vegetated along the length of the feature. The land surrounding the length of the feature is gently sloping at the head, and mostly flat near the convergence with Ichawaynochaway Creek.
Isolated Sinkholes

The Historic Circle at the Jones Center is situated upon a bluff on the west side of Ichawaynochaway Creek (Figure 24). Cherty Ocala Limestone outcrops in spots in this area, indicating that the bedrock surface is shallow. In the southern portion of the Historic Circle, there is a depressional feature that resembles a sinkhole. Some equipment and structures occupy portions of the depression. GPR surveys were completed to provide coverage of the Historic Circle and understand the nature of the bedrock surface (Figure 24).
In October 2020, a sinkhole collapsed beneath a fire break road along the north side of Highway 200 (Figure 25). The sinkhole is not discernable in the 2021 LiDAR DTM. The measurements from October 2020 indicate that it is approximately 2.75 meters deep, and 2.2 meters wide along its longest axis, oriented northeast-southwest (Figure 26). GPR surveys (Figure 27) were completed as close as possible to the sinkhole. A fallen tree prevented surveys along the north side of the sinkhole.
Figure 25. Location of sinkhole along Highway 200 that collapsed in Fall of 2020.
Figure 26. Looking southwest towards sinkhole that collapsed in October 2020 along the fire-break road north of Highway 200. Image: J Honings.

Figure 27. Sketch of GPR survey locations (black lines) relative to the sinkhole (gray circle) along Highway 200.
**Geophysical Data Collection**

Ground-penetrating radar (GPR) survey lines were oriented perpendicular to the hypothesized karst feature locations based on the patterns described in the literature and observed in topography from the aerial imagery datasets. Parallel transects were completed in an attempt to determine the spatial continuity and overall connectivity of the subsurface feature in the resultant datasets. GPR survey deployment utilized a push cart-mounted common offset with 100 MHz antenna and 1-meter spacing. Measurements were taken at 0.25-meter steps along the traverse as the equipment was pushed forward. Survey locations were limited due to heavy brush, thick surficial sand deposits, and ponding. GPR survey data were examined as cross-sections, and reflections were interpreted as geologic horizons and karst features. Access to ponds off-property was not available.

The picking of lithologies was guided by background information obtained from nearby well logs and local geologic publications. Water content strongly controls GPR signal propagation in the subsurface (Davis and Annan, 1989). Therefore, if the water table was at higher elevation than a karst feature, the signal attenuation may not have revealed the deeper karst feature in the GPR imagery for interpretation. Each cross section was analyzed for the presence and thickness of the soil horizon, coherent Ocala Limestone, vuggy limestone, and karst features. The dimensions of interpreted vuggy zones and cavities were measured in metric units.

**Results & Interpretation**

**Historical Imagery**

The earliest imagery available from the Jones Center archives is the 1936 map that shows one large lake connected to a smaller body of water to the east and disconnected from a linear feature to the west (Figure 28). By 1948, the linear feature appears to be filling in and the large
and small bodies are disconnected. By 1993, the linear feature is forested and there is evidence of center-pivot irrigation to the southeastern boundary. The 2011 false-color image shows vegetation growth and clear evidence of the center-pivot irrigation to the southeast (Figure 28).

Figure 28. (Top) 1936 map indicating surficial connection between Richardson Flat and Balden Pond; (Bottom) False-color IR image of the GIW sequence from 2006.

**Ground-Penetrating Radar**

The GPR cross sections that follow are normalized to depth instead of topography due to error in the elevation measurements by the GPS unit. The top of the soil is denoted by the color green, and was interpreted as beginning at the bottom of the direct surface wave reflections from the GPR instrument, and therefore as a depth of “zero.” The light blue color denotes the top of an interface interpreted as the epikarst or a strongly vuggy zone in the Ocala Limestone. Purple denotes what is interpreted as the top of coherent Ocala Limestone. Individual cavities or karst
features of interest are denoted with the color yellow.

**Geographically Isolated Wetlands**

For the survey completed along the main road dividing Richardson Flat and Balden pond (Figure 29), four (4) zones of interest were interpreted in the cross-section. Zones 1 and 2 in Figure 15 are both approximately 50m wide, Zone 3 is approximately 135m wide, and Zone 4 approximately 105m wide. Zones 1, 2, and 4 contain strong point reflectors, which are interpreted as dry, high-porosity zones within the limestone. Zone 1 is approximately 3.5m thick while Zones 2 and 4 are around 7m thick. The point reflectors in Zone 3 are subdued, which is attributed to the presence of water causing attenuation of the GPR signal at depth. This zone is approximately 5.5m at its thickest, but the signal noticeably fades at a depth shallower than the other 3 zones. The location of Zone 3 aligns with the lowest elevations in both Balden Pond to the east and Richardson Flat to the West, and this alignment matches a dominant fracture orientation identified in the literature. All zones identified in the cross section should be viewed as karstic zones, with Zone 3 serving as the primary flow path.
Figure 29. GPR survey along the main road between Richardson Flat and Balden Pond, oriented North-South from left-to-right. Zones 1, 2, & 4 (purple) and 3 (yellow) are discussed in the text. A metal object on the surface was encountered near the 300m position of the survey.

The survey oriented north-south across the middle of Richardson Flat did not reveal any features, attributed to attenuation of the signal due to saturated clay cover (Figure 30). The surveys within the gauged pond at the lowest elevation within Richardson Flat also revealed reflections that confirmed the presence of a sinkhole feature. These reflections (Figure 31 and Figure 32) extend to a depth of approximately 5.5 meters below the ground surface. The depth slices allowed 3D visualization of the higher porosity zone that is truncated by the depth of penetration, and a representative image is included as Figure 33. The lateral continuity of reflectors is constrained due to clay content in the soils in Richardson Flat.
Figure 30. Survey oriented north-south across the middle of Richardson Flat. There are few reflections attributed to the thick clay soil cover.

Figure 31. GPR survey within the depression in the southwest corner of Richardson Flat, oriented west-to-east from left-to-right. A funnel shape is present in the right side of the image.
Figure 32. GPR survey within the depression in the southwest corner of Richardson Flat, oriented north-to-south from left-to-right. A funnel shape is present in the right side of the image.

The true elevations relative to mean sea level of Zone 3 from the road survey, the sinkhole bottom from the Richardson Flat gauged pond, and the base level of the Ichawaynochaway Creek stream bed reveal a likely connection in the subsurface (Figure 34). Because these ponds are aligned in a manner matching a prominent fracture orientation in the region, and speleogenesis is enhanced at pre-existing openings in carbonate bedrock, it can be determined that subsurface connection between the sequence of ponds and Ichawaynochaway Creek exists through karstic flow paths. The flow path may occupy a main channel along the main fracture, such as Zone 3, but the entire pathway itself could meander over several hundreds of meters, as evidenced by zones 1, 2, and 4. It is possible that Zones 1, 2, and 4 are additional flow paths originating from different or intersecting fractures than that of Zone 3.

Because these karstic zones and their surficial expressions as ponds are hundreds of meters wide as a group, and connection exists in the subsurface, the GIW sequence should now be viewed more as a uvala karst feature.
Figure 33. Depth slice between 3-3.5 meters below ground surface within the gaged pond in the southwest corner of Richardson Flat. The red, yellow, and light blue colors coincide with the higher velocity, and therefore higher porosity, sediments within the sinkhole funnel.

In the aerial and LIDAR imagery, the GIWs and the lowest elevation points within them aligned similar to the dominant northeast-southwest fracture orientation. A total of eleven GPR surveys were completed within the GIW sequence. Nine (9) of the surveys were completed as a small grid over a gauged depression in the southwest corner of Richardson Flat. Two additional surveys were completed, one through the middle of Richardson Flat, and one along a road dividing Richardson Flat and Balden Pond to the east.
The survey across the main road dividing Richardson Flat and Balden Pond revealed a zone of relatively faint point reflectors aligned with the lowest elevation points of both wetlands. It is possible that these reflectors are subdued due to water saturation. This is interpreted as another zone of concentrated vugs in the epikarst. The zone begins approximately 1.5m deep and continues until the signal is attenuated at 8m depth, for a thickness of approximately 6.5m. The width of the zone is about 150m. There are additional zones of stronger point reflectors adjacent to the interpreted vuggy zone, which are possible channel-fill sands.

The transect completed across the middle of Richardson Flat did not reveal much of the subsurface due to attenuation by the saturated, clayey sediments. Further to the west, the small grid survey within the gauged depression revealed point reflectors that resemble a sinkhole funnel. These reflectors reach a depth of approximately 5.5 meters below the ground surface.

