November 2019

The Peculiar Nature of Florida's Sandhill Wetlands, Ponds & Lakes— Their Ecohydrology, Relationship with the Regional Aquifer & Importance within the Landscape.

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The Peculiar Nature of Florida's Sandhill Wetlands, Ponds & Lakes—Their Ecohydrology, Relationship with the Regional Aquifer & Importance within the Landscape.

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Geology
with a concentration in Ecohydrology
School of Geosciences
College of Arts and Sciences
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Date of Approval:
04 November 2019

Keywords: Groundwater wetland, Groundwater pond, Groundwater lake

Dedication

For my darling husband

whose unfailing support, patience and expertise

are woven inextricably into this document…

abracapocus…

&

To Uncle Craig who reminded me:

"Whether you think you can or you can't, you're right."

(H. Ford)

Acknowledgments

Sincere gratitude to my professors at the University of South Florida for their outstanding instruction in the field of hydrogeology (and to Dr. Vacher's rightful, delightful insistence on quantitative literacy). Kind thanks to Drs. Thomas Crisman, Mark Stewart and Len Vacher and to Terrie Lee for their early participation in my committee and to Drs. Thomas Crisman, John Kiefer, Sarah Kruse and Matthew Pasek for their later participation in my committee—the thoughtful contributions of each are greatly valued. Extra special gratitude to Dr. Mark Rains, my advisor, who saw immediately the peculiarity of the sandhill wetlands and waters and took me in to do them scientific justice. Additional thanks to those generous folks and organizations who contributed to this endeavor:

Educational & Research funding:
EcoHydrologix LLC
University of South Florida
Southwest Florida Water Management District (SWFWMD)
Fred L. & Helen M. Tharp Endowed Scholarship Fund

Outstanding field or lab support:
Tim Fallon; Hilary Flower, PhD; Jason LaRoche, PG, MS; Laura Lotero, MS; Dana Noble; Mark Rains, PhD;
Christine Downs, PhD; Sanaz Esmaeili, MS; Sajad Jazayeri, PhD; Sarah Kruse, PhD

Crucial laboratory analyses:
Zachary Atlas, PhD, USF Center for Geochemical Analysis & Jessica Wilson, MS, USF Stable Isotope Lab

Valued editorial review:
Jason LaRoche, PG, MS
Caroline Masek, PE, MS

Exceptional data provision:
Hernando County Utilities Department – water level and wetland health data
Southwest Florida Water Management District – borehole, ROMP & monitor well water level data
Natural Resources Conservation Service – borehole & GPR data
National Oceanic and Atmospheric Administration – precipitation data
United States Geological Survey – monitor well water level data

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Abstract

This dissertation explores the ecohydrology of Florida's peculiar and poorly studied sandhill wetland and water features, particularly those located in west-central Florida. The primary research goals include: compilation and summarization of the available ecohydrologic information for features across Florida; comparison of water level and water geochemistry data between sandhill wetlands and waters and the regional aquifer to provide evidence of regional hydrologic control; and use of geophysical applications to examine the hydraulic connections between sandhill wetlands and waters and the regional aquifer.

From this research, a natural history of sandhill wetland and water ecohydrology is presented, highlighting: the differences between sandhill wetland and water features across the state; challenges these features bring to researchers and regulators; and the need for a statewide classification system and continued study. Comparisons of water level and water geochemistry data show the hydrology of west-central Florida features is controlled by the regional aquifer. Ground penetrating radar and electrical resistivity along with borehole, water level and lithologic data were used to develop hydrogeologic configurations. These configurations were used to develop a conceptual model of the mechanisms of wetland-aquifer hydraulic connection, showing it as a function of aquifer confinement and overburden thickness. A fundamental ecohydrologic model also was developed, which suggests the hydrologic regime and ecological expression of sandhill wetlands and waters occur as a function of site-specific geomorphology (depth and size) relative to the typical range of the regional water table.

Chapter 1: Dissertation Introduction

This dissertation explores the peculiar and poorly studied ecohydrology of Florida's sandhill wetlands and waters (the latter of which includes lakes, ponds, sinks and their contiguous wetlands). They are a unique variant of geographically isolated wetlands (GIWs) and waters, which are embedded in the imperiled sandhill upland communities of northern peninsular Florida and the Panhandle. The hydrology of sandhill wetlands and waters varies regionally as a function of their karst hydrogeology. For some, the hydrology is controlled locally by a surficial aquifer, similar to other GIWs (e.g., Carolina Bays, prairie potholes). Others are rare or unique in their control by a large, regional water-supply aquifer. Despite these differences, sandhill wetlands and waters across the state express similar ecohydrologic attributes, including widely varying hydrologic cycles (which may span years or even decades) and ecological conditions that shift widely in response. The extreme variation is such that during hydrologic low periods, ponds and lakes often present as wetlands, and during hydrologic high periods wetlands often present as ponds or lakes. This fickle quality distinguishes them from other GIWs and presents challenges to those managing them. Made more challenging is the lack of a statewide definition for sandhill wetlands (sandhill lake has been defined) and the use of variable terms to describe sandhill wetlands and waters of any variety (e.g., "ephemeral wetland," "temporary pond," "water table lake" and others) in the scant few publications for which they are described.

With few studies available specific to sandhill wetlands and waters, research presented here is intended to summarize what is known about their ecohydrology and to present new research conducted at the School of Geosciences of the University of South Florida (USF). This dissertation is organized into four chapters; this brief introduction represents the first.

Chapter 2 presents a natural history of sandhill wetland and water ecohydrology. It examines the few available studies specific to sandhill wetlands and waters and incorporates pertinent findings from studies of a broader group of features (e.g., seepage lakes), of which sandhill lakes are a subset. It also draws from studies of wetlands and waters seemingly of the sandhill type, but (due to limited hydrologic information) were not confirmed to be (e.g., karst wetlands, temporary ponds). In whole, Chapter 2 summarizes the hydrogeologic, hydrologic and ecological attributes of sandhill wetlands across the state, highlighting their regional differences, the challenges they bring to researchers and regulators and the need for a statewide classification system.

Chapter 3 presents new research in sandhill wetland and water hydrology conducted at USF. It examines water chemistry and water levels of sandhill wetlands and waters in west-central Florida, providing evidence that their hydrology is controlled by the regional water table. Data suggest that water chemistry of sandhill wetlands and waters is a function of their depth relative to limestone—those deep enough to mix with water residing in limestone reflect a limestone water chemistry, while those too shallow reflect rainwater mixed with water residing in surficial sand. Water level comparisons between sandhill wetlands and waters and the regional water table show synchronous fluctuations, with high to extremely high correlation and consistent deviations over time.

Chapter 4 presents new research into the mechanisms by which sandhill wetlands and waters are hydraulically connected to the regional aquifer. Geophysical tools, including ground penetrating radar and electrical resistivity, along with borehole, water level and lithologic data are used to construct site-specific hydrogeologic configurations. From these configurations, a conceptual model of the mechanisms of wetland-aquifer hydraulic connection is presented, with models varying as a function of aquifer confinement and overburden thickness. Chapter 4 also proposes a fundamental ecohydrologic model, which suggests that hydrologic regime and ecological expression occur as a function of site-specific geomorphology (depth and size) relative to the typical range of the regional water table.

Chapter 2: Florida's Unique and Imperiled Sandhill Wetlands & Waters - A Natural History

ABSTRACT

Embedded in the sandhills of northern peninsular Florida and the Panhandle are a special, poorly studied class of geographically isolated wetlands (GIWs) and waters known as "sandhill" wetlands and waters. They vary greatly in their shape, depth and size, but share the common attributes of: a xeric setting in a karst terrane; a direct or indirect hydraulic connection with the regional aquifer; a hydrology that varies widely; and an ecology that varies widely in response.

While often regarded as depauperate, these unique features contribute important functions on the landscape—offering biodiversity, flood storage and wildlife habitat. With few publications documenting their ecohydrology, they are not well understood and vulnerable to impacts and loss from residential and commercial development, dredge and fill, mowing, dumping, groundwater production and the uncertain consequences of a changing climate. Research presented here is intended to: summarize what is known about the ecohydrology of sandhill wetland and water features; present new findings from studies in west-central Florida; promote the recognition and classification of sandhill wetlands and waters as a distinct variant of GIWs and waters; and encourage additional research to fill broad data gaps and safeguard sandhill wetlands and waters as a valued natural resource.

BACKGROUND & INTRODUCTION

Florida's sandhill wetlands and waters, the latter of which include ponds, lakes and sinks (often with contiguous wetlands occurring as a fringe or adjacent pool[s]) (Figure 2-1) are a class of geographically isolated features found in northern peninsular Florida and the Panhandle. They vary greatly in their shape, depth, size and complexity, but share the defining characteristics of:

- occurrence in a xeric setting of a karst terrane;
- direct or indirect hydraulic connection with the regional aquifer, where it is unconfined or semi-confined;
- hydrology that varies widely (which for some wetlands may include years or even decades without surface water);
- ecology that varies widely in response, generally as a sandy bottomed treeless mix of grasses and sedges (shallow features) or open water (deeper features) (Nowicki et al., in prep.; Nowicki et al., in prep.; FNAI, 2010; and CH2M Hill, 2003).

