HYDROLOGY AND WATER QUALITY OF ISOLATED WETLANDS EMBEDDED IN A LONGLEAF PINE / WIREGRASS FOREST: INFLUENCE OF CONNECTIVITY TO EPISODIC FLOWS

by

JAMES BURTON DEEMY

(Under the Direction of Todd C. Rasmussen and Jeffrey Hepinstall-Cymerman)

ABSTRACT

The Dougherty Plain physiographic province of southwest Georgia is characterized by karstic topography with deeply incised streams, deep sandy soils with interbedded clay lenses, and approximately 11,600 isolated wetlands. The goal of this project was to propose and locally conceptual models of episodic surface flows in the Dougherty Plain. The first specific objective was to determine if episodic flows change when passing through wetlands. Secondly, we monitored water quality of wetlands connected to episodic surface flows and those isolated from such events. Third objective was to determine if wetland hydropattern differed between wetlands connected to episodic flow events and isolated wetlands. Our first study found that isolated wetlands alter episodic surface flow water quality. Secondly, episodic surface flows alter the water quality of isolated wetlands after the cessation of flow. The third study found hydropattern differences in wetlands connected to episodic surface flow and those isolated from such events.

INDEX WORDS: Dougherty Plain, Episodic flow, Isolated wetlands, Nutrients, Organic matter, Pathogens, Sediments, Streams
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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The Dougherty Plain is a physiographic province in Southwest Georgia with few headwater streams. Instead, this 670,000-ha landscape is dominated by approximately 12,000 depressional wetlands that are always or predominantly isolated (Martin et al., 2012). Many of these wetlands are connected hydrologically by episodic overland flow as the result of large storms that saturate soils and produce surface runoff. Efficient and effective long-term management of water resources in this region will require an understanding of the effects of land uses on the hydrology and water quality within these wetlands, as well as episodic wetland discharges to local rivers and streams.

Episodic flows provide sources of water (Wilcox et al., 2011, McDonough et al., 2015, Costigan et al. 2016) as well as dissolved and suspended matter (e.g., nutrients, dissolved carbon, sediments, coarse woody debris). In some ecosystems, short duration inputs of matter and energy contribute to temporal variation in stream communities and can have lasting impacts on nearby perennial streams (Gu et al. 2012, Strayer 2014). Lasting impacts can be in the form of woody debris or sediment deposition in the channel (O’Hop and Wallace 1981, Gomi et al. 2001, Gomi et al. 2005, Rickerman and Koschi 2010).

Events that occur over short periods of time and have lasting or disproportional effects on the long term functioning of an ecosystem are known as “hot moments” (McClain et al. 2003). Likewise, “hot spots” refer to cumulative effects from small yet biogeochemically active areas.
that provide carbon and nutrient processing disproportional to their spatial coverage (McClain et al. 2003).

Isolated wetlands connected to episodic surface flows may alter water quality through sedimentation and increased biogeochemical processing (Laudon et al. 2016) or dilution from potential soil-water discharges. Isolated wetlands could represent disproportionally important locations within Dougherty Plain watersheds and act as hot spots of nutrient processing, carbon export and sediment retention. Additionally, episodic flows could represent periods that have a disproportionately long-term effect on the biogeochemistry, carbon availability and sediment inputs to perennial waters in the Dougherty Plain.

Ecotone processes at the interface of aquatic and terrestrial systems in particular have disproportionate ecological function relative to spatial area. Ecotonal areas can be particularly rich in biodiversity, sometimes serve as refugia for rare or threatened species, and can be zones of increased biogeochemical activity produced by dynamic wetting and drying (Xiao et al. 2012, Zhu et al. 2013, Jones et al. 2014).

Depending on hydrologic regime, ecotones between boreal forests and peatlands have elevated levels of biogeochemical activity that makes them distinct from both the uplands and wetlands they connect (Mitchell and Branfireun 2006). Ecotones between boreal forests and peatlands were active enough that they could be considered hotspots and it was deemed appropriate to consider them separate in sampling regimes when determining catchment scale biogeochemical processing (Mitchell and Branfireum 2005).
In regions that have a high density of hydrologic features (wetlands, headwater streams) it is possible for these ecotones to be a critical component of biogeochemical cycling and water quality (Seitzinger et al. 2006). Land-water interface between freshwater wetlands and uplands in lakes of North China can be a hotspot of annamox activity accounting for up to one fifth of the nitrogen lost in these wetlands and may even reduce NO$_2$ exports from wetlands (Zhu et al. 2013). Dynamic periods of wetting and drying in ecotones can produce hotspots of carbon processing that spatially shift through time as various factors (geomorphology, detrital buildup, vegetation, bioturbation) affect the hydrology of the ecotone (Fenner et al. 2011). Shifts in function have also been noted in small streams over time (particularly seasons) creating hot moments along the ecotone of dynamic small hydrologic features (Agren et al. 2007).

Episodic flows that create linkages between wetlands, terrestrial ecosystems, and perennial flowing waters can have effects lasting beyond the duration of storm flow even when wetlands may seem distant (Golden et al. 2016). Isolated wetlands (i.e., wetlands surrounded by uplands) can be embedded along surface flowpaths. These wetlands may affect the quantity and quality of runoff reducing flows and sequestering sediments (EPA 2013, Rains et al. 2016, Golden et al. 2016). Potentially, the large areas between the isolated wetland and upland forest ecotones along such flowpaths could form hotspots of biogeochemical activity within the larger landscape (Lane et al. 2015, Cohen et al. 2016).

Elevated levels of biogeochemical activity have been observed in backwater and flow-through wetlands with dynamic hydrologic connections to other waters within the Atchafalaya basin relative to continuously connected wetlands (Jones et al. 2014). Headwater wetlands
connected to streams through small, intermittent channels have also been shown to alter streamflow and chemistry disproportionate to their size in Maine (Morely et al. 2011).

Isolated wetlands can therefore act as hotspots of biogeochemical activity within a landscape, especially agricultural landscapes, where the dominant uplands have relatively low biogeochemical activity (Lane et al. 2015). Isolated wetlands are frequently embedded within agricultural landscapes of several regions of the United States. These wetlands occur most often in glaciated (prairie pothole region of the Midwest) or karstic regions (coastal plains of northern Florida and southwestern Georgia). Isolated wetlands of less obvious geologic origin are also common along the coastal plain of the mid-Atlantic (Delmarva bays) and southeastern states (Carolina Bays). Vernal pools in California could also be considered biogeochemical hotspots due to their elevated level of nutrient cycling compared to nearby uplands (Rains et al. 2006).

Generally, anthropogenic connections that drain wetlands to nearby streams are damaging to the wetland and receiving stream (Blann et al. 2009). However episodic flows that naturally connect these features may be overall less harmful and could potentially benefit nearby streams. Where these wetlands are prone to occur isolated from perennial surface features, they are often in high densities as wetland complexes within a watershed, and thus cumulatively have potential to provide a disproportionate role in the ecology and hydrology where they occur (Morely et al. 2011). Particularly in agricultural regions in which headwater streams are few, episodic connectivity between isolated wetlands and streams potentially serve important functions to downstream perennial streams through temporary inputs of materials and energy normally associated with headwater streams (Van der Valk and Jolly 1992, Gleason et al. 2011).
Despite the variable nature of stormflows, restored wetlands can trap sediment, process nutrients and carbon (Jordan et al. 2003, Eimers et al. 2008). Headwater streams embedded within agricultural landscapes in Illinois were found to export to downstream waters the majority of nitrate that entered the stream (Royer et al. 2004). Wetlands embedded along headwater channels and episodic storm flows could help mitigate the effects of nitrate runoff due to their importance in acting as sinks for inorganic nitrogen (Scott et al. 2007). Wetlands can also mitigate storm runoff discharge from agricultural landscapes in headwater or temporary episodic flows (Stanfield and Jackson 2011).

**Project Goals and Objectives**

The goal of this project is to determine the biogeochemical and hydrologic function of small isolated wetlands and episodic storm flows embedded in a longleaf pine / wiregrass ecosystem on the Dougherty Plain. The first objective is to determine how episodic flows change as they pass through and between wetlands. Secondly, we wish to determine how the water quality differs between wetlands that are inter-connected during episodic surface flows as opposed to those that are isolated during such events. The third objective is to determine how wetland hydropatterns differed between wetlands connected to episodic flow events and isolated wetlands.

**Dissertation Structure**

Chapter 2 provides a summary of the hydrogeology of the Dougherty Plain of southwest Georgia. Chapter 3 is a study that describes water quality of an episodic surface flow event that occurred at our field site in February 2014. Chapter 4 is a one-year monitoring study of isolated
wetland water quality of 31 isolated wetlands after the episodic surface flow studied in Chapter 3. Chapter 5 is a probabilistic analysis of long-term wetland stage data for the same 31 wetlands examined in Chapter 4. The final chapter of the dissertation (Chapter 6) outlines the major conclusions from this study.

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CHAPTER 2

SURFACE AND SUBSURFACE HYDROLOGY RESEARCH NEEDS IN THE
DOUGHERTY PLAIN, SOUTHWEST GEORGIA, USA

Deemy, J.B., and T.C. Rasmussen. Prepared for submission to Southeastern Geology
Abstract

Hydrologic studies of the Dougherty Plain have focused on groundwater-stream interactions and the effects of center pivot irrigation. Episodic surface flows and isolated wetlands have not been well studied but may be a substantial hydrologic component of this region. The Dougherty Plain physiographic province of southwest Georgia has karstic topography with deeply incised streams, sandy soils, interbedded clay lenses, and permeable, vuggy carbonate bedrock. Over 12,000 isolated wetlands, of widely ranging size and shape, contribute to the distinct hydrology of this region. This study uses the current hydrologic understanding of the Dougherty Plain to propose a conceptual model and define research needs for understanding the role of isolated wetlands and episodic flows in the region. Based on our conceptual model we pose three major hypotheses: 1) isolated wetlands are significant local and collective components of the surface hydrology, 2) episodic flows connecting typically isolated surface waters to perennial streams contribute significant fluxes of material and energy to downstream waters, and 3) groundwater is a significant factor in some isolated wetlands, baseflow in ephemeral streams, and influences selected reaches of episodic flow paths. Testing these hypotheses will greatly improve our understanding of surface and subsurface hydrology in the Dougherty Plain.