For both locations, the true elevation of the point reflectors along the fracture orientation continue to the elevation of the Ichawaynochaway Creek stream bed. Attenuation of the waves in the subsurface due to water content has truncated the features and what may lie deeper. However,
the true elevations of the features can be described as the main fracture, and likely a subsurface karst conduit, extending through the wetland sequence until it reaches Ichawaynochaway Creek. The GIW sequence should now be viewed as a uvala feature due to nested sinkholes within these ponds, and their subsurface connection through a several-kilometer landscape.

The sinkhole complex surveys (Figure 20 above) were depth-corrected using the velocity of dry sand, 0.150 m/ns. The GPR imagery revealed a thick surficial sand deposit between 6-8 meters thick. This surface was truncated by a planar reflector, beneath which reflections were typically point reflectors. This was determined as the bedrock surface, and the reflectors present in this zone were interpreted as vuggy limestone. Figure 35 below is the survey line that best represents the typical survey from the group. The additional surveys are included in the appendices.

![GPR survey along the western perimeter of the sinkhole complex, oriented north-south from left-to-right. The green line is the top of the soil, and the purple line indicates the interpreted bedrock surface. Point reflectors beneath this surface are vuggy Ocala Limestone.](image)

**Figure 35.**

**Draws**

For the hypothesized preferential subsurface flow path, located within the slough containing the lineament of sinkholes matching the fracture orientation described by (Brook and Allison, 1986; Rugel et al., 2019), a total of 23 cross sections were interpreted. Each cross section
was assigned a name in which the first letter corresponded to the position in the valley, with “A” serving as the southwestern-most survey, and “W” as the survey nearest to Ichawaynochaway Creek. Depth slices along the entire draw were generated for 3D visualization of the reflections with depth. These images depict the presence of the vuggy to cavernous depths along the draw and are included as Figure 36 and Figure 37. Representative GPR lines from certain positions in the draw are included in Figure 38 through Figure 42. Average depth of penetration was 7.2 meters. The average top of epikarst was 2.3 meters below the ground surface, and was 3.5 meters thick. The typical depth to the top of coherent Ocala Limestone bedrock, when imaged, was 4.4 meters. Cavities were determined to exist in six of the surveys, and excluding the Creekside survey, were 4.8 meters wide by 3 meters tall. The Creekside survey (Figure 42) revealed much larger cavities, which was expected due to visible fissures in the stream outcrops of Ocala Limestone. The vuggy karst zone was on average 14 m wide and 4 m thick.
Figure 36. Depth slices at 3-3.5 meters below ground surface along the draw. The red, yellow, and light blue reflectors coincide with the higher porosity zones interpreted in the GPR imagery.
Figure 37. Depth slices at 4-4.5 meters below ground surface along the draw. The red, yellow, and light blue reflectors coincide with the higher porosity zones interpreted in the GPR imagery.
Figure 38. Transect “B,” oriented west-east from left-to-right, with a total horizontal length of 40 meters. The yellow box denotes an interpreted cavity yet to collapse, and is approximately 9 meters wide, and 3.5 meters tall.

Figure 39. Transect “I,” oriented NW-SE from left-to-right, with a total horizontal length of 34 meters. The yellow shape denotes an interpreted vuggy zone approximately 17 meters wide, and 4 meters tall.
Figure 40. Transect “L,” oriented NW-SE from left-to-right, with a total horizontal length of 31 meters. The yellow box denotes an interpreted cavity approximately 2.5 meters wide and 6 meters tall.

Figure 41. Transect “S,” oriented north-south from left-to-right, with a total horizontal length of 25 meters. The yellow bracket denotes vuggy zone at least 13 meters wide and 5 meters tall, but is truncated by the boundaries of the cross section.
Figure 42. Transect “W (Creekside),” oriented north-south from left-to-right, with a total horizontal length of 66 meters, and was surveyed on a road that runs perpendicular to the west bank of Ichawaynochaway Creek. The yellow boxes denote cavities in the limestone.

Figure 43. Looking west at the approximate survey location of the Creekside survey (preceding figure). Yellow boxes denote areas that appear to be enhanced fissures continuing into the bank. These fissures align with the structures discussed in the literature.

Three (3) survey lines were collected perpendicular to the Larke Drain, which extends hundreds of meters from Ichawaynochaway Creek (Figure 23), but does not contain flowing water or exhibit evidence of being a surficial flow path. This feature was identified with the aid of aerial photography and the 1-meter resolution DTM from LiDAR data. For the Larke Drain draw,
average depth of penetration was 7.2 meters. The average top of epikarst was 2.3 meters below the ground surface, and was 3.5 meters thick. The typical depth to the top of coherent Ocala Limestone bedrock, when imaged, was 4.4 meters. Cavities were determined to exist in six of the surveys, and excluding the Creekside survey, were 4.8 meters wide by 3 meters tall. The Creekside survey revealed much larger cavities, which was expected due to visible fissures in the stream outcrops of Ocala Limestone. The vuggy karst zone was on average 14 m wide and 4 m thick.

Figure 44. Eastern survey of the "Larke Drain," oriented south-north from left-to-right, approximately 1,050 meters long, penetrating to a depth of 15 meters. The yellow boxes denote cavernous zones in the subsurface, directly beneath the surface express.
Figure 45. Middle survey of the "Lark Drain," oriented south-north from left-to-right, approximately 420 meters long. The yellow box denotes a strong concentration of vugs and likely cavities in the subsurface, directly beneath the surface expression of the feature.

Figure 46. West survey of the "Lark Drain," oriented south-north from left-to-right, approximately 870 meters long. The yellow boxes denote several zones of concentrated vugs and likely cavities in the subsurface. These zones are approximately 7 meters tall.

**Isolated Sinkholes**

Seventeen (17) lines were collected in the Historic Circle. Most of the surveys depicted a shallow depth to the epikarst, which was expected due to cherty outcroppings of the Ocala Limestone. In the southwest corner of the Historic Circle, the topography depresses, which
suggests the presence of a sinkhole. A survey was completed within this depression and is included as Figure 47 below. A vuggy zone is interpreted within the subsurface of the feature.

Figure 47. GPR line from the Historic Circle, oriented north-south from left-to-right. The north end of the survey is underlain by sands, and transitions to clay deposits overlying vuggy Ocala Limestone.

Nine (9) lines were collected adjacent to the sinkhole along Highway 200. A continuation of the cavity is visible in surveys that crossed the trajectory of the fracture system to the southwest of the sinkhole. An example of this is included as Figure 48 below.

Figure 48. GPR line from the Highway 200 Sinkhole. The pink box outlines the zone of the fracture trajectory from the existing cavity. The continuation of the cavity is visible in the upper 5 meters depth of the survey.
Discussion

Previously, the working conceptual model for numerical groundwater models in the Dougherty Plain consisted of a two-layer approach, unconsolidated sediments overlying the Ocala Limestone formation. The integration of ground-penetrating radar (GPR) surveys informed by aerial photography and 1-meter resolution LIDAR data has allowed for the identification of concealed karstic flow paths in the region. Patterns in surface topography and karst features that matched the alignment of a prominent fracture system in the region served as initial clues for exploring the location of subsurface flow paths.

Characterization of cross-sectional GPR data within two draws of differing scales revealed connection beneath the land surface that is not otherwise manifested as an active surface water flow path. The paleo stream valley draw containing the sinkhole lineament and the larger-scale “Larke Drain” have a strong lateral connection in the subsurface by means of touching-vug porosity, and in some instances, cavities. The vuggy zones can be as wide as tens of meters in the smaller feature, to hundreds of meters wide at the Larke Drain scale. The sinkholes, surface depressions, and other depressional features yet to collapse can be viewed as funnels to the subsurface flow paths. These features may be used as analogs to similar topographic patterns identified using the LIDAR and aerial imagery reconnaissance approach.

The physical conceptual model for analogous topographic patterns is now refined using the dimensions interpreted from the GPR data. The new conceptual model for smaller draw features should include a soil and unconsolidated sediments layer that is approximately 2.5m thick. The underlying epikarst layer should be approximately 6.5-7m thick with a concentrated vuggy zone and at least 10m wide. Sinkhole funnel shapes and cavities should be constrained to the thickness of the epikarst, and slightly shorter in width than the entirety of the vuggy zone, and should truncate
the epikarst. For the larger draw features, the soil thickness should remain at approximately 2.5m and a 7.5m thick epikarst. The entire width of the vuggy zone should be around 400 meters, and 5 meters thick or until truncated by the bottom of the conceptual model. Cavities and sinkholes could be omitted from the conceptual model due to the prominence of the touching-vug megaporosity zone that is several hundred meters wide throughout the length of the feature.