Figure 2-1. Sandhill wetland-pond complex, west-central Florida.

Sandhill wetlands and waters take their name from their occurrence in sandhill—xeric communities characterized by widely spaced longleaf pine (*Pinus palustris*) and turkey oak (*Quercus laevis*), scattered shrubs and a grassy understory occurring atop marine sands of both steep and gently rolling hills and ridges (Figure 2-2) (FNAI, 2010). Sandhill

Figure 2-2. Sandhill upland, west-central Florida.

was once a major part of an expansive longleaf pine natural community mosaic throughout the southeast United States (U.S.); this community has experienced a 98% areal decline within its range due largely to agriculture, plantation forestry, and fire suppression (Noss et al., 1995; Kautz, 1998; Stein et al., 2000). Sandhill is classified as "Imperiled" in Florida and "Very Rare" globally due to their rarity or vulnerability to extinction, as are the wetlands and waters within them (FNAI, 2010). In conservation or managed areas, sandhill wetlands and waters may persist largely in a natural state and benefit from prescribed fire and other ecological treatments (Figure 2-3), while others bear sign(s) of alteration, impacts, or complete and total loss to their buffers or interiors from fire suppression, dredging, fill, roadways, lawns, mowing (Figure 2-4), residential/commercial development, agriculture, mining activities, silviculture, hog rooting, livestock or other factors (HCUD, unpublished data; FNAI 2010).

Figure 2-3. Sandhill wetland interior, post-fire (prescribed).

Figure 2-4. Mowing/vehicle damage to wetland transitional zone soil and vegetation.

Little is known of sandhill wetland and water ecohydrology; in part because "sandhill wetlands" in particular are not defined in the literature, and because sandhill wetlands and waters of any variety are often referenced by other names (e.g., "ephemeral" wetlands, "temporary" ponds, "water table" lakes) and often as a variant of a broader group of features (e.g., "karst ridge" wetlands, "karst" ponds, "seepage" lakes and "sinkhole" lakes) (FNAI, 2010; Knowles, et al., 2003; Kindinger et al., 1999; Sutter and Kral, 1994; Dodd, 1992; and Deevey, 1988). Also, features referenced as sandhill "lakes" may actually be large or deep wetlands or ponds. For the purposes of this report, "wetlands" are distinguished by their impermanent hydroperiod and shallower nature, which supports emergent or aquatic vegetation. In contrast, "waters" include deeper features such as ponds, lakes or sinks, which are permanently inundated and too deep for vegetation to establish. Ponds and sinks are distinguished from lakes by their smaller area and insufficient fetch to produce wave action. Sinks are further distinguished by their open shafts (cut visibly into limestone), which are not infilled with overburden. While the distinctions between feature types may seem semantic, they are an important first step in the development of a sandhill wetland and water classification system.

Sandhill lakes have been defined by state agencies charged with protecting them from significant harm from groundwater production and for conservation as natural areas. The St. John's River Water Management District (SJRWMD), which regulates wetlands and waters in Florida's northeastern peninsula, defines "sandhill lakes" as those of sinkhole origin surrounded by sandy soils to 2 m or deeper that are nutrient-deficient and subject to extreme water level fluctuations (Richardson et al., 2004). This definition does not, however, distinguish lakes from ponds or deep wetlands. The Florida Natural Areas Inventory (FNAI, 2010) defines "sandhill upland lakes" as rounded solution depressions in deep sandy uplands without surface water inflows or outflows and with direct or indirect hydraulic connections with the (regional) aquifer. They describe water levels that may fluctuate substantially or dry completely during extreme droughts. Water is described as clear, acidic, moderate and soft with variable mineral content. These definitions are generally consistent with the defining characteristics of sandhill lakes (or deep wetlands) elsewhere in Florida, although water chemistry and other differences within and between regions are apparent (e.g., Nowicki et al., in prep.; Pollman et al., 1991).

Most of what is known of the ecohydrology of sandhill wetlands and waters comes from studies by and for the SJRWMD to develop lake level regulations for those features found within its district. CH2M Hill (2003) provided a thorough literature review building on pertinent geologic, hydrologic and ecological studies to develop a conceptual water resources model of sandhill lake functions and values. Richardson et al. (2004) subsequently evaluated soil morphologies that could be tied to lake stage to support minimum lake levels regulation. Jones Edmunds (2006) reviewed literature related to wetland plant physiology, soil capillary fringe and oxidation-reduction potential and presented a threshold to maintain sandhill wetland vegetation and soil, given reduced hydrologic conditions from historical. Nkedi-Kizza and Richardson (2007) investigated physical properties of soils associated with sandhill lakes and provided measures of capillary fringe and the anaerobic zone above the water table. Findings from these studies have been used to improve the means by which regulations for sandhill lakes in the northeastern peninsula are established and evaluated (SJRWMD FAC 40-c, 2019).

Additional findings from a series of U.S. Geological Survey (USGS) studies of "seepage lakes" in the Florida Central Lake District (which includes much of the northeastern peninsula) and Panhandle have contributed greatly to understanding their hydrogeologic and/or hydrologic components (e.g., Lee et al., 2014; Sacks et al., 2008; Sacks, 2002; Swancar et al., 2000; Sacks et al., 1998; Lee and Swancar, 1997; Grubbs, 1995; Sacks et al., 1992). Seepage lakes are generally defined as those without surface outlets (Deevey, 1988). Sandhill lakes are thus a subset, but with a distinct widely varying hydrology, often with contiguous wetland communities that shift (in time and space) in response (Richardson et al., 2004). Key highlights from these seepage lakes studies include:

- confirmation that breaches in the semi-confining unit beneath the lakes indirectly connect the lakes to the regional aquifer and are often numerous and of various types and sizes;

- an improved understanding that these connections do not control lake levels, rather they influence vertical lake leakage due to hydraulic head differences; and
- recognition that most seepage lakes in this study area exhibit positive net groundwater inflow but negative net precipitation; this makes them vulnerable to impacts from a drier climate and surface water/groundwater withdrawals (especially those of the sandhill type, which are better connected to the regional aquifer and more vulnerable to its drawdown).

For sandhill wetlands and waters in west-central Florida, Henderson (1986) provided evidence for a direct hydraulic connection between a (sandhill) lake and the regional aquifer. More recently, Nowicki et al. (in prep.1) found direct hydraulic connections between 15 sandhill wetlands and waters (including the one in Henderson's study) and the regional aquifer. In a companion study, Nowicki et al. (in prep.2) used geophysical tools to develop conceptual models of: 1) the mechanisms and types of hydraulic connections between sandhill wetlands and waters and the regional aquifer; and 2) their fundamental ecohydrology as a function of geomorphology. These studies distinguished west-central Florida sandhill wetlands and waters from others in the state whose hydrology may be influenced, but not controlled, by the regional aquifer.

Given the relatively limited information available specific to the ecohydrology of sandhill wetlands and waters, this chapter is intended to summarize: 1) their ecohydrologic attributes and defining characteristics, recognizing the differences between features in different parts of the state; 2) their many important functions and values; and 3) challenges that result from their relative uniqueness relative to other types of isolated wetland and water features, which necessitate a statewide classification system.

STUDY AREA

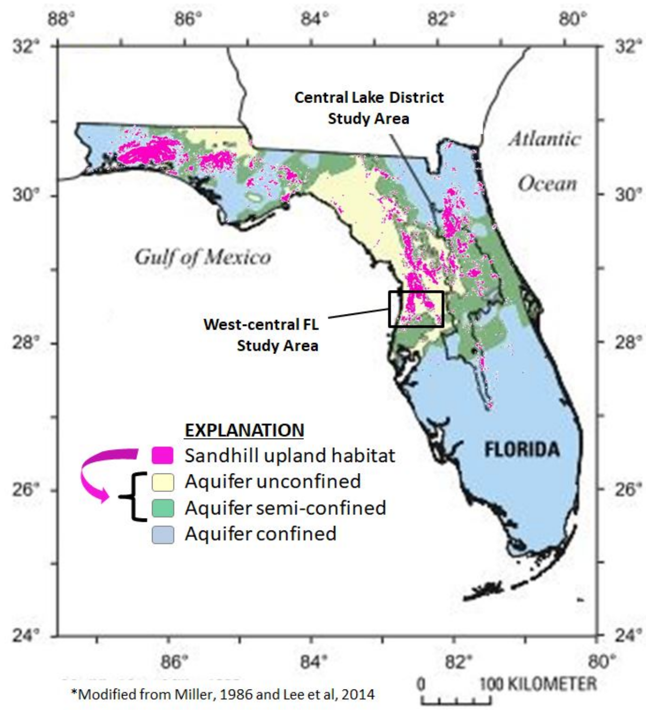

Figure 2-5. Potential areas of sandhill wetlands and waters. Note, sandhill wetlands and waters may be found in areas where sandhill overlies the regional aquifer where it is unconfined or semi-confined.