Keywords: isolated wetlands, episodic flows, Dougherty Plain
Introduction

Numerous studies have been conducted to define the hydrology of the Dougherty Plain. Yet, the complexity of hydrologic processes in the region has resulted in a poor understanding of the surface and subsurface hydrology related to recharge/discharge events, episodic surface flows, and isolated wetlands. Isolated wetlands, episodic surface flows, and interactions between surface and groundwater are major contributors to these complex processes.

The Dougherty Plain is a karstic 7,650-km² physiographic province located on the Southeastern Coastal Plain of southwest Georgia with parts in eastern Alabama and northwestern Florida (Figure 1). Deep sandy soils and interbedded clay lenses occur over highly permeable, vuggy carbonate bedrock (Hicks and others 1987, Torak and Painter 2006, Warner Gordon and others 2012). Low-order streams are uncommon, and perennial streams are incised through overburden materials into the underlying bedrock. General elevation slopes north to south, from approximately 91 m to 40.5 m AMSL (Hicks and others 1987) with an average relief of 2.4 m/km.

Forestlands (short rotation forest plantations and remnant natural forests) are the dominant land cover (44%) with row-crop agriculture and pasture also being an important part of the landscape (37%). Development in the area is limited to less than 7% of the landscape, with the remaining 12% consisting of grass-, scrub-, and barren-lands along with open water and emergent herbaceous wetlands (Table 1).

Depressional features often occur along lineaments that result from the preferential dissolution along bedrock joints (Brook and Allison, 1983, Hyatt and Jacobs 1996, Rugel and others, 2016). Sinkhole formation is increasing, and has been attributed to rapid groundwater
level changes due to aquifer pumping as well as flood events (Hyatt and Jacobs 1996, Warner Gordon and others 2012, Cahalan 2015). Isolated wetlands often develop in these depressions, with water levels controlled by local precipitation, evapotranspiration and in some cases episodic surface and subsurface inflows (Server 1965, Hicks and others 1987). Precipitation increases from north (1168 mm/yr) to south (1524 mm/yr) along the Dougherty Plain (Bush and Johnston 1988).

Groundwater and streams have been major focal areas of research while isolated wetlands, episodic surface flows and interaction between surface waters and groundwater has received little attention. Our objectives are: 1) To review the existing body of knowledge of the Dougherty Plain to define a conceptual hydrologic model for the region; 2) Identify research needs for understanding surface and subsurface hydrology based on this conceptual model; and 3) Propose a research framework for addressing these research needs.

**Major Surface Waters**

The Chattahoochee and Flint Rivers are the major perennial streams in the Dougherty Plain. Both rivers originate north of the Dougherty Plain and join to form the Apalachicola River in Lake Seminole. (Cooke 1943, Hicks and others 1987). Lake Seminole and Chickasawhatchee Swamp are the two largest waterbodies within the region (Dalton and others 2004). Major tributaries to the Flint River within the Dougherty Plain include Spring Creek, Ichawaynochaway Creek, and Chickasawhatchee Swamp (Cooke 1943, Hicks and others 1987). Most Chattahoochee and Flint River tributaries originate northwest of the Dougherty Plain in the Red Uplands of the Southeastern Coastal Plain and are well established streams before entering the Dougherty Plain (Cooke 1943). Major perennial surface waters in the Dougherty Plain derive
baseflow from direct contact with bedrock and springs along the flow channel (Hicks and others 1987).

**Soils**

Soil depths and textures exhibit large variability on the Dougherty Plain of southwest Georgia. Soils tend to be acidic, kaolinitic, argillic or kandic, with low base saturation. Upland soils (i.e., A and E horizons) are generally 15-150 cm thick, and are typically characterized by sand or loamy sand textures (West and others 1998). Subsoil (i.e., Bt and BC horizons) textures range from clay to sandy loams. Sand grains in upland soils are either thinly coated or un-coated.

Upper slopes are commonly fine-loamy sands and lower slopes are commonly fine-loamy sands that have more clay content (West and others 1998). Soils in depressions contain 2- to 20-cm thick organic layers (Oa horizons) and are typically thin loamy sands or sandy loams. Subsoils are typically characterized by sandy clay or clay textures (West and others 1998).

**Geologic Setting**

Dougherty Plain bedrock is made from sedimentary formations from the Cretaceous (Providence Sands) and Paleocene (Midway and Wilcox groups), as well as more recent Tertiary (Clairborne and Ocala) and Quaternary deposits (Herrick and Legrand 1964, Ripy and others 1981, Gibson 1982, Hicks and others 1987, Torak and Painter 2006, Warner Gordon 2012).

Undifferentiated overburden consists of quartz sands (fine to coarse), non-calcareous clays, silicified carbonate boulders that overlay the carbonate formations (Ocala or Suwannee, depending on the area) and Miocene sediments throughout the Dougherty Plain (Herrick and Legrand 1964, Miller 1986, Hicks et al 1987).
Portions of the Suwannee Formation (Oligocene) overlay the Ocala to the east of the Flint River, but in much of the Dougherty Plain, solution weathering has removed the carbonate layers down to the Ocala Formation (Miller 1986, Hicks and others, 1987). The Suwannee is heavily weathered in the Dougherty Plain, and generally consists of thin, broken features in select portions of Dougherty and Mitchell Counties (Hicks and others 1987, Torak and Painter 2006). The Ocala and Suwannee have lithologic similarities that make discerning thickness of each formation difficult where they co-occur (Hicks and others 1987, Warner 1997).

The Ocala Formation (Upper Eocene) underlays large portions of both Georgia and Florida and under portions of southern Alabama (Cooke 1943). This geologic feature is widest in the southwest and narrows northeastward. At the Dougherty Plain’s northern edge, the Ocala is approximately 8 m thick (Hicks and others 1987), increasing to a thickness of more than 85 m in southern parts of the region.

The Lisbon Formation (Middle Eocene) or the Clinchfield Sand (Upper Eocene) (Herrick 1972, Hicks and others 1987) confines the Ocala from below. This formation can be 3-m thick at the northern end, thickening to 30 m at Albany, and is consistent at 30 m southward. The Clinchfield Sand overlies northern portions of the Lisbon and is at its thickest (11 m) at its northern end, thinning to absent in the central parts of the Dougherty Plain (Torak and Painter 2006).

**Subsurface Hydrology**

Complex and concomitant interactions of overburden thickness and texture, thickness of the Ocala, hydraulic gradient, and patterns of surface drainage control downward and lateral
migration of water in the Dougherty Plain (Hicks and others 1987, Stewart and others 1999, Warner Gordon and others 2012). Hydrologic interaction between surface and subsurface water is common in streams connected to the Upper Floridan aquifer (Hicks and others 1987). While groundwater flows through both micropores (i.e., the geologic matrix) as well as macropores (e.g., voids, lineaments) in the Ocala (Screaton and others 2004).

**Undifferentiated Overburden**

Proportions of sand and clay are the primary lithologic factors controlling the permeability of the undifferentiated overburden (Hayes and others 1983). Estimated vertical hydraulic conductivity is between $3 \times 10^{-4}$ and 0.9 m/d, with a median of $9 \times 10^{-4}$ m/d (Hayes and others 1983). Estimated horizontal hydraulic conductivity can range from $1 \times 10^{-3}$ to 9.1 m/d, with a median of $6 \times 10^{-3}$ m/d (Hayes and others 1983). Transmissivity was estimated for the Dougherty Plain by using an average saturation thickness, with values ranging from $6 \times 10^{-4}$ to 300 m$^2$/d, with a median of 0.09 m$^2$/d (Hayes and others 1983).

**Upper Floridan Aquifer**

The Ocala hydraulically connects to the Lisbon Formation, the Clinchfield Sand and the Suwannee Carbonate. Considerable macroporosity and hydraulic connectivity allow northern portions of the Lisbon as well as the heavily weathered Suwannee to be part of the Upper Floridan aquifer (Hicks and others 1987, Torak and Painter 2006). Collectively, these formations make up the Upper Floridan aquifer, which can be 50 ft thick at the northern end and 475 ft thick at the south end (Hicks and others 1987).

The Lisbon below and low permeability layers in the undifferentiated overburden above confine the Upper Floridan (Torak and Painter 2006). Interestingly, low permeability layers
within the Upper Floridan can act as confining within the northern part of the aquifer (Hicks and others 1987, Warner Gordon 2012).

High permeability zones within the Ocala Carbonate are the primary transmissive units within the Upper Floridan aquifer (Torak and Painter 2006, Warner Gordon and others 2012). Permeability in the aquifer underlying the Dougherty Plain is caused by microporosity (e.g., small, highly connected pore space), as well as macroporosity (e.g., conduits, solution cavities). Variability in transmissivity of the Upper Floridan can be accounted for by differences in micro- and macroporosity among the Lisbon Formation, Clinchfield Sand, Ocala and Suwanee (Warner Gordon and others 2012).

Larger conduits tend to be found near the Flint River and the Pelham Escarpment (Torak and Painter 2006). In eastern portions of the Dougherty Plain, carbonate dissolution in the bedrock has created a network of conduits that transports water from disappearing streams near the Pelham Escarpment to springs along the Flint River (Hicks and others 1987, Warner Gordon 2012). In major discharge areas (i.e., near the Flint River) the macropore permeability is high and transmissivity can be as much as 150,000 ft$^2$/d.

*Groundwater Recharge and Discharge*

Recharge in the Upper Floridan can be considerable and near scales of meters per year, depending on lithologic characteristics of the area (Hayes and others, 1983, Hicks and others, 1987). Precipitation and lithologic heterogeneity determine groundwater recharge in the Dougherty Plain (Warner Gordon 2012), the majority of which occurs between December and March due to lower evapotranspiration rates during the winter months (Hicks and others 1987).
Undifferentiated overburden can form semi-confining, perching layers, as well as zones of high vertical conductivity, causing heterogeneous recharge (Hicks and others, 1987). In portions of the Upper Floridan, recharge can be as high as 3 m per 10 cm of precipitation (Stewart and others, 1999). Recharge dynamics near the Flint River are highly variable with ground water response to precipitation being between almost none to multiple meters per year (Torak and Painter 2006). Additionally, large portions of the Ocala responding to precipitation recharge as a single unit due to the interconnectedness of solution conduits (Stewart and others, 1999).