Figure 49. 3D diagram depicting the Balden Pond-Richardson Flat wetland sequence as a karst uvala. The purple line indicates the boundaries of the conceptualized uvala. The orange dashed lines are traces of the fracture system documented in the region.

The insights gained on the existence of subsurface flow paths within draws can be applied to make new assumptions regarding the connectivity of other landscapes. Throughout the Jones Center and Dougherty Plain, there are several sequences of geographically-isolated wetlands (GIWs) that align along the dominant fracture orientations described in the literature and observed in the geophysical data. Although there are no visible surficial flow paths between these ponds, it can now be assumed that there is subsurface connectivity existing through karstic vuggy zones and sometimes conduits. Although these wetlands are traditionally viewed as spill-and-fill features, perhaps they should be considered as perched water tables in which lateral movement from the
clayey catchment would ultimately percolate to the aquifer via sinkhole funnels or a highly-vuggy epikarst. Ultimately, these features connect to the surface streams such as Ichawaynochaway Creek and Big Cypress Creek at the Jones Center, and analogous streams outside of the Property. Future studies should address other landforms in order to confirm the existence of these subsurface flow paths.

The application of GPR and interpretation of the data have revealed flow paths at the meter- and kilometer-scale within the Jones Center at Ichauway, which can be analogous to features observed throughout the Dougherty Plain. GPR has proven effective within these landforms, although there are limitations of the equipment related to mobility and attenuation due to water content of the subsurface. Future studies could refine what the GPR has revealed by use of electrical resistivity tomography (ERT), seismic, or other geophysical methods. Survey design should be guided by landscape context clues interpreted from aerial and LIDAR imagery.

Preferential subsurface flow paths have been identified along a noticeable and consistent topographic pattern across the Dougherty Plain. These clues should guide the implementation of newer, high-efficiency center-pivot irrigation systems throughout the region. Land management and conservation efforts should prioritize these features as a direct connection to the subsurface UFA.

The historical aerial photographs and maps indicate that the individual ponds are filled with water at different times. Balden Pond and Sea Pond are holding water more often than Richardson Flat. 1948 shows that it is one large pond, everything is full of water. The rest of the land surface is not submerged. Perhaps all water in the region moved into these ponds, the large flowpath. The surface can be connected at times, especially in saturated conditions, but is less likely now that irrigation is prominent since 1970s. If these wetlands have spill-and-fill behavior, it would be
under 2 main conditions: 1) The clay lense within the depression has caused ponding of surface water such that water exceeds the lip of the pond and flows laterally, and 2) the aquifer stage rises, thus filling the ponds even more. In the first scenario, this would be returning water to the aquifer that was “pirated” by a confining clay layer, assuming that the lateral movement of water was followed by percolation through materials that facilitated vertical movement. Because the vertical movement to the aquifer would occur once removed from clay, this would reach

The lowest points are sinkholes and therefore funnels into the subsurface. Subsurface reflections reveal that the funnel extends to the base level or streambed elevation of Ichawaynochaway Creek. They are the same elevation relative to sea level. This means that whatever water seeps through the clay lense of the wetland will reach a higher-vertical K zone which is part of the overall flow path. The clay lense could be “broken” at the funnel point, as that is where material will be falling into the larger cavity below the sinkhole. The reflectors beneath the main road transect within the horizontal space that aligns with the lowest depressions in each pond are visible, but faint compared to what has been interpreted as a channel fill sand on top of the epikarst. The fact that these numerous point reflectors are faint could mean that the feature contained water at the time of the survey in Summer 2019. This would support the interpretation that the subsurface flow paths aren’t a conceptual straight line, but a zone about as wide as the ponds are. The “main channel” is a higher porosity zone that would align with the lowest points of the sinkholes. There could be more than one main channel. Main channel is “highest K” with vuggy / epikarst zone surrounding it. We could argue that the series of ponds in this study are parts of a larger uvala feature (White, 1988), or sinkholes nested in a much larger sinkhole. The scale of the feature is “large scale” (Ford) as opposed to the prior conceptual model that these were stand-alone sinkholes.
The clay is a vertical aquitard. The fill-and-spill flow to other ponds would only occur in saturated conditions, and if it moves water horizontally out of pond, that could facilitate percolation to the aquifer. Saturated conditions would also mean that the aquifer could be high and mix with wetlands water. If the GIWs are a clay lense that pinches out, the lateral flow of a perched water table could eventually reach deeper aquifer if it reaches a unit that facilitates the percolation, such as the pure and vuggy Ocala Limestone. Dolomitized areas may not have the same behavior.

A clay bottom of the GIW is produced by chemical weathering of the carbonate bedrock substrate, and through accumulation of clayey sediments and organic matter at the bottom of the pond. The ponding is a result of a perched water table atop the clayey bottom sediments, and movement of surficial water is through evapotranspiration or lateral flow when volume exceeds the basin during saturated conditions.
CHAPTER 5. FIELD GUIDE TO THE GEOLOGY AND GEOMORPHOLOGY OF THE JONES CENTER AT ICHAUWAY

Introduction

A century ago, Robert W. Woodruff, chairman of The Coca-Cola Company, sought solitude quail hunting within the longleaf pine and wiregrasses of the Dougherty Plain in southwestern Georgia, and established Ichauway as his own hunting reserve. Woodruff was an outdoorsman who appreciated the variety of ecosystems of the property, and maintained the landscapes throughout his ownership. Following his death, the Robert W. Woodruff Foundation established what is now known as the Jones Center at Ichauway, devoted to ecological research, natural resource management, and conservation to continue his vision.

The Jones Center at Ichauway (Ichauway) is 29,000 acres of forests, wetlands, shrubs, and streams, all of which are natural and maintained. It is home to over 1,100 vascular plant species and over 370 vertebrate species. Several ponds, wetlands, and Ichawaynochaway Creek host a variety of aquatic ecosystems. Ichawaynochaway Creek flows southward through Ichauway for 13 miles before its confluence with the Flint River, which is part of the greater Apalachicola-Chattahoochee-Flint (ACF) River Basin.

Disputes have persisted for nearly four decades over water resources in the ACF Basin, where agricultural extraction of groundwater from the Upper Floridan Aquifer (UFA) (Hicks et al., 1987) causes water shortages (Brantley et al., 2018), shifts from perennial to intermittent streamflow, and prolonged low-flow and no-flow durations in surface streams (Brantley et al., 2018; Gordon et al., 2012). These changes have adversely impacted both natural and human systems that depend on that streamflow (Peters et al., 2008; Ruhl, 2005; Tetzlaff et al., 2007; Winter, 1999). If the rate of groundwater recharge equals the rate of groundwater extraction, then
aquifer sustainability can be ensured. However, within the ACF Basin, groundwater extraction is expected to increase from 3.9 million m$^3$/day (1,030 mgd) in 2020 to 4.3 million m$^3$/day (1,136 mgd) by 2050 (2017a; 2017b). Current estimated extraction (2015) of the UFA in the Dougherty Plain is 1.7 million m$^3$/day, which exceeds the 0.9-1.2 million m$^3$/day (237-328 mgd) estimated sustainable yield range of the aquifer (GWPCC, 2017). With the expected increase in agricultural demand, there is an increased need to understand the groundwater-surface water interactions that link recharge areas to discharge areas (Torak and Painter, 2006).

Recently, researchers have pinpointed areas thought to be locations of focused recharge (hot spots) to the UFA and hope to use this knowledge to inform decisions related to irrigation management and forest restoration (Barrie, 2019; Qi et al., 2020; Qi et al., 2022). However, validating these hot spots and understanding how they connect to the subsurface flow system is challenging. Identification of preferential flowpaths in the subsurface that link recharge to discharge points could guide the implementation of irrigation and forest restoration programs designed to support the local economy while minimizing the impacts of water use on surface streams and their ecosystems. Conceptualization of these flow paths across the broader region would inform decisions related to land management and groundwater modeling projects tasked with improving sustainability of the aquifer.

To optimize water resource sustainability around Ichauway and on the greater Dougherty Plain, it is important to understand the evolution of the landscape over geologic time, and how that evolution impacts the flow of water. The purpose of this Field Guide is to describe key locations of hydrogeologic interest at Ichauway in which the visible geology is representative of what is common throughout the Dougherty Plain as a whole. Additionally, the description at each location will discuss the importance of the subject landscape to the ACF watershed, and its
function for the movement of water at or below the surface.
Stop 1. The Woodruff House and Historic Circle

Figure 50. Location of Stop 1, indicated by the yellow star. Approximate Coordinates: 31° 14’ 01.1” N, -84° 28’ 04.2” W (31.233645, -84.467841)

Our journey through Ichauway’s history begins at the Historic Circle, in the front lawn of the Woodruff House. Although the buildings around the Historic Circle give a glimpse of about one century into the past, we will venture much further back in time, between approximately 34-56 million years ago, to a far different landscape. There are several outcroppings and boulders of rock within the front lawn and along the bluff that will take us back in time. When taking a closer look at the texture of these boulders and immovable masses of rock, there are visible features such as bivalve shell fossils and holes where fossils have been removed. These shell fragments are remnants of one of Ichauway’s earliest known “native species,” saltwater mollusks. What does finding a fossil of a saltwater organism within a rock in a landlocked terrain mean? The nearest salt water is in the Gulf of Mexico, over 80 miles away from Ichauway.
Preserved within these rocks are a landscape history and several important clues to the evolution of Ichauway through time.