Florida’s sandhill wetlands and waters are found in the northern peninsula and Panhandle in areas where sandhill communities are underlain by an unconfined or semi-confined regional aquifer (Figure 2-5).

Climate

The climate of Florida’s northern peninsula and Panhandle is humid subtropical. Annual temperatures range 15 - 28°C across the study area, with average winter lows to 7°C and average summer highs to 32°C. The 30-year (1980-2010) normal annual rainfall ranges from 120 – 134 cm in the northern peninsula to 166 cm in the Panhandle (NOAA Climate.gov). Most of the rain (44% - 41% and 32%, respectively) falls in the summer, with the rest distributed fairly equally among seasons. Annual evapotranspiration for the period 1996 – 2011 averaged 113 – 120 cm in the Panhandle and 120 - 135 cm across the peninsula, with inland lakes averaging up to 155 cm, exceeding the long-term annual average rainfall (Lee et al., 2014).

Hydrogeologic Setting

As described by Miller (1986), the geology of Florida is generally comprised of a thick sequence of carbonate rocks (limestones and dolostones) blanketed by thinner deposits of unconsolidated siliciclastic sediments (sand and clay) of variable composition and thickness. Over much of Florida, clay sediments of the Hawthorn Group cover the buried limestone surface and separate it from overlying sand deposits. These clays form the confining unit between the unconfined surficial aquifer (sand) at land surface and the underlying Upper Floridan aquifer (limestone). In parts of northern peninsular Florida and the Panhandle, however, the confining unit is absent because the Hawthorn clays have been mostly removed by erosion during lower sea-level stands through time (Figure 2-5). In these areas, the Upper Floridan aquifer extends into the overlying sand as the unconfined water table, and the surficial aquifer is no longer present. In areas where clays are present but are thin, discontinuous, and/or breached, semi-confined conditions exist, resulting in weak confinement and increased hydraulic connection between the surficial and Upper Floridan aquifers. Also, where near-surface carbonates dissolve and concentrate insoluble clays within the limestone, a clayey residuum may develop over the limestone surface. While often laterally discontinuous, this low permeability material can form as a thin veneer or can thicken to more than 30 m, creating locally semi-confined conditions (Miller, 1986).

Wetlands and waters in the study area are typically surface expressions of subsidence, a characteristic feature of the study area's karst terrane (Tihansky and Knochenmus, 2001). Wetland and water features can range in size from less than 1 to more than 170 ha and from less than 0.5 m to more than 20 m in depth—their shape and size generally a function of overburden depth and composition and subsidence type (Tihansky and Knochenmus, 2001). Subsidence occurs when the limestone surface dissolves and forms cavities into which the overburden settles. Where settling is gradual, cover subsidence sinkholes form, producing depressions on the land surface of various shapes and size (Sinclair, 1990). This type of variation is well demonstrated at the Sand Hill Scout Reserve in west-central Florida where small steep-sided sinks, large multi-pool wetlands, ponds and wetland-pond complexes are all found in close proximity (Figure 2-6) (Nowicki et al., in prep.). Subsidence of this kind generally occurs in areas where the overburden is relatively thin and composed mostly of sand (Sinclair, 1990). Rapid subsidence

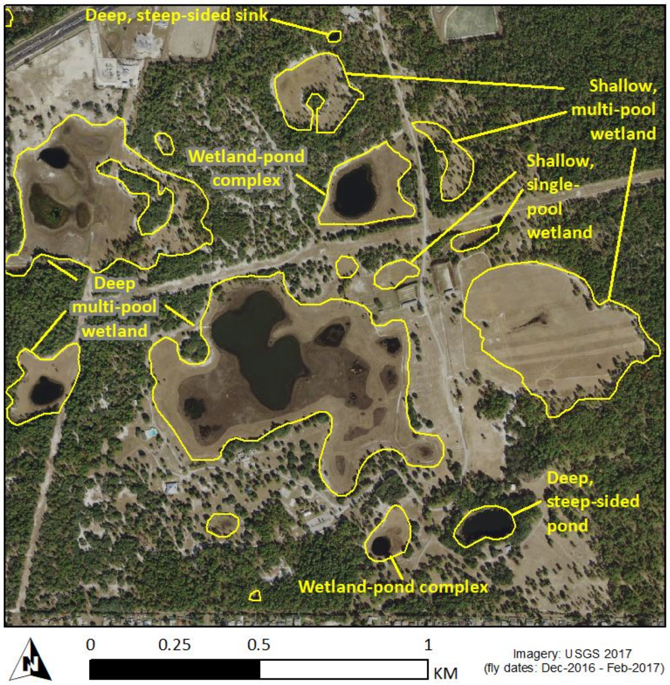

Figure 2-6. Aerial image of sandhill wetlands and waters. Sandhill Scout Reserve, Brooksville, west-central Florida, USA (from Nowicki et al., in prep.).

generally results in cover collapse sinkholes, which produce depressions that are often circular in shape and greater in depth. This generally occurs where the overburden is thicker and includes a greater concentration of clay (as typically occurs in the Central Lake District and Panhandle) (Sinclair, 1990). Dissolution beneath the limestone surface also occurs in karst terrane, producing the "tiny vugs to gigantic caverns," which make the Upper Floridan aquifer so highly transmissive and productive (Tihansky and Knochenmus, 2001). Beneath the property shown in Figure 2-6 are two connected, enormous room-sized caverns at extreme depths, including the deepest (110 m) known in the continental United States (Floridatraveler.org, 2016).

SANDHILL WETLAND & WATER HYDROGEOLOGY

Of the thousands of wetlands and waters formed by subsidence or collapse, not all are of the "sandhill" type. As previously noted, sandhill wetlands and waters are distinct in their expression of widely varying water levels, which result from a direct or indirect connection with the regional aquifer (Nowicki et al., in prep.; CH2MHill, 2003; FNAI, 2010). Conceptual hydrogeologic models of the mechanisms for these connections are proposed by Nowicki et al. (in prep.) as summarized here (Figure 2-7):

- In MODEL 1, the features have a direct hydraulic connection with the regional aquifer. This occurs in areas where the regional aquifer is unconfined, and the features are embedded in it. Features of this kind are essentially surface water reflections of the regional aquifer.
- In MODEL 2a, the features have an indirect hydraulic connection with the regional aquifer. This occurs in areas where the regional aquifer is semi-confined, and the overburden is relatively thin. The features are embedded in the surficial aquifer, which connects to the regional aquifer through breaches in the semi-confining unit. The features may exchange water with the regional aquifer, likely as a surficial-regional aquifer hybrid.
- In MODEL 2b, the features also have an indirect hydraulic connection with the regional aquifer through breaches in the semi-confining unit, but the overburden is too deep for water from the regional aquifer to enter the features.

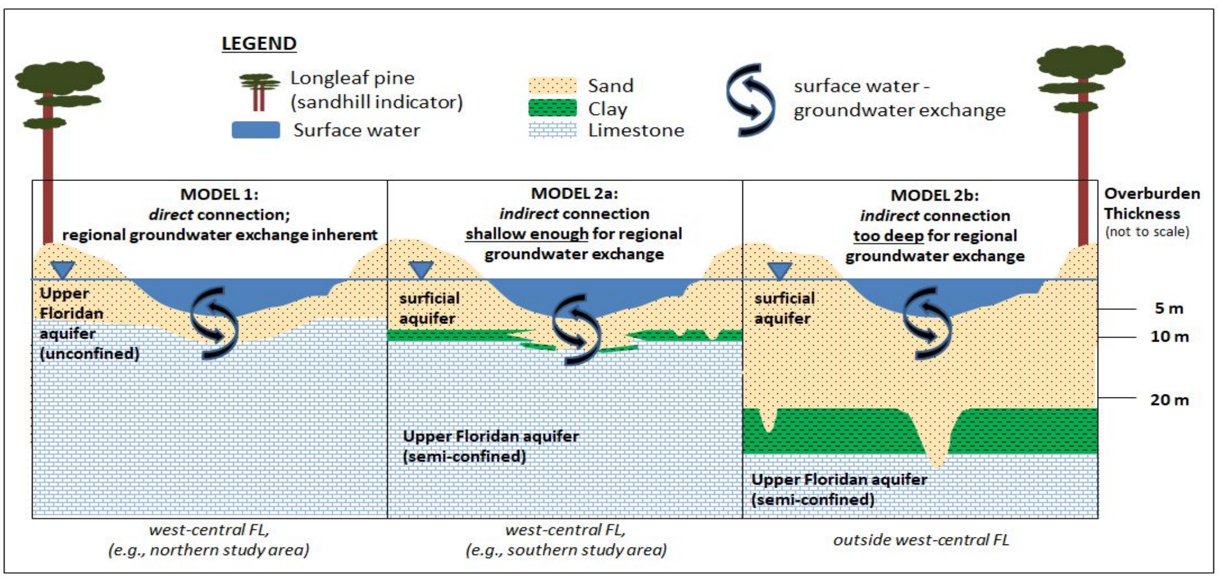

Figure 2-7. Generalized sandhill wetland & water hydrogeologic models. The degree and depth of aquifer confinement determines how the wetland and water features hydraulically connect with the regional aquifer. Where the aquifer is unconfined, the features are embedded in it and thus have a direct connection, and surface water-groundwater exchange is inherent (MODEL 1). Where the regional aquifer is semi-confined, the features are embedded in a surficial aquifer and have only an indirect connection with the regional aquifer. The depth between the features and regional aquifer determine whether surface water and regional groundwater are exchanged (MODEL 2a) or not (MODEL 2b) (from Nowicki et al., in prep. CH4).