Upland recharge to the Upper Floridan aquifer flows through weathered carbonate toward ephemeral and perennial streams, particularly the Flint River (Hicks and others 1987). Down-gradient movement toward groundwater discharge points in streams occur under typically observed climate and weather conditions.

Surface-Subsurface Interactions

Natural or anthropogenic changes to baseflow influence major streams because perennial features in the Dougherty Plain are incised into the Upper Floridan. These deeply incised streams can also influence the Upper Floridan if natural or anthropogenic effects change surface waters. Discharge from the Upper Floridan provides baseflow to the perennial streams in the Dougherty Plain (Maslia and Hayes 1988), and as such, aquifer water levels influence stream stages throughout the year.

Irrigation Effects
Irrigation and industrial water use are the primary causes of recent low-flow and no-flow conditions in southwest Georgia because there are no significant changes in precipitation patterns between post- and pre-irrigation years (Golladay and others 2007). Numerous small streams and drainages in close proximity to groundwater pumping have been identified as vulnerable to extreme low flow conditions within the lower ACF (Albertson and Torak 2002). For example, irrigation using surface water and groundwater significantly influence Ichawaynochaway Creek (Rugel and others 2009).

The combination of these two irrigation methods result in observed rapid responses of streams (Couch and McDowell 2006, Rugel and others 2009). Many streams, such as Ichawaynochaway Creek have experienced significantly reduced summer seasons baseflow during the current irrigation era relative to pre-irrigation years, causing some streams to switch from gaining to losing streams (Albertson and Torak 2002). Single day minimum stream flow has decreased approximately 40% for Ichawaynochaway Creek and 46% for Spring Creek (Golladay and Hicks 2009).

Irrigation has also led to extensive no-flow periods (up to six months) in Spring Creek (Rugel and others 2009), which can be exacerbated during seasonal and extended droughts (Rugel and others 2012, Golladay and Hicks 2013). Due to the interconnectedness of conduits in the aquifer, no distinct cones of depression are associated with heavy groundwater withdrawals in the Dougherty Plain (Hicks and others 1987, Warner Gordon and others 2012).
**Isolated Wetlands**

Isolated depressional wetlands are an abundant feature on the Dougherty Plain (Hicks and others 1987) with an estimated 11,600 occurring throughout this physiographic province of Georgia (Martin et al 2012). The hydrology of these wetlands is primarily driven by precipitation and evapotranspiration with some wetlands receiving inputs from one or more of the following: occasional episodic surface flows, rare river flooding events, or extreme high ground water periods. Regional water tables can influence these wetlands when groundwater levels are above normal (Hendricks and Goodwin 1952). When wetland stages are high, additional precipitation can cause spillage that allows groundwater recharge or episodic flows (Figure 4). These wetlands may have been insignificant to groundwater recharge during normal precipitation conditions (Hendricks and Goodwin 1952), but recent increases in groundwater withdrawals (Rugel and others 2012) could increase the importance of these small inputs during occasional spill events.

**Proposed Conceptual Model**

We present three hypotheses related to a conceptual model of isolated wetlands and episodic flows on the Dougherty Plain of Southwest Georgia:

1. Isolated wetlands are significant local and collective components of the surface hydrology;

2. Episodic flows connecting typically isolated surface waters to perennial streams contribute significant fluxes of water, nutrients, carbon and organisms to downstream waters; and
3. Groundwater is the dominant hydrologic factor in some isolated wetlands, baseflow in ephemeral streams, and influence select reaches of episodic flow paths.

**Proposed Research Needs**

We suggest testing the first hypothesis (conceptual model) at local scales using detailed hydrologic monitoring and both statistical and physical modeling of isolated wetlands in context of connectivity to other waters. At regional scales we suggest incorporating isolated wetlands as features in spatial models (i.e. SWAT). At local scales, we also suggest testing this hypothesis by monitoring wetland biological, chemical and physical water quality in context of connectivity to other waters. In regional scale studies, we suggest using remote sensing methods for comparing eutrophication, sediment content and inundation frequency of typically isolated wetlands in context of connectivity to other waters.

At local scales, we suggest testing the second hypothesis with detailed monitoring of episodic flow paths, particularly where these flows connect isolated wetlands within complexes or connected isolated wetlands to nearby streams. While isolated wetlands have been rigorously modeled in the Dougherty Plain (Martin et al 2012), we found no formal mapping investigations or spatial assessment of episodic flows in the Dougherty Plain. Therefore, we suggest using both remote sensing and geographic information systems methods to map and create likelihood indices for episodic flow paths in the Dougherty Plain.

We suggest testing the third hypothesis using both field and modeling approaches. Data collected from surface waters during routine monitoring, such as conductivity or samples for ion analysis, could be used in mixed modeling analyses to establish the end members of hydrologic
inputs. Connection between groundwater and isolated surface water bodies could also be modeled using mass balance approaches in combination with USGS groundwater elevation data. A major underpinning assumption of wetland hydrology studies in the Dougherty Plain is that leakage is negligible, however, there are no rigorous studies testing this assumption.

Conclusions

The geology and hydrogeology of the Dougherty Plain has been thoroughly studied, as have the perennial surface waters of this physiographic province. While further investigation of both topics is highly important, our review highlighted research needs surrounding temporarily inundated surface waters in the Dougherty Plain. Another focal area that we identified is the links between groundwater and small isolated wetlands. These wetlands fill and spill at irregular episodic intervals which could infiltrate to groundwater. Additionally, it is not known if wetlands receive groundwater inputs when aquifer levels spike during abnormally wet years. This highly distinct physiographic province is an ideal setting to study temporary waters and connections between seemingly isolated aquatic systems.

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### Tables

**Table 2.1.** Land use and land cover of the Dougherty Plain (Source: 2006 National Land Cover Dataset).

<table>
<thead>
<tr>
<th>Land use / Land cover</th>
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<tr>
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<tr>
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<tr>
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</tr>
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<td>0.4</td>
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<td><strong>Total</strong></td>
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<td><strong>11.7</strong></td>
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Figure 2.1. Location map for the Dougherty Plain physiographic province in southwest Georgia.

The region includes all or parts of ten Georgia counties and shows a distinct lack of small order streams.
<table>
<thead>
<tr>
<th>Era</th>
<th>Period</th>
<th>Epoch</th>
<th>Group</th>
<th>Formation</th>
<th>Hydrostratigraphy</th>
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<td>Suwanee</td>
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<td>Upper Eocene</td>
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<td>Upper Floridan aquifer</td>
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<td>Claiborne aquifer</td>
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<td></td>
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<td>Paleocene</td>
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<td>Bashi and Hatchetigbee</td>
<td>Wilcox aquitard</td>
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<td></td>
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<tr>
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<td></td>
<td></td>
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<td>Tuscahoma</td>
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</tr>
<tr>
<td></td>
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<td>Nanafalia and Baker Hill</td>
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<td>Providence aquifer</td>
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</tbody>
</table>

**Figure 2.2.** Litho- and hydro-stratigraphy of the Dougherty Plain (modified from Hicks and others, 1987 and Warner Gordon and others, 2012).
Figure 2.3. Soil series (A), geology (B), isolated wetlands and other water bodies (C), land use / land cover (D), soil drainage (E), soil texture (F), elevation, (G) slope-percent rise (H)
Figure 2.4. Conceptual models of isolated wetlands and episodic flow on the Dougherty Plain, Southwest Georgia. A) Episodic connections that link isolated wetlands to nearby perennial streams, which are maintained by groundwater baseflow but could be substantially affected by episodic surface inputs. B) Transient connections between individual isolated wetlands. C) Ephemeral streams that receive episodic inputs from runoff generated stormflows and baseflow during seasonally or annually high groundwater levels.
Figure 2.5. Proposed research needs related to isolated wetlands and episodic flows on the Dougherty Plain of Southwest Georgia, including the effects of isolated wetlands on hydrology and water quality (top), the effects of temporary or episodic flows on perennial and seasonal streams (middle), and the interaction of surface and groundwater in wetlands, episodic flows and seasonal streams (bottom).
CHAPTER 3

HYDROLOGY AND WATER QUALITY OF ISOLATED WETLANDS:
STORMFLOW CHANGES ALONG TWO EPHEMERAL FLOWPATHS

Abstract

A large storm (~173 mm of rainfall) generated a three-week episodic surface flow event between Feb 15 and Mar 9, 2014, through a flat, unchanneled swales on karstic, depressional landscape with numerous isolated wetlands in Southwest Georgia. This event resulted in overland and concentrated flows between and through isolated wetlands that rarely interact. This study examines the hydrologic and water quality changes along two flowpaths within the longleaf-pine, wiregrass ecosystem at the Joseph W Jones Ecologic Research Center at Ichauway. Overland (sheet) flow was generated by offsite agricultural fields as well as by onsite (natural forest) vegetation. A suite of physical parameters, nutrients, and pathogen indicators were monitored daily at five sites along the first flowpath (two wetlands), and at two sites along the second flowpath (one wetland). A general trend of decreasing sediment, nutrient, and pathogen concentrations was observed as water moved between and through usually isolated wetlands. Two field-measured parameters, specific conductance and turbidity, were strongly ($r > 0.8$) to moderately ($r > 0.5$) correlated with most other measured water quality parameters, which suggests that they can be used as proxies for these laboratory-measured parameters (e.g., ammonium, nitrate, phosphate, and suspended solids) for rapid assessments of water quality in these systems.

Keywords: isolated wetlands, stormflow, agricultural runoff, water quality, Dougherty Plain, nutrients
Introduction

Water resource managers in the southeastern United States are facing new challenges due to increased agricultural development and burgeoning populations (Rugel et al. 2012). Aquatic systems in the region routinely suffer from water-quality impairments due to stormwater inputs of sediments, nutrients, and pathogens. These nonpoint inputs are large and frequent due to the region’s high precipitation and intensities. Once generated, stormwater is rapidly conveyed to nearby waterways, with occasional detention prior to discharge.