Figure 51. Example of a cherty Ocala Limestone exposure in the Historic Circle. Photo: J Honings.

Figure 52. Cobble-sized piece of cherty Ocala Limestone at Ichauway, with visible bivalve fossils. Photo: J Honings
The bedrock formation nearest to the surface and outcropping at Ichauway is referred to as the Ocala Limestone. Limestone is a rock comprised primarily of the mineral calcite, or calcium carbonate (CaCO\(_3\)). It is typically formed by precipitation from solution or by organisms that utilize it for their shells or skeletal parts. Inorganic precipitation of calcite from solution occurs as travertine in caves or as “tufa.” Organic precipitation environments are reefs or shallow marine environments, as is the case with the Ocala Limestone’s origin. Referring back to the term *Uniformitarianism*, rock outcrops and fossilized mollusks within them are evidence that Ichauway was once part of a shallow marine landscape. Specifically, the environment was a marine platform that extended across most of what is now the Southeastern United States before sea level retreated to its current position. The Ocala Limestone Formation has been dated ranging between 33.9 and 56 million years old, corresponding to the Eocene Epoch (Appendix 3).

Sea level once submerged what is now the continental United States to the extent of the “Fall Line” south of the Appalachian Mountains (Figure 53). As sea level retreated to its modern position, the shoreline shifted with it, moving terrestrial depositional environments such as beaches, swamps, and river deltas seaward (Figure 54; for further reading on this concept, refer to Walther’s Law of Facies). This shift facilitated the shallow burial of the former marine platform by sands and clays, a process that continues today with modern rivers and swamps along the active Gulf of Mexico coastline. Over that approximately 34-million-year period, the platform was cemented and hardened to become the Ocala Limestone we observe today in surface exposures.
Figure 53. The Ocala Limestone is included in the Oligocene and upper Eocene sedimentary rocks, while other shades of yellow and orange indicate rocks that were also deposited during the Cenozoic as sea level gradually retreated. Map Source: Miller (1990).
You may realize that the stone itself is quite hard. Regular limestone and carbonate minerals fizz readily with application of dilute hydrochloric acid (HCl), a concept that will be covered in more detail later. Apply a drop or two of the acid to the surface of the rock. Does it
fizz? Is it a violent fizz, or subdued? In the historic circle and nearby areas such as the skeet shooting range, the Ocala Limestone contains chert nodules, where silica in solution in seawater or groundwater has precipitated within the limestone after deposition. Chert itself is more resistive to both physical and chemical weathering than calcite.

You may notice that these exposures of the Ocala Limestone in the historic circle are mostly boulder-sized and larger, or even in-place as coherent bedrock. The depth-to-bedrock of the Ocala Limestone at the historic circle is very shallow, if not exposed as outcrop. Ground-penetrating radar surveys reveal planar reflectors near the surface. The shallow burial to subaerial exposure (outcropping) of the Ocala Limestone at Ichauway and the Dougherty Plain carries importance in the development of the Upper Floridan Aquifer within the sediments. Since these exposures are as a whole, in-place, we would assume that the gently-dipping formation would continue laterally until a depositional pinch-out, where it becomes thinner to a point in which it vanishes.

Looking to the east, towards Ichawaynocheway Creek, the relatively flat historic circle forms a bluff that transitions into the stream valley of the creek. Ocala Limestone boulders are scattered along the hillside and throughout the pasture. Based on their size and the relative amount of energy needed to move these rock fragments, we can infer that the boulders have not moved very far, and were likely displaced by either rapid water or collapse from stream undercutting at the paleo-position of the Ichawaynocheway Creek.
Stop 2. The Paleo-Course of the Ichawaynochaway Creek

Figure 55. Location of Stop 2, indicated by the yellow star. Stops 3 & 4 are located further east along the road. Approximate Coordinates: 31°14'58.0"N, 84°28'41.2"W (31.249453, -84.478112)
Figure 56. Zoomed view of Stops 2-4 with 1-meter resolution LiDAR as the basemap. The small blue shapes in the center of the image are sinkholes, which visibly align along the prominent fracture orientation.

The route taken from the Historic Circle to where we now stand has traced the boundary between the uplands of Ichauway to the west and the Ichawaynochaway Creek stream valley to the east. Though there is not an active channel visible, the terrain contains several paleo-channels and stream meander cut-offs that once hosted the main channel. Look to the east of the road, and you will see a winding depression that loops around a sandy mound of earth. This is a former meander of Ichawaynochaway Creek that has been abandoned, and the sandy mound is a point bar deposit.

The hydraulic conductivity of sand relative to clay facilitates the vertical movement of water through the soil to the water table. To the west, there is higher clay content in the soil, evidenced by the rusty color. The higher clay content in the upland soils serves as a confining layer to the aquifer, and will limit vertical percolation of rainwater through it. As
Ichawaynochaway Creek incised the landscape both laterally and vertically, these clayey soils were removed, and sandy sediments like the point bar were deposited within the valley. The removal of the low-permeability clay layer for sandy, permeable sediments essentially developed a groundwater recharge hot spot within the floodplain of Ichawaynochaway Creek.

Figure 57. Looking east from the boundary of the Ichauway uplands towards the Ichawaynochaway Creek stream valley. The continuous, bending depression is the paleo-stream channel, and eastward from the depression is a series of point bar sand deposits. Photo: J Honings
Stop 3. The Sandy Sinkholes of the Turkey Woods

The approximate coordinates of this stop are 31°14′57.7″N 84°28′23.7″W (31.249371, -84.473262). As we observed at Stop 1, carbonate minerals (calcite) present in the Ocala Limestone dissolve with application of weak acid. Carbonic acid, also known as acid rain, is formed when carbon dioxide from the atmosphere and soil processes mix with rainwater as it moves through both media. This solution moves vertically through the soil and reaches the water-rock interface (water table), where speleogenesis (dissolution and formation of karst) begins. The global equation for speleogenesis is included below:

\[ \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \]

At the landscape scale, acidic surface and groundwater dissolve the host limestone bedrock to create cavities and enhance existing voids in the rock, developing what is referred to as karst topography. Landscapes with karst topography are dominated by solution as the key geomorphic agent. Typically, karst involves highly soluble rock, such as limestone, and well-developed secondary porosity from dissolution. Pre-existing secondary porosity in the rock, such as a fracture system, will enhance speleogenesis due to exposure of more surface area. Landforms indicative of karst terrain include dolines (sinkholes) and uvalas (coalescing sinkholes that form a larger depression), disrupted surface drainage (i.e. sinking streams), caves, and underground drainage systems. Sinkholes like the ones we are observing are formed when a cavity develops in the limestone underground, overlying sediment moves into the void, and the land surface depresses or collapses altogether (Figure 58 & Figure 59).
The limestone itself contains pore space between the sediment and fossil grains within it when it is formed. This percentage of void space within the bulk rock as a whole is referred to as primary porosity. Karstic processes develop a secondary porosity, void space created after the rock is formed. Both the original and secondary porosity within the Ocala Limestone allow the rock formation to serve as an aquifer, and in the case of Ichauway, the Upper Floridan Aquifer (UFA). An aquifer is a rock formation that contains a sufficient porosity and permeability to transmit economic volumes of water (Fetter, 2018; Freeze and Cherry, 1979). The UFA is unconfined to semi-confined at Ichauway depending on location, meaning that the aquifer is connected to the surficial systems and can receive recharge from precipitation and losing stream reaches, or it is slightly capped by clayey sediments. Overall, there is no regional, laterally-continuous, impermeable soil or rock formation that prevents recharge to the aquifer.
Figure 59. View from the bottom of a large sinkhole duplex within sandy soils of the Turkey Woods. Ground-penetrating radar equipment (yellow & black device) is included for scale.
These sinkholes are a precursor to much larger-scale features, like we will observe later at Stop 5, Richardson Flat and Balden Pond. These sinkholes are situated very close to each other, and could even be considered to combined. As karst processes continue, especially along the main fracture plane, these sinkholes will coalesce into a much larger depression feature called a uvala (Figure 60).