Sandhill wetlands and waters may occur as single-pools of one feature type (e.g., wetland, pond, lake or sink) or as single pools of two types (e.g., a wetland occupying the shallow periphery of a deeper feature as in a wetland-fringed pond or wetland-fringed lake) or as multi-pool complexes where a pond or lake occupies a deeper pool and wetland(s) occupy shallower pool(s), all within the same isolated basin (e.g., wetland-pond complex or wetland-lake complex). Wetlands may be found in association with sinks, but their occurrence is often limited to a very narrow fringe along an eroded area(s) of the sinks' periphery. As proposed by Nowicki et al. (in prep.), the type of sandhill feature that manifests (and the type of ecohydrology that is subsequently expressed) is a function of depression geomorphology relative to the typical range of the regional water table (Figure 2-8). To paraphrase: for deep depressions whose bottoms intersect the regional water table below its typical range, inundation is permanent and open water prevails; a lake manifests if the depression is large enough for wave action to occur, otherwise a pond does. Ponds whose bottoms are not infilled with overburden manifest as sinks. For shallower features, whose bottoms intersect the regional water table in the upper part or above its typical range, inundation is seasonal or intermittent, and a deep or shallow wetland manifests, respectively. Features composed of multiple depressions may express a mosaic of ecohydrologic expressions (e.g., wetland-pond complex). Depressions too shallow to intersect the regional water table develop as uplands. Features represented by MODEL 2b were not specifically included in this ecohydrologic model, as it was developed for sandhill wetlands and waters in west-central Florida whose hydrology is controlled by the regional water table. The model may, however, be applicable to MODEL 2B features (Figure 2-7), in the context of the surficial aquifer (in which they are embedded).

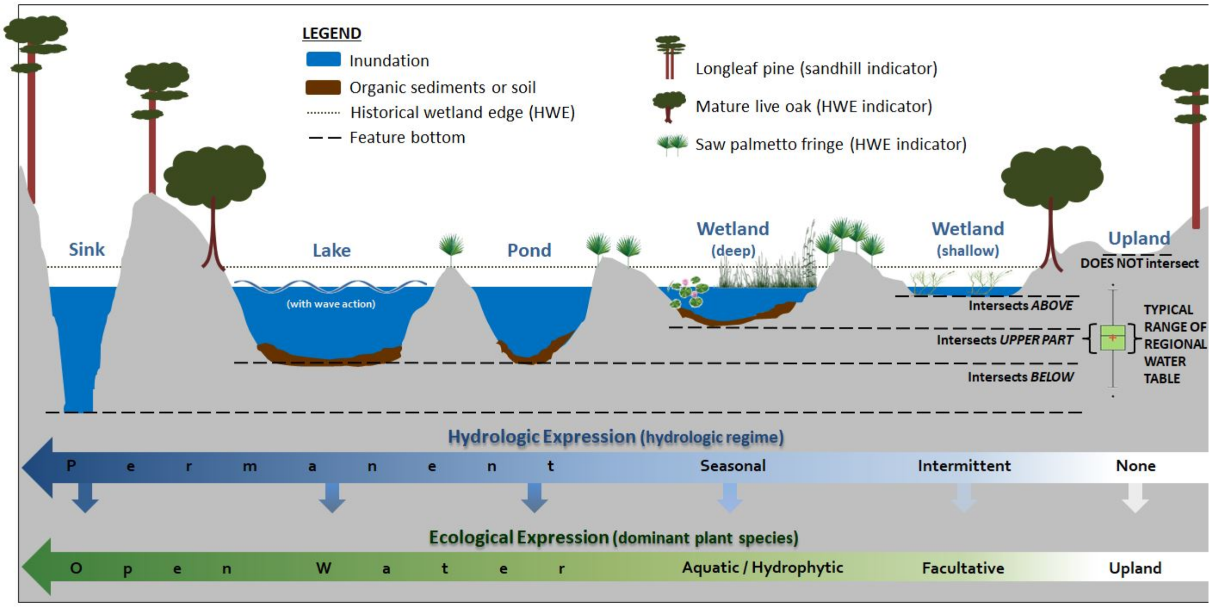

Figure 2-8. Proposed conceptual model of sandhill wetland & water ecohydrology in west-central Florida. Geomorphology is a fundamental control on sandhill wetland & water ecohydrology. Where the wetland/water bottom intersects the regional water table determines the hydrologic regime, which determines the ecological expression (accumulation of organic sediments or soils and plant species composition)(from Nowicki et al., in prep.).

SANDHILL WETLAND & WATER HYDROLOGY

Regardless of the mechanism of connection to the regional aquifer or type of feature that forms, sandhill wetlands and waters across the state share a widely varying hydrologic cycle that may span 20 years or longer (CH2MHILL, 2003; Merritt, 2001; Annable et al., 1996). This occurs because in all cases, "the wetlands and waters occupy depressions of karst origin in xeric communities where climate is similar, and water levels vary widely in response to regional or regionally influenced groundwater fluctuations" (Nowicki et al., in prep.). Features whose water levels are influenced, rather than controlled by, regional groundwater fluctuations (i.e., MODEL 2b, Figure 2-7) occur mostly in the Central Lake District and Panhandle. For these features, the water table of the surficial aquifer controls their hydrology, and sub-lake geology determines whether or not they will be of the sandhill type. For those that are (i.e., those underlain by a breached semi-confining unit), their water levels vary widely as a result of greater vertical outflow but would not be expected to rise and fall in sync with the regional water table. Sandhill waters of this kind exhibit both flow-through and recharge/discharge conditions (CH2MHILL, 2003; Knowles et al., 2003; Swancar et al., 2000; Sacks et al., 1998; Lee, 1996; Grubbs, 1995).

Features whose water levels are controlled by regional groundwater fluctuations (i.e., MODELS 1 and 2a, Figure 2-7) are most abundant in west-central Florida, but may be found elsewhere where similar hydrogeologic conditions exist (Nowicki et al., in prep.; Nowicki et al., in prep.). Water levels in these features are highly correlated with those of the regional water table (R^2=0.84 – 0.99) and with elevation offsets due mostly to differences in wetland-well position along the regional hydraulic gradient (Nowicki et al., in prep.; Henderson, 1986). Water levels of sandhill wetlands and waters of this kind also synchronize with each other (Figure 2-9 , HCUD unpublished data) and documented by Henderson (1986). This figure shows water levels of features of very different geomorphologies that are located within 17 km of each other. Their water levels are not only very highly correlated (0.92 $\geq R^2 \geq$ 0.99), but some converge to coincident elevations during periods

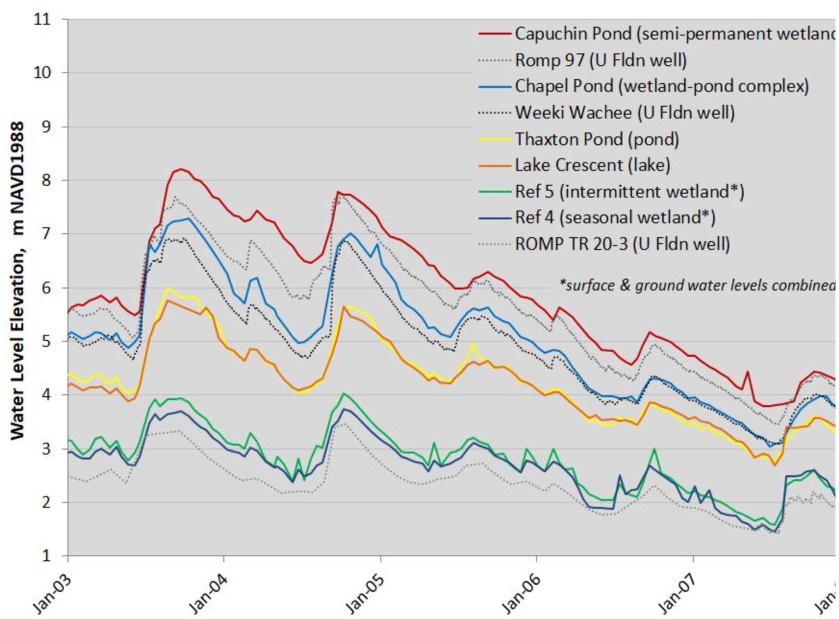

Figure 2-9. Water levels for sandhill wetlands and waters in west-central Florida. Note the wide fluctuations between high and low hydrologic conditions (2003-2004 and 2007, respectively) and the synchronicity with the regional water table (U Fldn wells) and among features of different geomorphic types (HCUD unpublished data).

of extreme high or extreme low hydrologic conditions. This presumably occurs as the slope of the regional water table flattens between the features in response to these extreme conditions. This type of synchronized water level fluctuation contrasts with that of wetlands and waters in the Central Lake District and Panhandle (e.g., MODEL 2b, Figure 2-7), where proximal wetlands may fluctuate very differently due to differences in their sub-lake geology (Tihansky, 1996; Grubbs, 1995). Flow-through conditions with respect to the regional aquifer were documented by Henderson (1986) for a (sandhill) lake in west-central Florida and are suggested to be the norm for other wetlands and waters in the area, although recharge/discharge conditions also may occur.