Isolated wetlands are a frequent feature within agricultural landscapes across the United States. While many of these wetlands occur in glaciated (e.g., the prairie-pothole region of the Midwest) or karstic regions (e.g., coastal plains of northern Florida and southwestern Georgia), isolated wetlands of less obvious geologic origin are also common along the coastal plain of the mid-Atlantic (e.g., Delmarva bays) and other Southeastern states (e.g., Carolina Bays). Wetland complexes may play a disproportionate role in the ecology and hydrology of the watershed relative to their spatial area. Also, episodic connectivity between isolated wetlands and streams potentially serve important functions to downstream perennial streams through temporary inputs of materials and energy, particularly in regions with few low-order streams.

Isolated wetlands have the opportunity to improve water quality by fostering sedimentation and increased biogeochemical processing (Pennock et al. 2010, Laudon et al. 2016). Wetlands can also collect and store upland stormflows during periods of intense precipitation (Lane and D’Amico 2010). The small area of wetlands embedded along flowpaths may act disproportionately to improve stormwater quality relative to larger upland areas due to their longer residence times and concomitant assimilation of pollutants.
The Dougherty Plain of southwestern Georgia (Figure 1) is a 669,000-ha physiographic region with approximately 12,000 isolated wetlands (Hicks et al. 1987, Martin et al. 2012). The region lacks headwater streams because deep sands are underlain by highly permeable, vuggy carbonate bedrock that serves as the primary landscape drainage system. Overland and concentrated flows are rare, only occurring in response to large storm events (Hicks et al. 1987).

Depressional features with embedded wetlands are common within this carbonate environment (Hicks et al. 1987, Martin 2012). When overland flows occur, water accumulates in depressional features (commonly wetlands), which may then overflow into ephemeral flowpaths, and thence into other wetlands or perennial waterways. For most rainfall events, this fill-and-spill system effectively retains stormwater flows and entrained pollutants.

While the landscape was originally forested, the region was converted to pasture and row-crop agriculture over the past century (Martin et al. 2013). These agricultural practices have altered both the timing and quality of stormwater runoff, which results in increased nonpoint discharge and loading. Within this agriculturally dominated landscape lies a remnant longleaf-pine (*Pinus palustris*), wiregrass (*Aristida stricta*) forest ecosystem with embedded wetlands on a 12,000-ha property managed by the Joseph W. Jones Ecological Research Center (Ichauway) in Baker County, Georgia (Drew et al., 1998). At Ichauway, episodic stormflows arise in upland areas that then pass through normally isolated wetlands, which may flow into perennial streams following extreme rainfall events.

Stormflows provide episodic sources of water (Wilcox et al. 2011, Hosen et al. 2014, McDonough et al. 2015) as well as dissolved and suspended matter ranging from nutrients and dissolved carbon to sediments and coarse woody debris (Fenner et al. 2011, Yang et al. 2013). In
some ecosystems, such short-duration inputs of matter and energy can have lasting impacts on nearby perennial streams or provide pulses that contribute to temporal variation in stream communities (Gu et al. 2012, Strayer 2014). While pulses of nutrients or carbon stimulate microbial communities (Buffam et al. 2001) and can lead to episodic blooms of algae or filter feeding organisms, lasting impacts can be in the form of woody debris or sediment deposition in the channel (O’Hop and Wallace 1983, Rickerman and Koschi 2010).

Also, the relatively large ecotone between isolated wetlands and upland forests can result in biogeochemical hotspots within the larger landscape (Xiao et al. 2012, Lane et al. 2015, Cohen et al 2016, Rains 2016). Elevated biogeochemical activity has been observed in backwater and flow-through wetlands with dynamic hydrologic connections to other waters within the Atchafalaya basin relative to continuously connected wetlands (Jones et al. 2014). The organic matter abundance in wetlands makes them natural sources and hotspots of DOM on the landscape during storm events. This is particularly true for wetlands that are forested or embedded in forests (Hinton et al. 1998, Inamdar et al. 2012).

Isolated wetlands can also act as hotspots of biogeochemical activity within agricultural landscapes (Palta et al. 2014, Marton et al. 2015) where the dominant uplands have relatively low biogeochemical activity (Zhu et al. 2013, Lane et al. 2015). Consequently, stormflow movement through isolated wetlands is of interest because of their potential roles as both hotspots and hot moments.

Recent findings concerning interactions between surface and groundwater have highlighted a need for further understanding of hydrologic connectivity within watersheds of the Dougherty Plain (Rugel et al 2016). Quantifying the water quality at various points along the
flowpath through Ichauway could highlight the role of uplands and the role of wetlands during these watershed hot moments.

Understanding the relative roles of isolated wetlands within flows could quantify their importance to the long-term health of watersheds in the Dougherty Plain. This insight is important from a management perspective because it informs management of both upland and wetland sections of episodic flow channels (Nadeau and Rains 2007).

The study goal is to quantify the degree to which isolated wetlands embedded within episodic flowpaths mitigate stormwater from agricultural areas, specifically our objectives were to: 1) Quantify temporal and spatial patterns of stormwater quality during a flow event; and 2) Determine the correlation among parameters to indicate possible monitoring variables that could be used to infer responses of other water quality variables.

Methods

Site Description

This study was conducted at the Joseph W. Jones Ecologic Research Center (Ichauway), which is dominated by a longleaf-pine, wiregrass forest with embedded isolated wetlands (Martin et al. 2013). Multiple episodic flowpaths are known to cross Ichauway and have been mapped through heads up digitizing. We selected two episodic flowpaths because they originate on agricultural lands (Figure 1), which are observed sources of stormwater runoff. These flows occur as overland flow through poorly defined channels that only inundate in response to discrete storm events. The flowpaths are typically upland ecosystems and are not dry streambeds.

Episodic stormflows from offsite agricultural sources and onsite forests travel through indistinct flowpaths that are underlain by deep sands with interbedded clay layers (Figure 2).
During our study period, stormflows were sufficient to fill these typically dry flowpaths and to hydrologically connect normally isolated wetlands. Between June, 2012 and March, 2015 three episodic surface flow events were observed (February 25th through March 7th 2013, August 24th through September 10th 2013, and February 15th through May 5th 2014). The last flow event was sampled during the first three weeks of flow (February 15th through March 9th 2014).

The smaller of the two flowpaths, Parmalee Drain, begins within an offsite agricultural field and then flows onsite for approximately 2 km to its confluence with Big Cypress Creek, an intermittent tributary to Ichawaynochaway Creek. Shortly after entering the site, Parmalee Drain passes through Wetland 27 (W27), which covers approximately 6.73 ha. Both the inflow and outflow of W27 were sampled for water quality. The inflow site (W27-in) is located approximately 150-m downstream of the site boundary, while the outflow site (W27-out) is about 300-m downstream of W27-in (Table 1). The inflow flowpath was moderately well defined and roughly 10-m wide but shallow and normally dry or too shallow to sample. The outflow location was better defined due to the presence of a road and culvert, where it is approximately 4-m wide.

The longer flowpath, Ichauway Drain, passes through agriculturally modified wetlands before flowing onsite. Once onsite, Ichauway Drain extends for some 12 km through multiple wetlands before its confluence with Ichawaynochaway Creek, a perennial tributary to the Flint River (Figure 1). Sampling in Ichauway Drain started at the site boundary (TID), and continued downstream at the inflow and outflow points of Wetlands 04 (W04) and 68 (W68). Inflow to Wetland 04 (W04-in) is approximately 2.3 km downstream of site inflows (TID), while the outflow (W04-out) is about 750-m downstream of inflows. Inflow to Wetland 68 (W68-in) is
about 510-m downstream of W04-out, and outflow (W68-out) is about 360-m downstream of W68-in. Inflow locations to both W04 and W68 are well defined, with saturated widths between 4-10 m, depending on flow conditions. While the outflow location from Wetland 04 is also well defined (width between 4-10 m), outflow from W68 was poorly defined, with a flow width between 20-50 m, depending on flow conditions.

**Data Collection**

A series of precipitation events occurred at Ichauway between Feb 13 and Mar 5, 2014. The combination of wet antecedent soil-water conditions along with copious precipitation (~173 mm, Table 2) generated substantial stormflows that filled normally dry flowpaths. These flows accumulated in isolated wetlands, mixed with antecedent wetland water, and resulted in spilling to downstream flowpaths. While most stormflows were contained onsite, some flow reached Ichawaynochaway Creek after filling the normally dry flowpaths.

Sampling began when five of the six sites along Ichauway Drain were inundated to a minimum depth of 10 cm and both sites on Parmalee Drain were inundated to 10 cm. Daily field observations and water-quality samples were collected for the first three weeks of flow (Feb 15 to Mar 9, 2014).

A total of 461 water-quality samples were collected out of the possible 483 samples (i.e., triplicate samples at seven sites for 23 days). The missing samples (less than five percent of the total) were not collected due to insufficient water depth (esp. W27-in) or benthic-sediment contamination.

Field measurements of water temperature and specific conductance at all sites were collected using an OTT Quanta Multiprobe (OTT Hydromet, Kempten, Germany). Concomitant
turbidity measurements were obtained using a Hach 2100p field turbidimeter (Hach Comp, Loveland CO). Triplicate, half-liter water samples were collected and filtered within 72 hours of collection using a 0.7-µm glass-fiber filter, placed in HDPE vials, and stored at 4°C prior to analysis. Nutrients (ammonium, nitrate, phosphate) were determined using an auto-analyzer (Lachat Quikchem 8500, Hach Company, Loveland, Colorado) and standard colorimetric methods in the analytical laboratory at the Joseph W. Jones Ecological Research Center (Battle and Golladay 2001).

Coliform bacteria (total coliform and E. coli) were analyzed using IDEXX Colilert Defined Substrate Technology (Desai and Rifai 2013). Because undiluted samples often exceeded the maximum detection limit, bacteria samples were diluted (2:1) with sterile, deionized water. Each 100-mL sample was mixed with Colilert media until dissolved, poured into a Quanti-tray 2000 (97-well) unit, sealed, incubated for one week at 38°C, counted to determine bacterial abundance, and then multiplied by the dilution ratio.