![Diagram of sinkhole evolution](image)

**Figure 60.** The evolution of compound sinkholes (left) into a uvala (right), through enhanced dissolution along pre-existing fracture planes (orange lines). Modified from (White, 1988).
Stop 4. The Turkey Woods Draw

Figure 61. Looking south-southeast from the hill at the lineament of sinkholes, oriented northeast-southwest, within the Turkey Woods. Approximate Coordinates: 31°15'05.2"N 84°28'22.6"W (31.251456, -84.472930). Photo: J Honings.

This stop is a draw that contributes drainage to Ichawaynochaway Creek, though more inconspicuous than the previous location. Looking to the north from the road, there is a noticeable bluff. Upon the bluff are large boulders of Ocala Limestone. Due to their relative size, it is assumed that these pieces are either in-place (the much larger ones) or “float,” a term used to describe large pieces of bedrock that have been eroded and left near their original location. By observing this, we can assume that the bedrock surface is at or near the surface, covered by a thin layer of soil and vegetation.

As you walk towards the bluff, you may notice growth of brush and small trees in the middle of the valley, many of which the bottoms are not visible. Carefully approach one of these clusters of brush, and you will soon realize that these have been growing from the bottom of a sinkhole that is approximately 2 meters deep. If you follow the valley downstream (southwest) or upstream (northeast), you will encounter several more sinkholes of similar size. The orientation of
this lineament of sinkholes and the paleo-stream valley itself is along a major fracture pattern within the Ocala Limestone identified and described in the Dougherty Plain (Brook and Allison, 1986) and in previous research at Ichauway (Rugel et al., 2019; Rugel et al., 2016; Rugel et al., 2012). In karst processes, secondary porosity such as the fracture system in the host limestone, will be an area where the dissolution will be concentrated. As this process continues, it will form sinkholes just like the bare, sandy ones at the previous stop and the ones observed here.

These surficial features are important clues to determining subsurface flow. It is conceptualized that in karstic aquifers, more than 90% of groundwater flow occurs within the cave or conduit systems (Worthington et al., 2000). Because these sinkholes are located in a linear manner that matches a known regional fracture orientation in the Ocala Limestone, it is hypothesized that the enhanced fracture would exist between, and connecting, the sinkholes until truncated by a feature such as the creek itself (Refer back to Figure 60). This enhanced fracture, or zone of enhanced dissolution, would serve as a flow path in the subsurface. In effect, locating sinkhole lineaments and similar features allows us to approximate the location of preferential subsurface flow paths.

Extensive ground-penetrating radar (GPR) geophysical surveys have been completed in this draw in an effort to visualize and characterize the flow path, and are included in Appendix B. Surveys were completed between known sinkholes, oriented perpendicular to the hypothesized flow path. Subsurface imagery reveals that there is enhanced porosity, and sometimes cavities, along the sinkhole lineament orientation as compared to the rock outside of the flow path.
Stop 5. Rhexia Pond (Wetland 53)

Figure 62. Location 5, Rhexia Pond, as indicated by the yellow star. Approximate Coordinates: 31°16'16.4"N 84°29'49.6"W (31.271213, -84.497103).

Rhexia pond and the adjacent wetland to the west were formed by cover collapse sinkholes, just like the features examined in the Turkey Woods at Stops 3 & 4, but are more mature depressions as they noticeably cover more area. Wetlands in the Dougherty Plain form when clay layers accumulate within the sandy depressions that are formed by cover collapse sinkholes in the underlying limestone (Deemy and Rasmussen, 2017; Hicks et al., 1987). Because these wetlands are formed by underlying sinkholes, there should exist some sort of vertical piping system within the epikarst that acts as a funnel to the subsurface (Kruse, 2014; Kruse et al., 2006). As mentioned, karst formation is favored along pre-existing joint and fracture systems (Ford and Williams, 1989; Palmer, 1991; White, 1988), which do exist at the Jones Center (Brook and Allison, 1986; Rugel
et al., 2019), so it is expected that wetlands, underlying sinkholes, and a connected conduit flow system would exist along this pattern. The surface-groundwater interaction is seepage through the clay layer and into the vertical piping system into the conduit system. These wetlands are ponded by precipitation into the wetland catchment, and may receive water through overland flow from adjacent wetlands during larger rain events in a fill-and-spill manner (Deemy and Rasmussen, 2017). For mature wetlands like Rhexia Pond the seepage rate may be very slow due to the thickness of the clay layer, making wetlands like this more hydrologically isolated.

Figure 63. Photograph of Rhexia Pond. Image: S Golladay
Prior to the center-pivot irrigation boom that began in the late 1970s, both Richardson Flat to the west and Balden Pond to the east were ponded year-round (Figure 65). Over-extraction of groundwater throughout the Dougherty Plain caused these wetlands to mostly dry up for much of the year, and they are now exist as grassy plains. Although surface water is intermittently ponded at these locations, there are clues that groundwater movement occurs beneath the landscape.
As described at previous stops, Brook and Allison (1986) concluded that a prominent fracture system in the limestone bedrock, oriented northeast-southwest, existed throughout the Dougherty Plain. Rugel et al. (2019) described evidence of this fracture system within stream outcrops of the Ocala Limestone along Ichawaynochaway Creek. When viewing the aerial image, draw your attention to the lowest points of Balden Pond and Richardson Flat, which align in the orientation described in the literature. Look at the landscape to the west, you will see a rather shallow wetland about 200 meters away. Even further to the west in the southwest end of Richardson flat is a gauged depression that often ponds. If you decide to walk to Balden Pond and look in its southeast corner, you will notice that is its lowest point.

At previous stops, it was mentioned that development of karst is enhanced along secondary porosity features in the host bedrock. Depressional wetlands at Ichauway are formed by the infilling, ponding, and vegetation of sinkholes, which funnel water into the subsurface aquifer. The lowest points in both ponds at this spot align along the aforementioned fracture system.
Additionally, as these processes continue and as depicted in Figure 60, sinkholes will coalesce into much larger depressions called uvalas. A uvala will contain a subsurface drainage system in which the sinkholes act as subsurface funnels to the groundwater.

Recent research related to water resources and subsurface flow at the Jones Center has utilized geophysical methods to investigate the subsurface geology of karstic features on the property. A GPR survey was completed along the main road dividing Richardson Flat and Balden Pond, perpendicular to the documented fracture orientation identified in prior research. A small, gridded GPR survey was completed in the gauged depression in the southwest corner of Richardson Flat. The interpreted subsurface images that follow provide insight on subsurface flow between the ponds, Ichauway, and the greater Dougherty Plain as a whole.

The high-density survey grid completed at the lowest elevation within Richardson Flat showed the presence of a sinkhole that extends to a depth of ~5.5 m below the ground surface (Figure 66). Discerning the lateral continuity of reflectors that indicate a sinkhole is difficult due to the clay content in the soil in Richardson Flat.

![Image: Select GPR images from the high-density grid over the sink point in Richardson Flat showing a high porosity zone (outlined in purple).]
There are four zones of interest in the survey line (Figure 67) that was completed along the main road separating Richardson Flat and Balden pond. Numbered from northern end of the survey line, zones 1, 2, 3, and 4 are approximately 50, 50, 135, and 105 m wide. Zones 1, 2, 3, and 4 have depths of approximately 3.5, 7, 5.5, and 7 m, respectively.

Zones 1, 2, and 4 contain strong point reflectors that are interpreted as dry, high-porosity zones within the limestone. The location of Zone 3 aligns with the lowest elevations in both Balden Pond to the east and Richardson Flat to the West, and this alignment matches a dominant fracture orientation identified in the literature. All zones identified in the cross section should be viewed as karstic zones, with Zone 3 serving as the primary flow path. The point reflectors in zone 3 are subdued, which is attributed to the presence of water causing attenuation of the GPR
signal at depth.

Figure 68. Topographic profile of the Sea Pond, Balden Pond, Richardson Flat, and George Sand Pond sequence towards Ichawaynochaway Creek. A consistent reflection pattern between 38 and 41 meters above mean sea level is evidence of a subsurface connection.