Studies on the water chemistry of Florida sandhill wetlands and waters are limited. Water chemistry descriptions presented by SJRWMD (CH2MHILL, 2003) borrow from descriptions for seepage lakes in general and from FNAI (2010), which defines sandhill upland lake water as "clear, circumneutral to slightly acidic, moderately soft water with varying mineral content". Henderson (1986) describes the water chemistry of a (sandhill) lake in west-central Florida as relatively soft, with a circumneutral pH, low ionic concentration and of a calcium-bicarbonate type. Nowicki et al. (in prep.) (paraphrased here) suggest that water chemistry for sandhill wetlands and waters in west-central Florida with a direct hydraulic connection (e.g., MODEL 1, Figure 2-7) varies largely as a function of their relative depth to limestone. For most of the deeper ponds and lakes studied, water type was calcium-bicarbonate with elevated specific conductance, calcium [Ca^{2+}] and/or pH due to surface water mixing with groundwater residing in limestone. For shallower wetlands, greater depth to limestone precluded mixing with groundwater residing in it. Their water chemistry reflected rainwater in contact with the wetland substrate and underlying surficial sands—Na^{+}, Cl^{-} and SO_4^{2}- ions were dominant in place of Ca^{2+} and HCO^{2}-$_{3}$, and pH was lower due to acidic organic matter in the substrate. The variation of water chemistry as a function of depth relative to limestone distinguishes the sandhill waters of west-central

Florida from those elsewhere in the state, whose chemistry is not at all influenced by water residing in limestone because of the much greater depth to limestone.

Limited hydrologic studies specific to Florida's sandhill wetland and water features have been published and have historically focused on those located in the northeastern peninsula (i.e., Central Lake District) and Panhandle, only a subset of which are of the "sandhill" type. Studies by Henderson (1986) and Nowicki et al. (in prep. & 2) reveal a class of sandhill wetlands and waters in west-central Florida that are distinct, not just from others in the state, but from most other geographically isolated wetlands and waters. Their direct or close, indirect connection with the regional aquifer and its control of their hydrology is rare, if not unique, among isolated wetlands and waters. Thus, they occur as groundwater endmembers along a hydrologic source continuum (Nowicki et al., in prep.). They are unlike those driven by precipitation such as raised bogs (Large et al., 2007) and karst pans (Wolfe, 1996) (Figure 2-10)) and are distinct from those whose hydrology is controlled locally by a surficial aquifer such as Carolina Bays (Lide et al., 1995), prairie potholes (Sloan, 1972, Richardson et al., 1992) and fens (Wilcox et al., 1986).

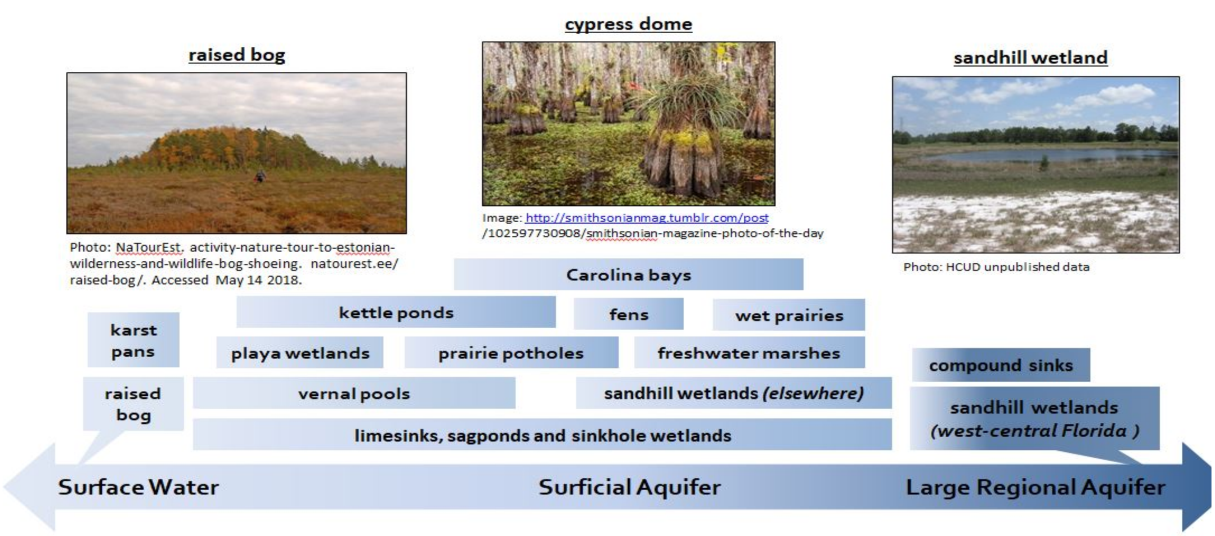

Figure 2-10. Sandhill wetlands as regional groundwater endmembers along an isolated wetland hydrologic continuum. (from Nowicki et al., in prep.).

SANDHILL WETLAND ECOLOGY

Figure 2-11. Examples of sandhill wetland & water ecological expressions, west-central Florida.

Sandhill wetlands are generally found as treeless assemblages of: 1) grasses, sedges and rushes on sandy substrates in shallow, intermittently inundated areas; 2) broad-leaf emergent or floating aquatic species on organic soils in deeper, seasonally inundated areas; and/or 3) open water in semi-permanently inundated areas, with organic sediments increasing with depth (HCUD unpublished data; CH2MHill, 2003) (Figure 2-11). Often, one or more assemblages occur in a single feature, either in a continuum (i.e., along a vertical gradient) or as a complex of multiple pools (e.g., wetland-pond complex or wetland-lake complex) as a function of the pools' hydrologic regimes (as described previously) (Nowicki et al., in prep.). Because the hydrologic regimes of sandhill wetlands and waters vary widely over both time and space, so do their ecological expressions, which expand and shrink in area as water levels rise and fall. During dry periods, for example, deeper pools typically characterized by open water or by broad-leaf emergent and floating aquatic species may shift to assemblages typical of shallower pools (e.g., grasses and sedges). The reverse may occur, as well, with typically grassy areas shifting to open pools during high water periods. The extreme hydrologic conditions produce a diverse mix of species tolerant of this type of variation. These conditions also are responsible for the absence, or short life span, of trees and shrubs. During hydrologic low periods, hydrophytic trees and shrubs often fail to establish or quickly die off (Figure 2-12), and facultative species (i.e., those found as often in wetlands as uplands) and/or upland species establish, sometimes as a ring along the landward edge of a deep zone (Figure 2-13).

Figure 2-12. Short-lived hydrophytic tree establishment resulting from widely fluctuating water levels of hydrologic low periods (above) and hydrologic high periods (below).

Figure 2-13. Short-lived facultative/upland tree establishment resulting from widely fluctuating water levels of hydrologic low periods (above) and hydrologic high periods (below).

During hydrologic high periods, inundation kills these trees and shrubs (hydrophytes and facultative species alike), perpetuating the largely herbaceous structure characteristic of most sandhill wetlands. Fire also plays a role in limiting tree and shrub abundance and distribution (HCUD unpublished data;

FNAI, 2010), but the absence of trees and shrubs in numerous fire-suppressed sandhill wetlands and waters reiterate hydrology as the primary control.

While not defined for "sandhill wetlands" in particular, vegetation assemblages described by FNAI (2010) for "depression marshes" are consistent with those described for sandhill wetlands across the peninsula (HCUD unpublished data, CH2MHill, 2003). Depression marshes are, by definition, located within fire-maintained matrix communities (e.g., sandhill, mesic flatwoods and dry prairie) and often exhibit zonation (i.e., concentric bands of vegetation along a moisture gradient) based on marsh depth and configuration. Typical vegetation composition and zonation for depression marshes are summarized as follows (FNAI, 2010):

Figure 2-14. Example of vegetation composition and zonation, sandhill wetland, west-central Florida

- a border of bluestem grasses (e.g., *Andropogon brachystachyus, glomeratus or virginicus var. glauca*) and other herbs (e.g., *Eupatorium leptophyllum, Dichanthelium* spp., *Lachnocaulon minus, Syngonanthus flavidulus*);
- an outer band of sparse grasses (e.g., *Aristida palustris*) and sedges (e.g., *Rhynchospora microcarpa, R. cephalantha, R. tracyi, R. filifolia, Xyris elliotti*), subshrubs (e.g., *Hypericum myrtifolium*) and patches of blue maidencane (*Amphicarpum muhlenbergianum*) or sand cordgrass (*Spartina bakeri);*
- a lower band of sparse to dense peelbark St. John's wort (e.g., *Hypericum fasciculatum*) with scattered sedges, rushes and herbs (e.g., *Xyris fimbriata*, *Eriocaulon compressum*, *E. decangulare, Rhynchospora inundata,* and *Eleocharis baldwinii);*

- an inner, deep zone of grasses like maidencane (*Panicum hemitomon*) or sawgrass (*Cladium jamaicense*) and broadleaf plants such as pickerelweed (*Pontederia cordata*) and bulltongue arrowhead (*Sagittaria lancifolia*); and
- floating-leaved plants (e.g., *Nymphaea odorata*) in the deepest of areas (FNAI, 2010).