Data Analysis

T-tests were used to determine differences in means between sites for each water quality parameter in Parmalee Drain using MATLAB (R2014a). Analysis of Variance (ANOVA) was computed between sampling sites for all water-quality parameters in Ichuaway Drain using MATLAB (R2014a). For ANOVA-identified significant differences (p<0.05), mean comparisons among sites were made using Tukey Honest Significant Difference tests using MATLAB (R2014a).
Results

Parmalee Drain

ANOVA analysis of daily stormflow samples along the smaller flowpath, Parmalee Drain, indicates significant (p<0.05) water-quality changes across Wetland 27. A comparison of inflows (W27-in) with outflows (W27-out) shows reductions in virtually all water-quality parameters, including nutrients (NH4, NO3, PO4), bacteria (ECOLI), and dissolved solids (COND, TURB).

This wetland is immediately downstream of agricultural fields and routinely receives stormwater following storm events. Between W27-inflow and W27-outflow mean parameter values decreased by an order of magnitude or more for NO3 and E.coli, and at least half for NH4, PO4, and turbidity.

Ichauway Drain

Fewer significant water-quality changes were observed along Ichauway Drain, with several parameters decreasing (NH4, PO4, COND, TURB). ECOLI decreased between TID and W68-out, but did not change significantly across either wetland. A significant NH4 decrease was observed between TID and W04-out, as well as between W04-in and W68-out, but not between TID and W04-in or within either wetland (Figure 3).

Parameter Correlations

We identified two physical parameters (one conservative and one non-conservative) that are strongly correlated with chemical or biological water quality parameters: specific conductivity and turbidity. These two parameters are rapid and effective field measurements that can potentially be used as field indicators or monitoring targets for parameters normally
requiring laboratory analytical techniques. Specific conductance most strongly correlated with Cl, NH4 NO3, and SO4, whereas turbidity most strongly correlated with mass of filtered solids, PO4, and Fl (Table 3.2). Temperature is an easily measured variable but does not appear to be as strongly correlated with other parameters.

**Discussion**

Substantial and significant water quality improvements were observed along each flowpath from agricultural areas though forested uplands and isolated wetlands. Improvements along episodic flowpaths were found for all three types of water-quality parameters (i.e., physical, chemical, biological), which provide evidence that these flowpaths are an important component of regional mitigation of agricultural runoff. While large water-quality changes were observed both spatially and temporally as a result of stormflows, a consistent primary mechanism (biogeochemical processes vs. stormwater dilution) was difficult to identify across parameters and drains.

The monitoring targets identified by parameter correlation show promise for management purposes because both specific conductance and turbidity are simple, rapid, and reliable field measurements. These parameters could be used in future studies on these two particular episodic surface flows to estimate water quality conditions during events where collection of physicochemical data is not a priority. Such studies might include sampling for fish, macroinvertebrates, or dispersing amphibians during episodic flow events (Zeng and Rasmussen 2005). Addition of a rapid physicochemical water quality assessment to such studies would provide insight to the water quality conditions and possible stressors faced by these organisms when using agricultural runoff generated flow events for dispersal.
Conclusions

This study presents stormwater-quality changes along two flowpaths within a longleaf-pine, wiregrass forest ecosystem at the Joseph W. Jones Ecological Research Center (Ichauway) located on the Dougherty Plain in Southwest Georgia. Both flowpaths receive episodic stormflows from offsite agricultural sources that then fill-and-spill as they travel through normally dry flowpaths and isolated depressional wetlands. The first flowpath travels through a single wetland, while the second, longer flowpath travels through an indistinct flowpath with embedded wetlands.

Water-quality during episodic flows improved for multiple biological, chemical, and physical parameters. A general trend of decreasing sediment, nutrient, and pathogen concentrations was observed as water moved between and through isolated wetlands.

Wetland 27 receives flows from Parmalee Drain, which originates in an agricultural field immediately adjacent to Ichauway. Flows in Ichauway Drain are also generated by offsite agricultural runoff that likely passes through multiple wetlands prior to entering the site, and then passes through a forested landscape with embedded wetlands (Wetlands 04 and 68), which are typically isolated except during episodic flow events.

Greater water-quality improvements were found when episodic flows had shorter flowpath residence times prior to entering the wetland; more gradual changes occurred when runoff had longer flowpath residence times. The observed improvement in water quality is the likely result of a combination of biogeochemical activity, physical sequestration, and flow dilution by runoff from adjacent longleaf-pine, wiregrass ecosystems. We conclude that –
regardless of mechanism – isolated wetlands in the Dougherty Plain improve the water quality of episodic flows.

Wetlands in the Dougherty Plain thus have the potential to improve the water quality of receiving streams, such as the Flint River and Ichawaynochaway Creek. Individually, these flows may not form a substantial portion of the flow in a given perennial waterbody, but may cumulatively account for a substantial portion of the sediment, nutrient, and pathogen load in episodic flows (Golden et al. 2016, Rains et al. 2016).

Water-quality improvements were observed in wetlands as well as in flowpaths embedded within forested landscapes, which suggests that wetlands and forested landscapes are useful for mitigating agricultural runoff. We were also able to identify the agricultural source for each flowpath, which served as a specific input of nutrients and sediments during episodic flow events. This was possible because of the unique topography of the karstic Dougherty Plain, coupled with the stormwater-quality characteristics of agricultural runoff. We suspect that water quality in coastal physiographic provinces with few headwater streams could be improved by focusing on these identified sources.

And finally, specific conductance and turbidity emerged as useful field parameters for assessing water-quality alteration by agriculture. Most parameters were strongly (r > 0.8) to moderately (r = 0.5) correlated with one (or both) of these parameters. Because these parameters are easily and reliably measured in the field, they would be useful for long-term monitoring of water-quality degradation, and can be used as proxies for parameters that are normally measured in laboratory settings (e.g., ammonium, nitrate, phosphate, dissolved organic carbon, and
suspended solids). These field parameters could also be used for future studies on the regional effects of episodic flows on the Dougherty Plain.

Acknowledgements

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Literature Cited


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DOI:10.1002/hyp.10610


DOI:10.1016/j.apgeochem.2012.10.004

Tables

Table 3.1. Wetland stage, area volume, sampling site locations, cumulative distance along flowpath, and number of samples collected. Sampling dates: 2/15/2014 through 3/9/2014.

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<th>Long.</th>
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Table 3.2. Correlations and significance of correlations between field and laboratory water-quality parameters.

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<th>p-value</th>
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Figures

Figure 3.6. The Joseph W. Jones Ecological Research Center at Ichauway is located on the Dougherty Plain of southwest Georgia (A). Episodic sampling sites are denoted in red
and orange along each respective drain, which have been mapped through heads-up-digitizing.

**Figure 3.7.** Conceptual models of Ichuaway (A) and Parmalee (B) Drains showing hydrogeologic cross-sections of these episodic flow systems.
Figure 3.3. Precipitation that initiated and sustained flow during the sampling period.
Figure 3.4. Wetland hydrographs during sampling period.
Figure 3.5. Physical water quality parameters, nutrients, and pathogen indicators along Ichuaway Drain. The same letter above two locations indicates no statistically significant difference (p>0.05). Decreases occurred for ammonium (a), phosphate (c), *E. coli* (g) specific conductance (h), and turbidity (i).
Figure 3.6. Physical water quality parameters, nutrients, and pathogen indicators along Parmalee Drain. The same letter above two locations indicates no statistically significant difference (p>0.05). Decreases occurred for NH4 (a), NO3 (b), PO4 (c), E. coli(g), specific conductance (h), and turbidity (i).
CHAPTER 4

WETLAND AND STREAM WATER QUALITY VARIATION

IN A KARSTIC LANDSCAPE WITH AGRICULTURAL INFLUENCES

Abstract

Large precipitation events can produce episodic surface flows that connect typically isolated wetlands to other nearby surface waters. The influence of episodic flows on isolated wetlands may endure beyond the temporal duration of a particular event. Our objective was to determine if wetlands connected to other surface waters by episodic surface flows with short (<2 year) return periods differ from those that are not regularly influenced by surface flows.

We monitored thirty-one isolated wetlands embedded in a restored longleaf-pine, wiregrass ecosystem centrally located within the Dougherty Plain physiographic province in southwest Georgia. Wetlands that we monitored fell into three categories: isolated from flows with return periods greater than two years (n=19), wetlands receiving agricultural runoff with return periods less than two years (agriculturally connected, n=6), and receiving forest or wetland runoff with return periods less than two years (forest connected, n=6). We also monitored nine stream sites for reference purposes; three sites on a small intermittently flowing stream (Big Cypress Creek), three sites on a third-order stream (Ichawaynochaway Creek), and three sites on a fourth-order stream (Flint River).

Sites were sampled monthly for one year following an episodic flow event to measure pathogen indicators (total coliform and E. coli), nutrients (ammonium, nitrate, phosphate, dissolved carbon), and physical parameters (wetland stage, suspended solids, specific conductance, temperature, and turbidity). Wetlands influenced by agricultural runoff behaved differently than isolated wetlands for several of the measured water quality parameters. Streams sites also differed from isolated and forest-influenced wetlands.
Introduction


Isolated wetlands have also become a focal point of environmental policy due to legal rulings (SWANCC 2001, Rapanos v. United States) where it was determined that the Clean Water Act only applies to isolated wetlands which have a “significant nexus” to nearby perennial waters (Nadeau and Rains 2007, Golden et al. 2016). These rulings prompted research into connections between isolated wetlands and nearby hydrologic features. Examples include hydrologic connections to groundwater (Rains et al. 2006), storm flows (Wilcox et al 2011), and even ecological connections (Gibbons 2003, Willson and Winne 2016), such as migratory species and species that use multiple ecosystems throughout their life cycle (Skagen et al. 2008, Subalasky et al. 2009).
Some isolated wetlands receive discharge from other wetlands or from episodic surface flows generated by upland runoff (Wilcox et al. 2011, Forbes et al. 2012). Such connections serve as temporary conduits of materials and energy between typically isolated features. For example, isolated wetlands embedded along surface flows may influence downstream water quality by reducing sediment transport and transforming nutrients (Wilcox et al. 2011). The quality of water discharged downstream would be a function of mixing antecedent water, precipitation, surface runoff to the wetland, and surface through flow. Isolated wetlands embedded along agricultural runoff surface flow paths will likely have lower water quality and thus discharge lower quality water to nearby streams (Wilcox et al. 2011, Lane et al. 2015). Wetlands that fill and spill due to forest runoff would likely export higher quality water than their agricultural counterparts.