The elevations of Zone 3, of the lowest point in the sinkhole in Richardson Flat, and the base level of the Ichawaynochaway Creek stream bed reveal a likely connection in the subsurface (Figure 68). Because these ponds are aligned with the orientation of fractures within the limestone, it can be inferred that a subsurface connection exists between the sequence of GIWs and Ichawaynochaway Creek. Because these karstic zones and the related surficial expressions are hundreds of meters wide, this GIW sequence is on the scale of and should be considered a uvala (Kranjc, 2013; White, 1988).
The uvala (Figure 69) can be viewed as the surface expression of the preferential subsurface flow path. However, as previously noted, approximately 90% of the groundwater flow is through conduits or other enlarged, continuous voids, implying that approximately 10% of the groundwater flow occurs through the primary porosity and the matrix of the Ocala Limestone. The spatial arrangement of these surface ponds and their deepest parts allow estimation of the extent of a subsurface conduit network. The application of geologic principles to the visible landscape and available data allow the “best guess” as to the true nature of the system. However, the location and extent of a conduit is only truly known through extensive surveying or coring efforts, or mapping through one that is physically traversable.
Stop 7. South of Ichauway Bridge near the Baseball Field: The Cover Sediments

Figure 70. Location of the Baseball Field stop, indicated by yellow star. Approximate Coordinates: 31°11’28.8”N 84°28’23.7”W (31.191340, -84.473248).

The soil has changed color and composition while traveling between stops on this field trip, alternating between mostly white-to-tannish sands to a reddish-orange clay (Figure 71). These sands (alluvium) were lain down by terrestrial depositional systems as sea level retreated from Ichauway to its modern position over 30+ million years. The clays are residuum from the weathering of the parent Ocala Limestone, and the thickness and distribution of the clay deposits vary throughout the Dougherty Plain. Clays are cohesive and water-tight, and do not facilitate the percolation of rainwater into the subsurface, rather forming ponds. This means that the clay is a semi-confining layer of the Upper Floridan Aquifer that is hosted by the Ocala Limestone. In the subsurface, the clays behave the same, and can lead to perched water tables above the UFA.
Figure 71. Photograph of reddish-orange clayey soil that is typical at Ichauway and the greater Dougherty Plain. This layer inhibits vertical movement of precipitation to the UFA beneath it.
Stop 8. The Swimming Hole: The Upper Floridan Aquifer

Figure 72. Approximate location of the Swimming Hole stop, indicated by yellow star. Approximate Coordinates: 31°11′28.8″N 84°28′23.7″W (31.191340, -84.473248).

This stop is along the west bank of Ichawaynochaway Creek, near the confluence with the Flint River to the south. It is accessed by traveling east from the Crafton House, parking at the end of the path, and carefully hiking down to the creek bank or viewing from the high ground. This side of the stream is the depositional bank, evidenced by the sandy beach. On the opposite east bank, there is a clear outcropping of the Ocala Limestone (Figure 73). Depending on creek stage, the outcrop forms an overhang due to a large cavity dissolved into it and the physical weathering from the creek flow itself.
Additionally, the Ocala Limestone itself has a different texture in this location, there are several large cavities in the rock, resembling Swiss cheese (Figure 74). There are two origins for these voids, one of which is the original primary porosity of the rock. The secondary porosity is from dissolution of the Ocala Limestone by acidic groundwater.
Figure 74. Looking west at an outcropping of the Ocala Limestone on the west bank of Ichawaynochaway Creek at the Swimming Hole. The large cavities in the rock are solutionally-enlarged voids from acidic surface and groundwater. Rock hammer for scale. Photo: J Honings
Summary

Over the course of this field trip, we have learned about some of Ichauway’s geologic history, and observed several clues about the subsurface flow of groundwater. At our first stop, we saw outcropping of the Ocala Limestone bedrock and learned that Ichauway was a shallow marine and reef environment over 30 million years ago. This was evidenced by the chemical composition of the rock and the remains of marine organisms preserved as fossils in the rock. Sea level gradually receded to its modern position, allowing sediment deposition to bury the limestone that now holds the Upper Floridan Aquifer.

At Stop 2, we observed how modern geomorphological agents, such as Ichawaynochaway Creek, rework the landscape. In this case, the creek has removed a semi-confining clay layer of soil, which enhances recharge to the UFA. At Stop 3, we learned about how the landscape is dissolving beneath itself through karstic processes. These sinkholes and sinkhole complexes are evidence of otherwise unseen subsurface processes common throughout Ichauway and the Dougherty Plain. At Stop 4, we built upon our knowledge of karst and saw how these processes are enhanced along pre-existing weaknesses and openings in the host limestone. This relationship is what determines the location of preferential flow paths in the subsurface, that sometimes manifests in surface flow. Stop 5 took the small-scale features from Stops 2-4 in the Turkey Woods and allowed us to observe them at a scale of several kilometers. These wetlands are part of a uvala (compound sinkhole) feature that extends throughout the landscape and connects to Ichawaynochaway Creek in the subsurface. Stops 2-5 have allowed us to identify hydrogeologic patterns using clues at different geological scales at Ichauway to inform us of the greater subsurface flow system.

At Stop 6, we revisited the semi-confining layer of the UFA, and discussed how thickness
and material can vary throughout the landscape and conceal the subsurface drainage features. At Stop 7, we concluded by observing the dichotomy of surface and groundwater dissolution on the host Ocala Limestone. We examined exposures of the limestone that provide insight into the heterogeneity of the rock itself and the large voids that exist within it. We hope this field excursion has helped you connect with the Ichauway landscape differently and given you a greater appreciation for the complex dynamics and immense time that has shaped it, both on the surface and underground. But most of all, we hope this new appreciation of the landscape helps you better understand the complexity of how water flows over and through it.
CHAPTER 6. SUMMARY

Agriculture is a major industry throughout the Southeastern United States, which utilizes surface and groundwater for row crops and pasture. These surface and groundwater resources flow across state and county boundaries, and sometimes overlap depending on scale, which has led to arguments over allocation and usage of the water. A recent example is that water resources of the Apalachicola-Chattahoochee-Flint (ACF) River Basin were subject of a Supreme Court case decision between Florida and Georgia (Klein and Sandfort, 2019). Georgia, like other states, has developed a State-wide management plan to conserve water by mid-century, relying on economic model projections (GWPC, 2017). The ACF River Basin overlaps with the Lower Flint-Ochlockonee (LFO) River Basin in the southeastern United States, and projections for the LFO watershed indicate that withdrawals will continue to exceed the sustainable yield of the Upper Floridan Aquifer (UFA), the primary groundwater resource in the region. Both the ACF and LFO basins flow through the Dougherty Plain province in southwestern Georgia, where efforts to sustain water while maintaining crop yield persist.

Due to uncertainty of the availability of water resources with climate change and intense human consumption, numerical groundwater models have been successfully utilized to predict water budgets (Alam et al., 2019; Ghazavi and Ebrahimi, 2018). In clastic sediments, the porous media are Darcian and generally easy to characterize, whereas the heterogeneity and unknown flow paths of karst aquifers are difficult to build into the model parameters (Hartmann et al., 2014). The limitation is not in development of the numerical and discretized models (Shoemaker et al., 2008), but in characterizing the nature of the karstic subsurface (Borghi et al., 2016). Karstic flow paths have often been overgeneralized as subsurface pipes (Peterson and Wicks, 2006) or as higher permeability zones embedded within a porous matrix (Wicks and Herman, 1995). More knowledge
of the geometry of the subsurface will facilitate refinement of groundwater modeling efforts in the Dougherty Plain and the drainage basins it lies within.

The Dougherty Plain of the Southeastern United States Coastal Plain is littered with hundreds of wetlands, of which are commonly referred to as geographically-isolated wetlands (GIWs). GIWs are completely surrounded by uplands at the local scale (Tiner, 2003), though this does not mean functional isolation hydrologically, ecologically, or physiochemically (Mushet et al., 2015; Tiner, 2003). The genesis of these wetlands is ponding within karstic depressions and sinkholes (Hicks et al., 1987; Kirkman et al., 2012). The surficial hydrology of these wetlands in the Dougherty Plain has been described as spill-and-fill behaviour by means of overland flow after high-precipitation events (Deemy and Rasmussen, 2017). Hydrologic movement in GIWs is difficult to observe in nature because these surficial connections are infrequent, of short duration, or the hydrologic connection is via obscure subsurface and groundwater pathways (Mushet et al., 2015; Tiner, 2003). It has been assumed that minimal connectivity exists with groundwater because the sediments underlying the wetlands are relatively impervious (Kirkman et al., 2012). Conceptualization of the connection from the ponds to the subsurface flow system would provide great insight into the region’s water sustainability efforts.