Similar vegetation and zonation have been described for temporary ponds in north-central Florida (LaClaire, 1995), karst ponds in Florida, Georgia and Alabama (Sutter and Kral (1994), Carolina bays (Sharitz, 2003), and other grass-sedge depressional wetlands in the southeastern United States (Kirkman et al, 2012). Zonation also has been described for other types of isolated wetlands outside the Southeast including prairie potholes (Kantrud et al., 1989) and vernal pools (Schlising and Saunders, 1982).

Vegetation associated with "sandhill upland lakes", as described by FNAI (2010), is similar in composition to that of "depression marshes", but restricted in its distribution to a narrow band along the shoreline or as a dense shrub thicket depending on water level fluctuations, fire frequency and shoreline slope. The width and distribution of the band expands during lower water level conditions and where shorelines slope gradually. The density of shrubs increases with fire suppression.

Zonation anomalies have been noted at sandhill wetlands and waters in west-central Florida. At some, hydrophytic trees such as laurel oak and water oak (*Quercus laurifolia* and *Q. nigra*, respectively) were found as a patch or fringe along or beyond the wetland edges, but not within the wetland interiors (as might be expected for species of their wetland affinity). At these and other wetlands, maidencane (an obligate wetland grass) was found growing along swaths from deep within the wetland interior to far beyond the wetland edges at elevations a meter or more above the maximum recorded inundation (Figure 2-15) (Nowicki et al., in prep.). Interpretation of ground-penetrating radar and electrical resistivity images suggest that beds of silty sand and clayey sand and limestone pinnacles are present

Figure 2-15. Zonation anomaly at sandhill wetland, west-central Florida.

beneath these areas. The lower permeability of these materials may retard moisture, allowing the hydrophytic vegetation to persist in areas that would otherwise be too well-drained for their growth. The mechanism is considered different than seepage (in which water oozes from the earth) or perching (which implies an underlying unsaturated zone), and may be due to enhanced capillary effects. The distribution of hydrophytic trees may alternatively (or in addition) be due to the more stable hydration that occurs at the wetland edge than in the interior (Nowicki et al., in prep.). The anomalous areas described here are different in structure and composition than the shrubby evergreen communities found in some ecotones of sandhill wetlands and waters across the state (as described above by FNAI for "sandhill upland lakes"). Hydration of these areas is attributed to "seepage" by FNAI and others (Jones Edmunds, 2006), although specific evidence is not provided.

SANDHILL WETLAND & WATER FUNCTIONS & VALUES

As described, the hydrologic cycle of sandhill wetlands and waters may span years or even decades, responding to periods of above and below normal rainfall, such as occurs during the El Nino and La Nina phases of the El Nino-Southern Oscillation [ENSO] climate cycle (respectively). These phases occur roughly every 3 - 7 years, but can last longer (NOAA Climate.gov). The resulting high and low water phases reveal starkly contrasted ecohydrologic conditions, which contribute alternating functions and values on the landscape. During the low phase: water recedes in ponds and lakes and disappears altogether in wetlands, expanding vegetated areas at the expense of open water; once submerged organic substrates become exposed and are oxidized, and vegetation assemblages shift waterward as facultative species and other less water-tolerant species encroach shallower areas. During the high phase: open water areas expand, resubmerging the oxidized soils and killing or shifting landward those vegetative assemblages not suited for deep or extended inundation. Compared to the hydrologic high phase, the seemingly depauperate conditions of the low phase may imply that ecohydrologic functions (and related socioeconomic values) are absent or ancillary, but they are arguably as important—each individually and collectively contributing functions and values other wetlands or waters may only offer in part.

Figure 2-16. Water storage during high water phase at sandhill pond, west-central Florida.

As described by CH2Mill (2003), during high water sandhill wetlands and waters store large quantities of water, reducing the risks and damages from flooding (Figure 2-16). Nutrients and solids introduced from surface runoff in disturbed areas also are stored and may be trapped in bottom sediments, resulting in improved water quality and aesthetics. Aquatic habitats expand, as do opportunities for recreation such as fishing, boating and skiing, which generally improve property value (Figure 2-17). The expansion also maximizes species dispersal, aquatic energy and detrital material capture and may trigger some floral and faunal species to reproduce (CH2MHill, 2003). Upland and weedy species are killed, resetting the ecology and contributing detrital material, which contributes to primary and secondary production (CH2MHill, 2003).

Figure 2-17. Aquatic habitat expansion of high water phase at large sandhill wetland, west-central Florida.

Figure 2-18. Concentration of resources and provision of foraging areas for waterfowl and wading birds during low water phase at sandhill wetland/pond/lake features, west-central Florida.

Figure 2-19. Provision of nesting areas during low water periods that are not available during high water at a sandhill wetland, west-central Florida.

During low water, these same wetlands and waters concentrate resources, providing foraging areas for waterfowl and wading birds (Figure 2-18), including rare or listed species such as little blue heron (*Egretta caerulea*), snowy egret (*Egretta thula)*, glossy ibis (*Plegadis falcinellus)*, white ibis (*Eudocimus albus*), and woodstork (*Mycteria americana*) (HCUD unpublished data; CH2MHill, 2003). Low water also provides nesting areas that are not available during high water, benefitting species like Florida sandhill crane (*Grus canadensis pratensis*) (Figure 2-19) and supporting critical breeding habitat for amphibians such as Florida cricket frog (*Acris gryllus dorsalis*) and oak toad (*Anaxyrus quercicus*). Conditions of both low and no water contribute greatly to biodiversity, favoring species well-suited to wetland conditions and those less water-tolerant, which establish in the drier conditions (HCUD unpublished data; CH2MHill, 2003) (Figure 2-20). Low and no water conditions also provide open space and opportunities such as hunting and birding and filter and absorb nutrients and other pollutants (CH2MHill, 2003).

While features of a single type (e.g., simple wetland or pond) may alternate functions and values over time (i.e., between high and low water phases), larger multi-feature complexes alternate these functions and values over space (i.e., between deep and shallow pools)—collectively and simultaneously offering the full range of functions and values available to them. This offering occurs on a grander scale, as sandhill wetlands and waters as a group contribute their functions and values as a broader mosaic across the landscape.

Figure 2-20. Example of biodiversity of floral species due to widely fluctuating hydrologic conditions at sandhill wetlands, west-central Florida.

CHALLENGES & SPECIAL CONSIDERATIONS

For their unique attributes, Florida's sandhill wetlands and waters present challenges to their understanding, management and protection. This is due in part to the lack of a statewide classification system for them. While sandhill lakes are recognized and defined by the SJRWMD and FNAI, sandhill wetlands are not; and sandhill wetlands and waters of any variety (lakes, ponds, sinks, fringe-features and complexes) are neither defined for areas outside the SJRWMD, nor distinguished by name in published literature. This adds to the difficulty of recognizing them as of the sandhill type and extracting and exchanging information about them. Much information has been gleaned from seepage lakes in the Central Lake District and Panhandle, but short of Henderson's study (1986) and recent studies by Nowicki et al., in prep. (1 & 2), little information is available for sandhill wetlands and waters in west central Florida. While features across the state are similar in their ecohydrology, those in the Panhandle are different in their limnology (CH2MHill, 2003), and those in west-central Florida are different in their hydrogeology and hydrology (Nowicki et al., in prep. & 2). Thus, findings from studies of features in one region are not necessarily applicable and may not advance the understanding of features in another region.

Adding to the challenge, identification of sandhill wetlands and waters is not always straight forward. One reason is that not all wetlands and waters occurring in sandhill are "sandhill" wetlands and waters, a name which (at least locally) implies not just their xeric location (i.e., sandhill), but a characteristic widely ranging hydrology and hydraulic connection to the regional aquifer. Wetlands and waters in sandhill where the aquifer is semi-confined may occur in close proximity, yet express different hydrologic cycles—some widely ranging (reflecting breaches in the semi-confining unit and an indirect hydraulic connection) and others more stable (reflecting a more intact unit and little to no connection) (Tihansky, 1996; Grubbs, 1995). Because ecological conditions may be very similar between sandhill and non-sandhill types, confirmation generally requires comparison of wetland and regional aquifer water level data (which are not always available); although the presence of mature cypress trees or other indicators of a stable wetland hydrology may be enough to rule out certain wetlands and waters.