Isolated wetlands devoid of short return surface connections to nearby streams may also be important to nearby streams because they can store and assimilate pollutants received from runoff. Lack of connection may also mean that isolated wetlands embedded in forests can serve as higher quality refugia or breeding grounds for species that move between wetlands and nearby streams, such as the American alligator (Subalasky et al. 2009, Kirkman et al. 2012).

The overarching goal of this project is to compare the lasting effects of episodic surface flows on isolated wetlands. Our first objective was to quantify the differences in water quality among isolated wetlands and wetlands that receive episodic through flow (agricultural or reference). Second, we compared our study wetlands to nearby streams to place wetland water quality into the context of nearby perennial and ephemeral hydrologic features. Our last objective
was to correlate rapid field measured parameters with less rapidly measured parameters to identify monitoring targets.

**Methods**

*Site Description*

The study was conducted on a 12,000-ha site located on lands managed by the Joseph W. Jones Ecological Research Center at Ichuaway in southwest Georgia (Figure 1). The study site is predominantly forested with a managed longleaf-pine, wiregrass ecosystem (Drew et al. 1998). The site is centrally located on the Dougherty Plain, a 669,000-ha physiographic region characterized by karstic topography with deep sands and interbedded clay lenses overlying highly permeable, vuggy limestone bedrock (Hicks et al. 1981, Hicks et al. 1987). This region has abundant pluvial isolated wetlands embedded in upland landscapes (Hicks et al. 1987, Martin et al. 2012) and is intensively developed for agriculture (Martin et al 2013). Episodic flows generated on agricultural fields often flow through isolated wetlands before emptying into perennial waterways on the Dougherty Plain.

*Data Collection*

Thirty-one pluvial wetlands embedded in forested uplands were monitored for one year after an episodic surface flow event. Based on observations made during the event, these wetlands were divided based on connectivity or isolation: 19 isolated wetlands (surface flow return frequency greater than two years), six wetlands that receive forest runoff (surface flow return frequency less than two years), and six wetlands that receive agricultural runoff (surface
flow return frequency less than two years). We also monitored nine locations three local streams: three locations on the Flint River (perennial fourth-order stream), three locations on Ichawaynochaway Creek (perennial third-order stream), and three locations on Big Cypress Creek (seasonally flowing stream) (Figure 1).

Sites were visited monthly for field measurements and sample collection. Field measurements of specific conductance and temperature were collected using an OTT Quanta Multiprobe (OTT Hydromet, Kempten, Germany) at all sampling sites (Figure 1). Concomitant turbidity measurements were determined using a Hach 2100p portable turbidimeter (Hach Company, Loveland, Colorado).

Water samples were analyzed for ammonium (NH4), nitrate (NO3), and phosphate (PO4) using a Lachat Quikchem 8500 (Hach Company, Loveland, Colorado) and standard colorimetric methods in the analytical laboratory at the Joseph W. Jones Ecological Research Center (Battle and Golladay 2001). All water samples were filtered within 72 hours of collection using a 0.7 µm glass fiber filter. Coliform bacteria were analyzed using standard methods for IDEXX Colilert Defined Substrate Technology (Desai and Rifai 2013). Because undiluted samples often exceeded the upper measurement limit, samples were diluted (2:1) with sterile, deionized water. The sample was mixed with Colilert media until dissolved, then poured in Quanti-tray 2000 (97-well) trays and sealed. Samples were incubated for one week at 38°C before determining coliform abundance (MPN).
Data Analysis

Differences in mean parameter values for log-transformed monthly measurements among sites were determined using Analysis of Variance (ANOVA) via MATLAB (R2014a) and used to examine patterns in water quality among wetland types and streams. Mean values were calculated as the mean value of all data collected for each sampling site type (isolated, reference, agriculturally influenced, stream). Approximately 6 to 12 samples were collected at each sampling location with some locations having fewer values due to lack of inundation. Where differences occurred, mean comparisons among site types were made using Tukey Honest Significant Difference (HSD) post hoc tests. Significance was determined by $\alpha<0.05$. Boxplots were used to illustrate patterns in parameter behavior among location types.

Correlations between specific conductance, temperature, turbidity, and all other parameters were used to identify monitoring target variables because these parameters are readily measured in rapid field assessments or with sensors in real time (Zeng and Rasmussen 2005). The concept was to quantify relationships between parameters that were simple / quick to measure and parameters that were expensive /time consuming to measure. Thereby using overall less complex parameters as proxy data for more complex parameters.

Results

Wetlands differed among connectivity types and from nearby streams across a number of parameters when monthly samples were aggregated (ammonium, nitrate, phosphate, E.coli, specific conductance, and turbidity). Ammonium levels were greater in agriculturally connected wetlands than streams and other wetlands (isolated, forest-connected wetlands). Nitrate
concentrations were greater in streams than wetlands that did not differ among connectivity types (Figure 3). Phosphate concentrations were greater in streams and agriculturally connected wetlands than isolated and forest connected wetlands.

Isolated wetlands and streams were similar for *E. coli*, which were lower than agriculture and forest connected wetlands. Specific conductance was highest in streams and did not differ among wetland types. Turbidity was greatest in agriculturally connected wetlands and streams.

Specific conductance and turbidity were moderately correlated with ammonium for wetlands. Weak but significant correlations existed between specific conductance and both phosphate and *E. coli* (Table 2). Turbidity was also weakly but significantly correlated with nitrate, phosphate, and *E. coli*. Temperature was weakly but significantly correlated with nitrate and total coliforms.

Ammonium and phosphate were strongly correlated with specific conductance in streams (Table 2). Specific conductance and nitrate were moderately correlated (negative) in streams. Specific conductance and *E. coli* were weakly but significantly correlated. Turbidity and *E. coli* were moderately correlated. Temperature was strongly correlated with nitrate and phosphate. Temperature was also moderately correlated with ammonium and *E. coli*.

**Discussion**

Isolated wetlands had lower average nutrient, pathogen, and sediment values than either forest or agriculturally connected wetlands. All three wetland types generally had lower nutrient, pathogen and sediment levels than nearby streams. Runoff nutrient inputs to agriculturally
influenced wetlands may account for higher ammonium levels in wetlands through potentially increased decay after greater production in the growing season (Rowland et al. 2016). Turbidity as expected was higher in agriculturally influenced wetlands than the other two wetland types (Bayley et al. 2012).

Higher levels of \textit{E. coli} in agriculturally influenced wetlands were not surprising (Collins and Rutherford 2004, Collins et al. 2005, Trevisan et al. 2010, Guber et al 2011) but similar levels in reference condition wetlands were unexpected. Wildlife use (particularly mammals such as deer, feral hogs, and coyotes) could be associated with \textit{E. coli} in wetlands (Parker et al. 2013, Parker et al 2015) and could account for our observations.

Higher levels of specific conductance in agriculturally connected wetlands could be due to runoff transporting carbonate derived from irrigation or agricultural chemicals to these wetlands. While high specific conductance in streams is likely due to streams being in direct contact with limestone bedrock and receiving base flow that contains relatively high levels of carbonate and other ions (Rugel et al. 2016).

\textbf{Conclusions}

Wetlands isolated from agricultural runoff had lower nutrient, pathogen, and sediment levels than wetlands connected to agriculture. In general, wetlands also had lower levels of these parameters than streams. These data presented are relevant to perennial surface water management in the Apalachicola-Chattahoochee-Flint (ACF) watershed because rapid agricultural, industrial, and urban development in the Dougherty Plain (Rugel et al. 2012), are making even small isolated waters an important aspect of management.
Groundwater and streams are tightly linked due to the karstic bedrock of the Dougherty Plain, which means that industrial, and agricultural use of groundwater can strongly influence surface water availability (Rugel et al. 2012, Rugel et al. 2016). Accordingly, isolated wetlands that not frequently linked to streams or groundwater become a potentially important surface water resource for anthropogenic and wildlife use in the region.

Acknowledgements

The Geological Society of America Student Research Grant supported this research. The J.W. Jones Research Center and the Robert W. Woodruff Foundation also provided funding. We would like to thank Dr. L. Katherine Kirkman for her enormous contributions to the design, intellectual support, analysis, and writing involved in this manuscript. Thanks also go to the Warnell School of Forestry and Natural Resources Landscape Ecology Laboratory and Warnell Aquatic Resources Group (WARG) for draft edits. Special thanks go to field technicians of the Joseph W. Jones Ecological Research Center Plant Ecology Laboratory for their assistance in the field.

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*Ecological Indicators*. 18:131-139


### Tables

Table 4.1. Description of wetlands at the J.W. Jones Ecologic Research Center at Ichauway, Southwest Georgia, USA. Connectivity types include isolate (iso), agriculturally influenced (Ag), and forested reference wetlands (Ref).

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<th>Vol. (m³)</th>
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<th>Max Stage (m)</th>
<th>Type</th>
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Table 4.2. Correlation strength and significance between monitoring targets and other parameters for each wetland type

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<th>Connected Reference Wetland Monitoring Parameters</th>
<th>Agricultural Runoff Connected Wetland Monitoring Parameters</th>
<th>Flint River Monitoring Parameters</th>
<th>Ichawaynochaway Creek Wetland Monitoring Parameters</th>
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85
Figure 4.1: The J.W. Jones Ecological Research Center is located within the Dougherty Plain of southwest Georgia. Sampled wetlands are light green-blue. Big Cypress Creek sampling locations (dark blue), Ichawaynochaway Creek sampling locations are medium light blue and Flint River sampling locations are royal blue.
**Figure 4.2:** Conceptual models of isolated wetland connected to temporary episodic flows (A), isolated from surface connections and isolated wetlands connected to reference condition episodic flows (B) showing geologic and hydrologic cross-sections of episodic through flow systems.
Figure 4.3: Biological, chemical and physical water quality. The same letter above two categories indicates no difference in means. Differences occurred in all parameters (NH4, NO3, PO4, FOC, FIC, FTC, E. coli, total coliforms, specific conductance, and turbidity).
CHAPTER 5

HYDROPATTERN VARIATION AMONG 31 OSTENSIBLY ISOLATED WETLANDS

IN A LONGLEAF-PINE, WIREGRASS ECOSYSTEM

Deemy, J.B., and T.C. Rasmussen. Prepared for submission to *Wetlands Ecology and Management*
Abstract

Small isolated wetlands occurring in dense clusters on the agriculturally developed Dougherty Plain represent substantial surface water storage in this physiographic province. Hydrologic characterization of small isolated wetlands can yield insight to their role within watersheds and as landscape features. The goal of this study was to characterize the hydrology of 31 isolated wetlands with specific regard to stormwater runoff influence embedded within a longleaf-pine, wiregrass ecosystem. Specific objectives included analyzing influence of wetland isolation and connectivity to reference condition stormwater runoff or agricultural stormwater runoff on various hydrologic characteristics of wetlands.