This dissertation has provided direct insight into the nature of the subsurface connections and flowpaths through the features investigated at the Jones Center and analogous features throughout the Dougherty Plain. Subsurface geophysical imagery has revealed that although there are clayey sediments within the wetlands, there is a lack of clay within the sinkhole funnels, which facilitates the vertical movement of ponded water to the subsurface flow system. Following vertical flow to the UFA, the hydrologic connectivity exists through the conduit system and vuggy porosity along the prominent fracture system in the Dougherty Plain.
Climate change and population growth signal the need to project water resources for the foreseeable future across the globe. The Dougherty Plain of the southeastern United States Coastal Plain is no exception, where the economies of agriculture, fisheries, and forestry products are vulnerable in a future with limited water availability. Contemporary resources in the Dougherty Plain and shared between surrounding communities and watersheds have already diminished, and are difficult to manage, with disputes prevalent for several decades. Efforts to conserve water have been made through strategic water planning groups, numerical groundwater modeling efforts, landscape management, incentives for reduction of irrigation, and public policy. However, complication in understanding and managing the water resources arises from the nature of the covered karstic landscape, within which drainage behaves differently than conventional, Darcian-flow aquifer systems due to the heterogeneity of the porous media. Improved understanding of the physical characteristics of hydrologic connectivity through the Dougherty Plain would provide information that will optimize the conservation efforts.

The geologic history of the Dougherty Plain allows for conceptualization of the dominant karst-forming mechanisms and prediction of the resultant morphometric patterns. The Dougherty Plain was once a shallow marine environment during the Eocene period, which was buried by terrestrial sediments as sea level regressed, and is continuously evolving as karst processes reshape the subsurface drainage. The development of karst in the Dougherty Plain is controlled by the diffuse recharge of chemically-aggressive allogenic water through the thick overlying sands and the bedding plane porosity of the Ocala Limestone. These characteristics facilitate the formation of shaft and canyon drainage, a system of vertical funnels into laterally-connecting conduits. Secondary porosity in carbonate rocks is host to enhanced dissolution, and the fracture system that exists in the Ocala Limestone would further the development of karst along the orientations of the
fractures after receiving the water from the diffuse recharge system. This background information provided the basis for predicting the location and geometry of subsurface karst features beneath the thick sediments and densely-vegetated terrain, and conceptualization of a mechanism for the known sinkholes and wetlands.

Because the Jones Center is an ecological preserve, conventional techniques for deducing the drainage of karst terrains such as tracer tests and extensive coring efforts were not feasible. The high-resolution LiDAR imagery and aerial photography allowed examination of the Jones Center terrain for features that would resemble a surface manifestation of the subsurface karst deformation and drainage system. Patterns in topography, sinkholes, and wetlands that matched the orientation of a prominent fracture documented by previous research were identified. Ground-penetrating radar surveys provided information of the subsurface in the spaces between the field-verified sinkholes and wetlands. These data were analyzed and interpreted for the thickness of sediment, location of epikarst surface, presence of vuggy porosity, and the physical dimensions of karst features.

Geophysical surveys provided snapshots into the subsurface, and synthesis of these data provided evidence for vertical and lateral karst connectivity at different scales within the Jones Center. The individual, relatively-isolated sinkholes can be conceptualized as small-scale features that have yet to develop visible connection with the surrounding landscape. The draws (intermediate-sized) and uvalas (large-scale) exhibit enhanced connectivity through the landscape and overall karst maturity. Sinkholes and wetlands function as funnels to the aquifer, and the lateral connectivity within the draws and uvalas exists mostly as highly-concentrated touching-vug porosity, with some instances of enlarged fractures and cavities that would suggest the existence of a conduit. Because the sinkholes and wetlands are surface expressions of karst, remote sensing
imagery of the Jones Center and greater Dougherty Plain terrain can be examined for these patterns and conceptualized as analogous drainage features based on their size. These refined conceptual models serve as inputs to numerical groundwater models that are utilized by resource planning groups and researchers. Additionally, the same karst geomorphic patterns can be used to optimize the location of future irrigation systems within a subsurface flow path to improve efficiency. Furthermore, inference of a subsurface flow path beneath a parcel of land could have implications for the allocation of incentives for irrigation reduction practices as local policy evolves.

Humans are not the only living population in the Dougherty Plain with stake in the availability of water resources, as the depletion of water resources has been detrimental to the aquatic and forest ecosystems of the Dougherty Plain. It is imperative that research and conservation efforts focused on these ecosystems are well-informed of the fundamentals of the hydrologic connectivity of the terrain. This research has produced an interactive educational program for the Jones Center at Ichauway tailored to the non-geologist. Key hydrogeologic features that are common throughout the region were identified at specific and accessible locations within the Jones Center property, and added as individual stops on the field trip. At each stop, the geologic processes and hydrogeologic function are described in detail. The participants will develop an understanding of the origins of the Dougherty Plain, and observe sequential steps of karst development from bedrock to sinkhole, wetland, and ultimately uvala. This activity will provide new insight to ongoing and future ecological research and landscape management strategies through the conceptualization of the groundwater-surface water interactions and connectivity.
APPENDIX A. ADDITIONAL GPR IMAGERY

The Turkey Woods Draw and Vicinity

Figure A.1. Transect “Alpha,” oriented NW-SE from left-to-right, with a total horizontal length of 33 meters. The top of the epikarst (light blue) was interpreted at a depth of approximately 2.2 meters, and the top of coherent Ocala Limestone occurring at 3.2 meters.
Figure A.2. Transect "Charlie," oriented NW-SE from left-to-right, with a total horizontal length of 13 meters. The top of the epikarst (light blue) was interpreted at a depth of approximately 1 meter, and the top of coherent Ocala Limestone at 4 meters.

Figure A.3. Transect “Delta,” oriented NW-SE from left-to-right, with a total horizontal length of 14 meters. The yellow shape denotes a funnel-shaped area with reflections that indicate a concentration of larger vugs, and is approximately 4.75 meters wide, and 2 meters tall.
Figure A.4. Transect “Echo,” oriented NW-SE from left-to-right, with a total horizontal length of 17.5 meters. The yellow arrow denotes a concentration of vugs to the left of the arrow, and is approximately 8.5 meters wide, and 2.5 meters tall.

Figure A.5. Transect “Foxtrot,” oriented west-east from left-to-right, with a total horizontal length of 19.5 meters. The yellow shape denotes a concentration of vugs, and is approximately 6.5 meters wide, and approximately 3 meters tall.
Figure A.6. Transect “Golf,” oriented west-east from left-to-right, with a total horizontal length of 31 meters. The yellow shape denotes a concentration of vugs, and is approximately 13 meters wide, and 3.5 meters tall.

Figure A.7. Transect “Hotel,” oriented SW-NE from left-to-right, with a total horizontal length of 55 meters. The yellow shape denotes a concentration of vugs, and is approximately 21 meters wide, and 5 meters tall.
Figure A.8. Transect “Juliett,” oriented NW-SE from left-to-right, with a total horizontal length of 38.5 meters. The yellow shape denotes an interpreted funnel-shaped vuggy zone, and is approximately 11 meters wide, and 5 meters tall.

Figure A.9. Transect “Kilo,” oriented NW-SE from left-to-right, with a total horizontal length of 48 meters. The yellow shape denotes an interpreted funnel-shaped vuggy zone, and is approximately 17 meters wide, and 4.5 meters tall.
Figure A.10. Transect “Mike,” oriented NW-SE from left-to-right, with a total horizontal length of 26.5 meters. The yellow shape denotes an interpreted large vug approximately 5 meters wide and 1.5 meters tall.

Figure A.11. Transect “November,” oriented NW-SE from left-to-right, with a total horizontal length of 31.5 meters. A concentration of vugs about 7 meters wide is present in the right (southeastern) side of the cross-section.
Figure A.12. Transect “Oscar,” oriented NW-SE from left-to-right, with a total horizontal length of 22 meters. The yellow bracket denotes a vuggy zone approximately 9 meters wide, and 1 meter tall.

Figure A.13. Transect “Paul,” oriented NW-SE from left-to-right, with a total horizontal length of 24.5 meters. The right side of the cross section includes a funnel shape that is at least 6 meters wide and approximately 3 meters tall, with a concentration of vug-like reflections below it.
Figure A.14. Transect “Quebec,” oriented north-south from left-to-right, with a total horizontal length of 45 meters. The yellow bracket denotes a vuggy funnel shape approximately 12 meters wide and 5 meters tall as it continues with depth through the coherent limestone boundary.

Figure A.15. Transect “Romeo,” oriented north-south from left-to-right, with a total horizontal length of 27 meters. The epikarst in this cross section has a strong presence of vug-like reflectors throughout, with a concentration of vugs denoted by the yellow bracket.
Figure A.16. Transect “Tango,” oriented NW-SE from left-to-right, with a total horizontal length of 20 meters. The yellow bracket denotes a concentration of strong reflectors that indicate vugs and a possible cavity, truncated by the limits of the cross section.