Another challenge with sandhill wetland and water identification is delineation of their boundaries. Delineation methods for wetlands require indicators of wetland soils (hydric), wetland plants (hydrophytes) and wetland hydrology (USACOE, 1987). Hydric indicators for sandy soils are based on presence or translocation of iron, manganese and carbon from repeat saturation and/or inundation, which (with the help of microbes) lead to oxygen depletion (USDA NRCS, 2018; Hurt et al., 1998). Because sandhill wetlands occur in sandy substrates naturally low in iron and manganese and organic material is often lacking in their shallowest areas due to frequent drying, hydric soil indicators may be difficult to identify (HCUD unpublished data; Richardson, 2004; CH2MHill, 2003). Adding further difficulty are relict indicators, which may be found up to 30 years after formation, especially for soils low in iron (CH2MHill, 2003; Vepraskas, 2001). These indicators may reflect hydrologic conditions that no longer exist, necessitating further analyses of the features' landscape positions and hydrologic regimes (CH2MHill, 2003; Vepraskas, 2001). Of the hydric soil indicators found in sandhill wetlands and waters, stripped matrix and sandy redox are most common (SWFWMD unpublished data; Richardson, 2004). Stripped matrix forms when iron-manganese oxides and/or organic matter are stripped from the soil matrix during saturation; sandy redox forms when iron in solution (Fe^{2+}) moves through the soil to oxidized areas and precipitates as masses and/or pore linings (e.g., root channels) (Vepraskas and Richardson, 2001). Relict stripped matrix indicators have been noted at sandhill wetlands and waters across the peninsula (SWFWMD unpublished data; CH2MHill, 2003).

Additional challenges are associated with spatial and temporal anomalies, such as hydrophytes (e.g., maidencane) growing well into the adjacent uplands (spatial anomaly) or dominance by non-wetland plants (especially in the transitional zone) during the low phase of the hydrologic cycle (temporal anomaly) (HCUD unpublished data). Lack of expression of hydric soils (or misinterpretation of relict soils) and lack of familiarity with the widely ranging sandhill wetland and water hydrology may reduce wetland boundary determinations by noteworthy amounts. For example, the boundary of the wetland shown in Figure 2-21 was determined (by unknown investigators) during a year when rainfall for the region was the 11th lowest on record (of 103 years, SWFWMD unpublished data) and water levels were

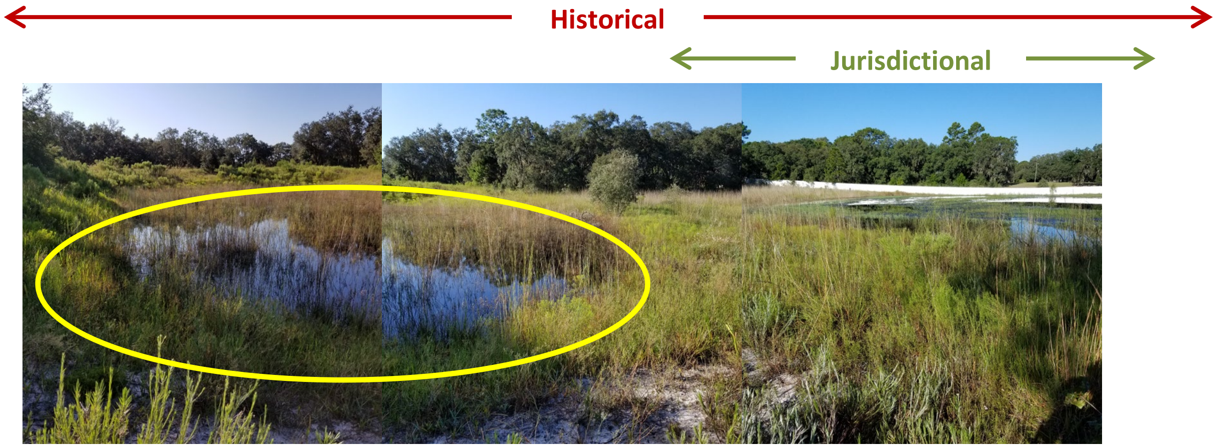

Figure 2-21. Excavated portion (encircled) of natural sandhill wetland, showing historical and underestimated jurisdictional wetland boundary. (HCUD unpublished data).

at or near the lowest on record (of 17 years, HCUD unpublished data). The boundary appears to have been delineated approximately a meter below the historical (i.e., pre-impacted) wetland edge, which allowed the landward portion of this wetland (in that area) to be excavated (likely to extract fill for residential purposes). The excavated portion is partially inundated in the photos (the water level shown is approximately 1.3 m below the historical wetland edge) and has been inundated every 3-4 years since excavation. This suggests that the jurisdictional boundary was markedly underestimated, with nearly half of the wetland transitional zone excluded as upland. While not utilized, water level data were available to better delineate the wetland's boundary, but often the data are not available; as such, the likelihood of underestimating sandhill wetland and water boundaries is probably very high. Similar challenges were noted by LaClaire (1995), who assessed temporary ponds in north-central Florida, noting that because the vegetation is adapted to the ponds' wet and dry cycles, a single sampling presents "only a small picture of the total community composition," which has implications for both wetland delineations and management.

The quirky ecohydrology of sandhill wetlands and waters also has implications for health and impact assessments. For sandhill wetlands and waters in the northwestern peninsula, current methods of evaluating potential (or actual) impact from groundwater production are focused on "normal" hydrologic conditions, which are expected to occur during years of normal rainfall (SWFWMD unpublished data). Because the sandhill wetland and water hydrologic regime is astatic (not operating around a mean, CH2MHill, 2003), saturation and inundation do not normally reach elevations expected by other types of wetlands and waters whose regimes are more stable (HCUD unpublished data). The consequences of not being fully inundated on a regular basis are expressed in the loss of (or failure to accumulate) organic soils and shift of species composition from hydrophytic to less water tolerant. These expressions have historically resulted in the perception of impact, rather than the inevitable hydrologic low phase of a sandhill wetland or water feature. Assessment methods, therefore, are best when they first consider the natural ecohydrologic potential of sandhill wetlands and waters based on their geomorphology and their relationship to the regional water table.

Health and impact assessments for sandhill wetlands and waters are also challenged by anomalous vegetation patterns, which may cause bias. An assessment performed along a slope where maidencane (a hydrophytic grass) dominates and is distributed well beyond the wetland edge (as described previously) may yield more positive results than an assessment performed along a slope where this pattern does not occur, and species are predominantly facultative. Similarly, the presence of hydrophytic trees such as laurel oak and water oak occurring as a fringe or patch along portions of the wetland periphery (as described previously) may imply good wetland health because they, too, occur in areas typically dominated by facultative species. Areas like these have been documented at multiple sandhill wetlands and waters in west-central Florida and may reflect an ancillary source of hydration instead of (or in addition to) inundation by groundwater (Nowicki et al., in prep.). As such, these areas should be identified and regarded cautiously for their interpretation of health and impact. Similar to the need to evaluate sandhill wetlands and waters over a broad temporal scale to see their full picture

(LaClaire, 1995), there too is the need to evaluate sandhill wetlands and waters over a broad spatial scale.

Beyond the challenges unique to sandhill wetlands and waters are those shared by other geographically isolated wetlands and waters, which as a group are less recognized for their role within landscapes. This is reflected in the recent repeal of Federal protection for certain isolated wetlands (proposed C.F.R. 2019). Kirkman et al. (2012) noted the irony that "the absence of a clear surface-water connection contributes to the uniqueness of these wetland habitats; yet this defining feature has also played a role in society's failure to recognize and protect the ecological services associated with them." They further noted the unique suite of rare species associated with depressional wetlands in the Southeast U.S. and their disproportionate contributions relative to their collective area (Whigham, 1999), especially those that are minimally disturbed (Goebel, et al., 2000). Fortunately, isolated wetlands in Florida are protected, but most regulations do not distinguish sandhill wetlands and waters from other types. This results in losses of wetland area and critical functions they provide, both individually and collectively within the landscape. It also contributes to destruction and degradation of their buffers, which are often converted to lawns (HCUD unpublished data).

A classification system would bring tremendous value in improving and expanding understanding of sandhill wetland and water ecohydrology. Sutter and Kral (1994) recognized the importance of classification for depressional wetlands across the Southeast, declaring the need for "an accurate regional community classification…to provide a common language to discuss, compare, and protect" them. This, too, is needed for sandhill wetlands and waters—a system that recognizes and distinguishes them from other types of isolated wetlands and thoughtfully highlights their key differences within the greater group, particularly as they relate to feature type and hydraulic connection. A classification system would enhance efforts already made by state water management districts and FNAI to better understand the unusual nature of sandhill wetlands and waters and ultimately to better regulate and protect them.