Keywords: agricultural storm runoff, Dougherty Plain, empirical cumulative density function, episodic flows, isolated wetland,

Introduction

Isolated wetland hydropattern has been understudied despite the recognized importance of the unique hydrologic and ecological roles of these ecosystems (Russell et al. 2002, Rains et al. 2006, Subalussy et al. 2009, Lane and D’Amico 2010, McDonough et al. 2015, Cohen et al 2016, Rains et al. 2016). Hydropattern is an important factor in biogeochemical processing (Palta et al. 2014, Marton et al. 2015, Laudon et al. 2016), aquatic habitat provision (Russell et al. 2002, Subalussy et al. 2009, Kirkman et al. 2012), climate moderation (Huryna et al. 2014), precipitation storage (Lane and D’Amico 2010), and storm runoff moderation (Wilcox et al. 2011).
Hydropattern is an important driver of plant communities and as a determining factor in wildlife communities (Konar et al. 2013, Holbrook and Dorn 2016). Wetland hydrology drives amphibian communities through fish persistence or absence (Holbrook and Dorn 2016). Hydrologic influence on amphibian community composition is also a potential driver of carbon and nutrient cycling due to differences in diets of larval amphibians in isolated wetlands. Amphibians are major components of the consumer trophic levels in isolated wetlands and could be a very important driver of isolated wetland biogeochemistry (Whiles et al. 2006, Atkinson et al. 2017).

Understanding hydropattern in isolated wetlands of southwest Georgia could inform water resource and aquatic habitat management. Ecological communities are likely driven by the long term cumulative hydropattern in wetlands rather than short term weather patterns. However, short pulses of inflows and outflows could cumulatively influence long term patterns in wetland hydrology. Empirical cumulative density functions have been suggested and shown to be useful tools in identifying patterns among cumulative wetland hydropatterns through stage frequency analysis (Nilsson et al 2013). Cumulative stage frequencies of wetlands isolated and connected to runoff generated flows can provide information regarding an important driver of these ecosystems. This information is based on accumulating effects of multiple wet and dry periods. It can also account for differing wetland responses to climate patterns.

The purpose of this study is to assess differences among wetlands that are isolated, connected to reference condition flows and those influenced by agricultural stormwater influence. The specific objectives of this study were to (1) compare wetland hydropattern across connectivity types, and (2) compare wetland hydropattern across vegetation types.
Methods

Site Description

The study was conducted in southwestern Georgia at the 12,000 ha Joseph W. Jones Ecological Research Center at Ichuaway. The Jones Center is predominantly vegetated with longleaf pine / wiregrass (Drew et al. 1998) and is centrally located on the karstic Dougherty Plain (Figure 1). This region has abundant isolated wetlands occurring in clusters (Hicks et al. 1987, Martin et al. 2012) and is predominantly developed for agriculture and plantation forestry (Martin et al 2013). Episodic flows generated on agricultural fields often flow through isolated wetlands before emptying into perennial waterways on the Dougherty Plain.

Data Collection

Data were collected from thirty-one pluvial wetlands that divided into various connectivity categories based on the observations made during several flow events (Table 1). Based on observations made during several surface flow events in 2013 and 2014, wetlands were divided based on connectivity or isolation: 19 isolated wetlands (surface flow return frequency greater than two years), six wetlands that receive forest runoff (surface flow return frequency less than two years), and six wetlands that receive agricultural runoff (surface flow return frequency less than two years). All wetlands have at least 10 years of bi-weekly stage data and many have been monitored bi-weekly since the mid-1990s (Table 2). Total recorded stage measurements for each wetland type were 8,473 (isolated), 2,612 (agriculturally connected wetlands), and 3,075 (reference connected) (Table 3).

Data Analysis
Cumulative stage frequency was determined using empirical cumulative distribution functions (ECDF) in MATLAB (R2014a). Empirical cumulative distribution function development and analysis for isolated wetlands is detailed in Nilsson et al. 2013. Empirical cumulative distribution functions for each wetland type were compared across connectivity types using Kolmogorov-Smirnov tests (Nilsson et al. 2013). Kruskal-Wallis tests were used to determine differences in dry bed frequency.

**Results**

*Connectivity Type*

When compared the average empirical cumulative distribution functions showed that isolated and agricultural runoff influenced wetlands differed (p=0.0209). Isolated wetlands and wetlands connected to reference runoff also differed in stage frequency distributions (p=0.0456). However, agricultural runoff influenced wetlands did not differ from wetlands connected to reference condition runoff stage frequency distribution (p=0.658). Dry bed frequency did not differ among connectivity types (p=0.8123) (Figure 3, Table 4).

Mean depths at the 1st percentile were similar between connectivity types 0.0057 m (isolated) and 0 m for both connected wetland types (Table 5). At the 25th percentile mean wetland stages began to differ more substantially between isolated at 0.503 m and the connected wetland types 0.3525 m (agriculturally connected) and 0.3175 m (reference connected). The relative difference between connected and isolated wetlands remained approximately the same at the 50th percentile: 1.02 m (isolated), 0.71 m (agriculturally connected), 0.65 m (reference connected). At the 75th percentile mean wetland stages began to further diverge between isolated
and connected wetlands with isolated wetlands at 1.5375 m, agriculturally connected at 1.0775 m, and reference connected at 0.9825 m. At the 99\textsuperscript{th} percentile the mean depths become further separated with isolated wetlands reaching 2.563 m, agricultural wetlands reaching 1.7628 m, and reference condition wetlands reaching 1.4817 m.

*Dominant Vegetation*

When compared the mean empirical cumulative distribution functions showed that cypress-gum wetlands and cypress savannas differed (p<0.001) (Figure 3, Table 4). Marshes and cypress savannahs also differed in stage frequency distributions (p=0.029). However, cypress-gum wetlands and marshes were similar in stage frequency distributions (p=0.226). Dry bed frequency did differed among cypress-gum swamps and cypress savannahs (p=0.032) (Figure 4).

At the 25\textsuperscript{th} percentile mean wetland stages began to differ with both cypress gum wetlands and marshes at 0.4625 m and 0.4725 m respectively and cypress savannahs at 0.315 m. The relative difference between vegetation types remained similar at the 50\textsuperscript{th} percentile: 0.94 m (cypress-gum), 0.96 m (marshes), 0.645 m (cypress savannahs). At the 75\textsuperscript{th} percentile mean wetland stages began to further diverge between cypress-gum wetlands / marshes (both at 1.4175 m) and cypress savannahs at 0.975 m. At the 99\textsuperscript{th} percentile the mean depths become further separated with cypress-gum wetlands reaching 1.9659 m, marshes reaching 2.575 m, and cypress savannahs reaching 1.4218 m.
Discussion

Differences in wetland stage frequency were found based on connectivity and vegetation type. Stage frequency differences between isolated wetlands and both types of connected wetlands are likely the product of the concomitant influence of occasional surface flow and wetland geometry. The extreme ends of the stage frequency distributions seem to be influenced by precipitation which agrees with previous observations in the Dougherty Plain (Hicks et al. 1987). The resulting water stored from precipitation appears to be substantially different among these wetlands based on the results of the empirical density functions and follow up percentile analysis.

Geomorphology may also be a driver in wetland plant communities as stage frequencies differed among wetland vegetation types. Hydropattern is a driver of wetland vegetation community composition; therefore it would be logical that communities may separate out according to stage frequency (Kirkman et al. 2000, Gann and Richards 2015, Ward et al. 2015). This provides an interesting context to future investigations of the relationship between geomorphology and hydropattern of isolated wetlands.

Interactions of hydrology and fire frequency have been suggested to produce different plant communities in wetlands of the Dougherty Plain (Stuber et al. 2016) which may suggest that stage frequency differences identified by this study are likely to contribute to differences in vegetation rather than vegetation driving differences in stage frequency. This may indicate that isolated wetland geomorphology controls hydrology and drives wetland plant community composition. While this study did not identify a difference in dry day frequency based on
connectivity, we did identify a range of dry day frequencies in each connectivity type which likely influences the vegetative community composition of these wetlands. In turn this has ramifications for the wildlife communities observed in these wetlands.

It is recommended that future research should improve on this study increasing the observation frequency to daily or finer scale temporal measurement frequency. We have confidence that our bi-weekly data is representative of the conditions in these wetlands due to the period of record length, however, we believe daily data would improve the study with more detailed information that may yield better insights to the dry day frequency. Another future aspect of this research should be the investigation of how stage frequency differences influences wetland nutrient cycling. Furthermore, concomitant feedbacks between biogeochemical cycles and faunal communities of isolated wetlands should be investigated as a function of stage frequency based on connectivity status and vegetation type.

Conclusions

This study presents analysis of long term hydrologic monitoring of isolated wetlands at the Joseph W. Jones Ecological Research Center. Wetlands were analyzed based on connectivity status (isolated, connected to agricultural runoff, connected to reference condition runoff) and dominant vegetation class (cypress-gum swamp, marshes, cypress savannahs). Our results indicate that isolated wetlands have different hydrologic drivers than both types of wetlands connected to episodic surface flows. We also found that each vegetation class is likely produced by different hydropatterns.
Isolated wetlands and connected wetlands differed in overall stage frequency but not in dry day frequency. Isolated wetlands also exhibited greater maximum depths. We believe that similarity in dry day frequency are because the wetlands all experience similar weather patterns due to close geographic proximity. However, stage frequency differs among wetland connectivity and we believe that connectivity is a product of geomorphologic differences in these two categories of wetlands.