Figure A.17. Transect “Uniform,” oriented north-south from left-to-right, with a total horizontal length of 28 meters. Reflectors below the epikarst boundary (light blue) are distributed throughout the cross section, indicative of a vuggy limestone.
Figure A.18. Transect “Victor,” oriented west-east from left-to-right, with a total horizontal length of 36 meters. The yellow arrow denotes the area to the right as highly concentrated with vugs, approximately 24 meters wide, 3.5 meters tall, truncated by cross-section boundaries.
The Richardson Flat – Balden Pond GIW Sequence

Figure A.19. Line 21 from the gauged depression in the southwest corner of Richardson Flat.

Figure A.20. Line 25 from the gauged depression in the southwest corner of Richardson Flat.
Figure A.21. Line 26 from the gauged depression in the southwest corner of Richardson Flat.

Figure A.22. Line 27 from the gauged depression in the southwest corner of Richardson Flat.
Figure A.23. Line 29 from the gauged depression in the southwest corner of Richardson Flat.

Figure A.24. Line 29 from the gauged depression in the southwest corner of Richardson Flat.
Figure A.25. Line 31 from the gauged depression in the southwest corner of Richardson Flat.

Figure A.26. GPR line oriented east-west across Richardson Flat.
Historic Circle

Figure A.27. GPR line from the Historic Circle.

Figure A.28. GPR line from the Historic Circle.
Figure A.29. GPR line from the Historic Circle.

Figure A.30. GPR line from the Historic Circle.
Figure A.31. GPR line from the Historic Circle.

Figure A.32. GPR line from the Historic Circle.
Figure A.33. GPR line from the Historic Circle.

Figure A.34. GPR line from the Historic Circle.
Figure A.35. GPR line from the Historic Circle.

Figure A.36. GPR line from the Historic Circle.
Figure A.37. GPR line from the Historic Circle.

Figure A.38. GPR line from the Historic Circle.
Figure A.39. GPR line from the Historic Circle.

Figure A.40. GPR line from the Historic Circle.
Figure A.41. GPR line from the Historic Circle.

Figure A.42. GPR line from the Historic Circle.
Figure A.43. GPR line from the Historic Circle.

The Sinkhole Duplex

Figure A.44. GPR line from the Sinkhole Duplex.
Figure A.45. GPR line from the Sinkhole Duplex.

Figure A.46. GPR line from the Sinkhole Duplex.
Figure A.47. GPR line from the Sinkhole Duplex.

Figure A.48. GPR line from the Sinkhole Duplex.
Figure A. 49. GPR line from the Sinkhole Duplex.

Figure A.50. GPR line from the Sinkhole Duplex.
Figure A.51. GPR line from the Sinkhole Duplex.

Figure A.52. GPR line from the Sinkhole Duplex.
Figure A. 53. GPR line from the Sinkhole Duplex.

Figure A.54. GPR line from the Sinkhole Duplex.
Figure A. 55. GPR line from the Sinkhole Duplex.

Figure A. 56. GPR line from the Sinkhole Duplex.
Highway 200 Sinkhole

Figure A.57. GPR line from the Highway 200 Sinkhole.

Figure A.58. GPR line from the Highway 200 Sinkhole.
Figure A.59. GPR line from the Highway 200 Sinkhole.

Figure A.60. GPR line from the Highway 200 Sinkhole.
Figure A.61. GPR line from the Highway 200 Sinkhole.

Figure A.62. GPR line from the Highway 200 Sinkhole.
Figure A.63. GPR line from the Highway 200 Sinkhole.

Figure A.64. GPR line from the Highway 200 Sinkhole.
Figure A.65. GPR line from the Highway 200 Sinkhole.

The Control Area

Figure A.66. GPR line from the control area.
Figure A.67. GPR line from the control area.

Figure A.68. GPR line from the control area.
Figure A.69. GPR line from the control area.

Figure A.70. GPR line from the control area.
Figure A.71. GPR line from the control area.

Figure A.72. GPR line from the control area.
Figure A.73. GPR line from the control area.

Figure A.74. GPR line from the control area.
Figure A.75. GPR line from the control area.
APPENDIX B. GPR DEPTH SLICES

The Turkey Woods Draw

Figure B.1. Depth slice from 0-0.5 m below ground surface from the Turkey Woods Draw.
Figure B.2. Depth slice from 0.5-1 m below ground surface from the Turkey Woods Draw.
Figure B.3. Depth slice from 1-1.5 m below ground surface from the Turkey Woods Draw.
Figure B.4. Depth slice from 1.5-2 m below ground surface from the Turkey Woods Draw.
Figure B.5. Depth slice from 2-2.5 m below ground surface from the Turkey Woods Draw.
Figure B.6. Depth slice from 2.5-3 m below ground surface from the Turkey Woods Draw.
Figure B.7. Depth slice from 3-3.5 m below ground surface from the Turkey Woods Draw.
Figure B.8. Depth slice from 3.5-4 m below ground surface from the Turkey Woods Draw.
Figure B.9. Depth slice from 4-4.5 m below ground surface from the Turkey Woods Draw.
Figure B.10. Depth slice from 4.5-5 m below ground surface from the Turkey Woods Draw.
Figure B.11. Depth slice from 5-5.5 m below ground surface from the Turkey Woods Draw.
Figure B.12. Depth slice from 5.5-6 m below ground surface from the Turkey Woods Draw.
Figure B.13. Depth slice from 6-6.5 m below ground surface from the Turkey Woods Draw.
Figure B.14. Depth slice from 6.5-7 m below ground surface from the Turkey Woods Draw.
Figure B.15. Depth slice from 7-7.5 m below ground surface from the Turkey Woods Draw.
Figure B.16. Depth slice from 7.5-8 m below ground surface from the Turkey Woods Draw.
Figure B.17. Depth slice from 8-8.5 m below ground surface from the Turkey Woods Draw.
Figure B.18. Depth slice from 8.5-9 m below ground surface from the Turkey Woods Draw.
The Gridded Survey within the Richardson Flat gaged wetland.

Figure B.19. Depth slice from 0-0.5 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.20. Depth slice from 0.5-1 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.21. Depth slice from 1-1.5 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.22. Depth slice from 1.5-2 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.23. Depth slice from 2-2.5 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.24. Depth slice from 2.5-3 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.25. Depth slice from 3-3.5 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.26. Depth slice from 3.5-4 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.27. Depth slice from 4-4.5 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.28. Depth slice from 4.5-5 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
Figure B.29. Depth slice from 5-5.5 m below ground surface within the gaged wetland in the southwest corner of Richardson Flat.
REFERENCES


Barrie, C. J., 2019, Groundwater Flow on a Karstic Landscape in Southwest Georgia: University of Georgia.


Evans, M. W., Snyder, S. W., and Hine, A. C., 1994, High-resolution seismic expression of karst evolution within the Upper Floridan aquifer system; Crooked Lake, Polk County, Florida: Journal of Sedimentary Research, v. 64, no. 2b, p. 232-244.


GWPC, 2017, Lower Flint-Ochlockonee: Regional Water Plan, Albany, Georgia, Black & Veatch and GWPC.


Hicks, D. W., and Golladay, S. W., 2006, Impacts of agricultural pumping on selected streams in southwestern Georgia: Report submitted to Georgia Environmental Protection Division. Atlanta, Georgia, USA.


Rugel, K., Jackson, C. R., Romeis, J. J., Golladay, S. W., Hicks, D. W., and Dowd, J. F., 2012, Effects of irrigation withdrawals on streamflows in a karst environment: lower Flint


White, W. B., 1988, Geomorphology and hydrology of karst terrains.


VITA

Joseph Peter Honings was born and raised in Peoria, Illinois. His passion for the natural world and conservation led him to the University of Iowa, where he acquired his Bachelor’s Degree in Environmental Sciences with a Geoscience Focus in 2013. While at Iowa, he developed a particular interest in hydrogeology and water resources conservation following a trip to India tasked with development of sustainable agricultural watersheds in rural areas. He was employed as an environmental consultant in Ankeny, Iowa for three years before a return to school at Illinois State University for his Master’s Degree in Hydrogeology in 2018. He began his PhD program in Fall 2018 at LSU, where he was involved with the LSU AAPG Student Chapter. He has served as a teaching assistant at both ISU and LSU, instructing introductory geoscience, hydrogeology, and field camp courses. He has participated and presented at meetings coordinated by the Geological Society of America, American Geophysical Union, Illinois State University, Illinois Lake Management Association, and LSU Geology & Geophysics. LSU Geology & Geophysics and the Jones Center at Ichauway funded the duration of his dissertation. He has received scholarships from Houston Energy, LLP, and Chevron Corporation, and grants from the Geological Society of America. He is lead author on one peer reviewed paper, and has published an internal Field Guide to the Hydrogeology of the Jones Center at Ichauway for outreach programs.