Wetland vegetation types at Ichuaway also exhibited differences in stage frequency and differences in mean dry bed frequency. We interpret this data to mean that wetland vegetation types are likely produced, at least in part, by differing hydropatterns. Cypress-gum swamps and marshes had similar stage frequencies and dry bed frequency so we believe that they have similar water storage characteristics but may also be driven by longer-term patterns in vegetation recruitment or fire frequency.

Stage frequency is an important hydrologic characteristic for understanding wetland ecosystems because it drives patterns in nutrient and carbon cycling which in turn influence the biological composition of these isolated features in the Dougherty Plain. Our results show that both connectivity type and vegetation type are associated with different stage frequency patterns. Vegetation is also associated with differences in dry bed frequency. Both of these findings have implications for how the biotic community of each wetland may be structured. Future research should build on this principle to understand the combined effects of connectivity and vegetation type on isolated wetland biogeochemistry as well as ecological structure and function.
Literature Cited


McDonough, O.T., Lang, M.W., Hosen, J.D., Palmer, M.A. 2015. Surface hydrologic connectivity between Delmarva bay wetlands and nearby streams along a gradient of agricultural alteration. Wetlands. 35:41-53


### Table 5.1: Wetland Description

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<th>Perimeter (km)</th>
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<th>Lowest Elevation (m)</th>
<th>Highest Elevation (m)</th>
<th>Max Stage (m)</th>
<th>Con. Type</th>
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Total: 14,160
Table 5.2. Mean wetland geometric parameters by type

<table>
<thead>
<tr>
<th>Wetland Type</th>
<th>Mean Max Stage (m)</th>
<th>Mean Area (ha)</th>
<th>Mean Perimeter (km)</th>
<th>Mean Volume (m³)</th>
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<tr>
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Table 5.3. Descriptive statistics for wetland stage ECDFs across connectivity and vegetation types.
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<th>n</th>
<th>Total Obs.</th>
<th>Mea</th>
<th>Std. Dev</th>
<th>Min (m)</th>
<th>Median (m)</th>
<th>Max (m)</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Cypress / Gum</td>
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104
Table 5.4. Kolmogorov-Smirnov comparisons of mean ECDFs for connectivity and vegetation type

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Table 5.5. Mean stage at select percentiles (m)

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<th>10th</th>
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<td>Cypress / Gum</td>
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<td>1.183</td>
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Figure 5.1. The J.W. Jones Ecological Research Center is located within the Dougherty Plain of southwest Georgia. Sampled wetlands are light green-blue. Temporary flow lines Big Cypress Creek, Ichawaynochaway Creek, and Flint River are light blue.
Figure 5.2. Conceptual models of isolated wetland connected to temporary episodic flows (A), isolated from surface connections and isolated wetlands connected to reference condition episodic flows (B) showing geologic and hydrologic cross-sections of these episodic flow systems.
Figure 5.3. ECDFs by connectivity and wetland vegetation type, top to bottom: isolated wetlands, agricultural runoff connected wetlands, reference condition wetlands, mean ECDFs by connectivity, cypress savannahs, cypress-gum swamps, marshes, and mean ECDFs by vegetation type.
Figure 5.4. Boxplots of mean dry bed frequency by connectivity types and vegetation types.
CHAPTER 6

CONCLUSIONS

Summary of Findings

Episodic Flow Water Quality

This study presents stormwater-quality changes along two flowpaths within a longleaf-pine, wiregrass forest ecosystem at the Joseph W. Jones Ecological Research Center (Ichauway) located on the Dougherty Plain in Southwest Georgia. Both flowpaths receive episodic stormflows from offsite agricultural sources that then fill-and-spill as they travel through normally dry channels and isolated depressional wetlands. The first flowpath travels through a single wetland, while the second, longer flowpath travels through an indistinct channel with embedded wetlands.

Water-quality during episodic flows improved for multiple biological, chemical, and physical parameters. A general trend of decreasing sediment, nutrient, and pathogen concentrations was observed as water moved between and through isolated wetlands.

Wetland 27 receives flows from Parmalee Drain, which originates in an agricultural field immediately adjacent to Ichauway. Flows in Ichauway Drain are also generated by offsite agricultural runoff that likely passes through multiple wetlands prior to entering the site, and then pass through a forested landscape with embedded wetlands ((Wetlands 04 and 68), which are typically isolated except during episodic flow events.
Greater water-quality improvements were found when episodic flows had shorter channel residence times prior to entering the wetland; more gradual changes occurred when runoff had longer channel residence times. The observed improvement in water quality is the likely result of a combination of biogeochemical activity, physical sequestration, and flow dilution by runoff from adjacent longleaf-pine, wiregrass ecosystems. We conclude that -- regardless of mechanism -- isolated wetlands in the Dougherty Plain improve the water quality of episodic flows.

Wetlands in the Dougherty Plain thus have the potential to improve the water quality of receiving streams, such as the Flint River and Ichawaynochaway Creek. Individually, these flows may not form a substantial portion of the flow in a given perennial waterbody, but may cumulatively account for a substantial portion of the sediment, nutrient, and pathogen load in episodic flows.

Water-quality improvements were observed in wetlands as well as in channels embedded within forested landscapes, which suggests that wetlands and forested landscapes are useful for mitigating agricultural runoff. We were also able to identify the agricultural source for each flowpath, which served as a specific input of nutrients and sediments during episodic flow events. This was possible because of the unique topography of the karstic Dougherty Plain, coupled with the stormwater-quality characteristics of agricultural runoff. We suspect that water quality in coastal physiographic provinces with few headwater streams could be improved by focusing on these identified sources.

And finally, specific conductance and turbidity emerged as useful field parameters for assessing water-quality alteration by agriculture. Most parameters were strongly ($r > 0.8$) to moderately ($r = 0.5$) correlated with one (or both) of these parameters. Because these parameters are easily and
reliably measured in the field, they would be useful for long-term monitoring of water-quality degradation, and can be used as proxies for parameters that are normally measured in laboratory settings (e.g., ammonium, nitrate, phosphate).

*Isolated Wetland Water Quality*

We monitored thirty-one isolated wetlands embedded in restored longleaf pine / wiregrass ecosystem centrally located within the Dougherty Plain physiographic province in southwest Georgia. Wetlands that we monitored fell into three categories: isolated from flows, receiving agriculturally generated episodic through flow, and receiving reference condition forest or wetland spill generated episodic flow. We also monitored nine stream sites for reference purposes; three sites on a small intermittently flowing stream (Big Cypress Creek), three sites on a third order stream (Ichawaynochaway Creek), and three sites on the Flint River. Wetlands influenced by agricultural runoff were different than isolated wetlands for several of the measured water quality parameters. Streams also differed from isolated and connected wetlands that were not influenced by agriculture.

The data presented are relevant to perennial surface water management in the Appalachicola – Chattahoochee – Flint rivers basin or ACF basin. Rapid agricultural, industrial, and urban development in the Dougherty Plain have forced the prioritization of water management in this physiographic province. Water demands and management needs upstream in the Flint and Chattahoochee of Dougherty Plain have also encouraged prioritization of water management in this physiographic province (Rugel et al. 2012). Groundwater and streams are tightly linked due to the karstic bedrock of the Dougherty Plain which means that industrial and agricultural use of groundwater can strongly influence surface water availability (Rugel et al. 2012, Rugel et al. 2012).
2016). Accordingly, isolated wetlands that are not often linked to groundwater become a potentially important surface water resource for wildlife. Therefore, water quality of isolated wetlands is a critical component of surface water management.

Isolated Wetland Hydrology

This study presents analysis of long term hydrologic monitoring of isolated wetlands at the Joseph W. Jones Ecological Research Center. Wetlands were analyzed based on connectivity status (isolated, connected to agricultural runoff, connected to reference condition runoff) and dominant vegetation class (cypress-gum swamp, marshes, cypress savannahs). Our results indicate that isolated wetlands have different hydrologic drivers than both types of wetlands connected to episodic surface flows. We also found that each vegetation class is likely produced by different hydropatterns.

Isolated wetlands and connected wetlands differed in overall stage frequency but not in dry days frequency. We believe these differences to be related to wetland geomorphology because this would likely produce differences in the overall hydropattern of wetlands. We believe that similarity in dry day is due to wetlands experiencing similar weather patterns. Stage frequency differs among wetland connectivity but we believe that connectivity is a product of geomorphologic differences and the differing stage frequency is a result.

Wetland vegetation types at Ichuaway also exhibited differences in stage frequency and differences in mean dry bed frequency. We interpret this data to mean that wetland vegetation types are likely produced, at least in part, by differing hydropatterns. Cypress-gum swamps and
marshes had similar stage frequencies and dry bed frequency but vegetative communities may be driven by patterns in vegetation recruitment or fire frequency.

Stage frequency is an important hydrologic characteristic for understanding wetland ecosystems because it drives patterns in nutrient and carbon cycling which in turn influence the biological composition of these isolated features in the Dougherty Plain. Our results show that both connectivity type and vegetation type are associated with different stage frequency patterns. Vegetation is also associated with differences in dry bed frequency. Both of these findings have implications for how the biotic community of each wetland may be structured. Future research should build on this principle to understand the combined effects of connectivity and vegetation type on isolated wetland biogeochemistry as well as ecological structure and function.

Summary of Conclusions

In summary, we identified several major hypotheses that can be tested by surface and groundwater research in the Dougherty Plain. These hypotheses highlight the frontier of research on isolated wetlands, episodic flows, and groundwater interaction with ephemeral or temporary waters on the Dougherty Plain. We hypothesized that isolated wetlands are locally and collectively significant components of the surface hydrology in the Dougherty Plain. Additionally we hypothesized that episodic flows that connect isolated surface water features to perennial streams contribute significant fluxes of water, nutrients, carbon and organisms to downstream waters. Lastly we hypothesized that groundwater may have a significant influence on some isolated wetlands, baseflow in ephemeral streams, and influence select reaches of episodic flow paths.
Our research found that isolated wetlands change and improve water quality of episodic flows, that episodic flows alter the water quality of isolated wetlands after the cessation of flow, and differences in isolated wetland stage frequency are also associated with connectivity to episodic flows. In future research, we believe that testing hypotheses related to groundwater and temporary surface waters (isolated wetlands, episodic flows and ephemeral streams) will yield substantial advances in our understand of hydrology in the Dougherty Plain.

**Literature Cited**