CONCLUSIONS

Florida's sandhill wetlands and waters are a special, understudied class of geographically isolated wetlands (GIWs) and waters embedded in the imperiled sandhill of northern peninsular Florida and the Panhandle. They are distinct from other isolated wetlands and waters in their karst origin, xeric setting and direct or indirect hydraulic connection to the regional aquifer. These connections result in widely fluctuating hydrologic regimes, which result in ecological communities that shift over time and space in response. While highly variable in their shape, depth, size and type (e.g., wetland, lake, pond, sink or multi-feature complexes), they share many common attributes, including:

- sandy substrates;
- a lack of trees or mucky soils indicative of stable water levels;
- a diverse mix of grasses and sedges, which exhibit zonation along a hydration gradient (in shallow areas) or open water (in deeper areas); and
- wetlands not fully inundating in years of normal rainfall and lengthy periods of dry conditions lasting years or even decades.

While sometimes regarded as depauperate, these unique features contribute important functions within the landscape, individually and as a diverse mosaic over time and space. They also offer socioeconomic values for recreation and aesthetics such as open space, birding and hunting. Lacking a recognized statewide definition and described by various names in the limited body of literature, they remain understudied, not well understood and vulnerable to impacts and loss from residential and commercial development, dredge and fill, mowing, dumping, groundwater production and the uncertain consequences of a changing climate. Information presented here summarizes what is known about sandhill wetlands and waters across Florida, highlighting their regional differences, which vary as a function of hydrogeology. This chapter also presents findings from recent studies of west-central Florida sandhill wetlands and waters, which are unique from others in the state in their geologic setting and hydrologic control. Finally, it emphasizes the need for a classification system that recognizes sandhill wetlands and waters as a distinct variant of GIWs and waters and encourages additional research to fill broad data gaps and ultimately safeguard sandhill wetlands and waters as a valued natural resource.

ACKNOWLEDGEMENTS

Special thanks to Jason LaRoche for editorial review of this chapter.

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Chapter 3: Hydrogeologic controls on geographically isolated wetlands & waters - Physical & chemical hydrologic evidence of connectivity to a regional water-supply aquifer

ABSTRACT

Florida's sandhill wetlands and waters represent a unique subset of geographically isolated features. Embedded in imperiled sandhill communities, these features exhibit a characteristic ecohydrology due to their karst origin, xeric setting and dependence upon a widely ranging shallow water table. For those features in west-central Florida, the shallow water table is that of the Upper Floridan aquifer, part of the massive Floridan aquifer system, which underlies all of Florida and parts of four other states. This dependence has important implications for natural resource management, public water-supply and regulation and is the focus of this study.

Water level elevations and/or geochemistry were compared for 19 wetlands, lakes and ponds and 12 monitor wells (10 in limestone, two in surficial sand). Hydrograph analyses indicate close tracking and similar elevations between most features and wells and very high correlation ($0.84 \leq R^2 \leq 0.99$). Geochemical analyses show: limestone water chemistry at many features, particularly for specific conductance, calcium (Ca^{2+}) and pH; rainwater chemistry at shallow wetlands; and rainwater-limestone mixing at the remaining features. Results suggest these features are surface water expressions of the underlying regional aquifer hydrology, distinguishing them from other GIWs and waters and establishing them as a groundwater endmember of the hydrologic continuum

KEYWORDS

Sandhill wetland, Groundwater wetland, Groundwater pond, Groundwater lake, Groundwater exchange, Hydraulic connection, Lisse effect

INTRODUCTION

This study examines the hydraulic connection between a unusual type of geographically isolated wetlands (GIWs) and waters in west-central Florida and a regional water-supply aquifer. Known locally as "sandhill" wetlands and waters for their occurrence in the sandhill upland communities (savannah-like prairies on rolling hills and ridges of deep marine sands, FNAI, 2010), these features are different from other GIWs because of their karst origin, xeric setting and widely fluctuating hydrology, which may include dry periods lasting years or even decades (Nowicki et al., in prep.; Jones Edmunds, 2006; CH2M Hill, 2005).

This study is part of a suite of studies intended to improve understanding of the unique ecohydrology of Florida's sandhill wetland and water features (which include ponds, lakes, sinks and their contiguous wetlands). In this study, water levels and water geochemistry from 19 features in west-central Florida were used as evidence that they are surface-water expressions of the Upper Floridan aquifer (U Fldn)—part of the expansive Floridan aquifer system, which is one of the most productive aquifers in the world (Miller, 1990). In a companion study, geophysical exploration, borehole and other data were used to develop conceptual models of: 1) the mechanisms of their hydraulic connection to the U Fldn; and 2) their fundamental ecohydrology (Nowicki et al., in prep.). The hydraulic connection of sandhill wetlands and waters to a regional aquifer distinguish them as a unique variant of GIWs and waters, which has important implications for natural resource management and for wetland and groundwater regulation.

BACKGROUND

Geographically isolated wetlands (GIWs) and waters are defined as aquatic islands in a terrestrial landscape (Edwards and Sharitz, 2000), wetlands surrounded by upland (Tiner, 2002), and there are other definitions depending upon scale and perspective (e.g., ecological or hydrologic isolation, etc.) (Liebowitz and Nadeau, 2003). Despite their name, GIWs may not be strictly hydrologically isolated (Leibowitz, 2015; Mushet et al., 2015; Rains et al., 2015). Current scientific thought regards isolation as a continuum that allows for some connectivity under infrequent circumstances such as high rainfall events. GIWs may connect to each other or to other surface waters via bank overflow or groundwater discharge to local or regional flow systems (Liebowitz and Nadeau, 2003). In doing so, these connections may contribute a significant nexus to Waters of the U.S., although Federal protection for this type of nexus are under repeal (proposed C.F.R. 2019). Beyond their potential connection, GIWs contribute significant landscape functions such as flood storage, water table regulation, nutrient and sediment retention, wildlife and aquatic habitat, among others (Novitzki et al, 1996).

For most GIWs, hydrologic control is local, be it meteorological or geological or both. This is true for Carolina Bays of the mid-Atlantic coastal plain (Lide et al., 1995); moraine, ice-scour, and kettle ponds of Alaska (Rains, 2011); playa wetlands of the Southern High Plains (e.g., Texas) (Tsai et al., 2007); prairie potholes of North Dakota (Sloan, 1972, Richardson et al., 1992); and vernal pools of California (Rains et al., 2006, Rains et al., 2011) and the northeastern U.S. (Brooks, 2004). It also is true for sandhill waters elsewhere in Florida (Jones Edmunds, 2006; CH2M Hill, 2005) and for many in Nebraska (Ginsberg, 1985). Few studies, however, offer evidence of hydrologic control of GIWs and waters by a large, regional aquifer. Ginsberg (1985) suggests some Nebraskan sandhill waters "are to some degree connected with the groundwater reservoir," but that they are not simply groundwater outcrops). Wolfe (1996) identifies certain compound sinks in the Highland Rim of Tennessee (an area of high local hydrogeologic heterogeneity) with water levels matching those of the regional aquifer, while others nearby have perched water tables. Blood et al., suggest regional control on the hydrology of certain isolated wetlands in the Dougherty Plain as a function of critical aquifer elevations of an interconnected groundwater system (1997). Henderson provides evidence of hydraulic connection between a sandhill lake (Hunter's Lake, one of this study's sites) and the regional groundwater system based on lake stage and water chemistry, which were similar to nearby U Fldn monitor wells (1986). Other definitive evidence of regional hydrologic control of GIWs was not found, highlighting both the uniqueness of the features of this kind and the need for their study, particularly given increasing groundwater demands for public supply, a changing climate and potential losses of federal protections for isolated wetlands (proposed C.F.R. 2019).

STUDY AREA

The study area is located in a xeric landscape of west-central Florida referred to as sandhill, a savannah-like upland community found on rolling hills and ridges on well-drained, sterile sandy soil in the northern half of peninsular Florida and the Panhandle (FNAI, 2010). Two physiographic provinces, Gulf Coastal Lowlands and Brooksville Ridge, are associated with the current study sites (White, 1970) (Figure 3-1). Land surface elevations generally range from 2 to 30 meters (m) above sea level (NAVD1988 datum) in the Gulf Coastal Lowlands and from 15 to 90 m in the Brooksville Ridge. Elevations at the study sites range from 0 to 19 m and 14 to 28 m above sea level, respectively.

Climate

The climate in west-central Florida is humid subtropical, with a 30-year (1980-2010) normal annual rainfall of 1341 mm (Brooksville Hernando Co Airport, Florida, USW00012818, 1981-2010) (Arguez et al., 2010). Most of the rain (57%) falls in the wet season (June - September) as convective storms; the rest falls in the dry season (October - May) as less intense frontal systems. Annual rainfall extremes ranging from 860 mm (SWFWMD Richloam Tower gage WY 1980, n.d.) to 2120 mm (SWFWMD Chassahowitzka gage WY 2003, n.d.; SWFWMD Richloam Tower gage WY 2003 n.d.) have been recorded at local gages, generally in association with drought and La Nina events or with tropical storm and El Nino events, respectively. Annual evapotranspiration averages 1000 mm for the region (Bidlake et al., 1996), and annual average lake evaporation can exceed the long-term annual average rainfall (Sacks et al., 1994; Lee et al., 1997; Swancar et al., 2000).

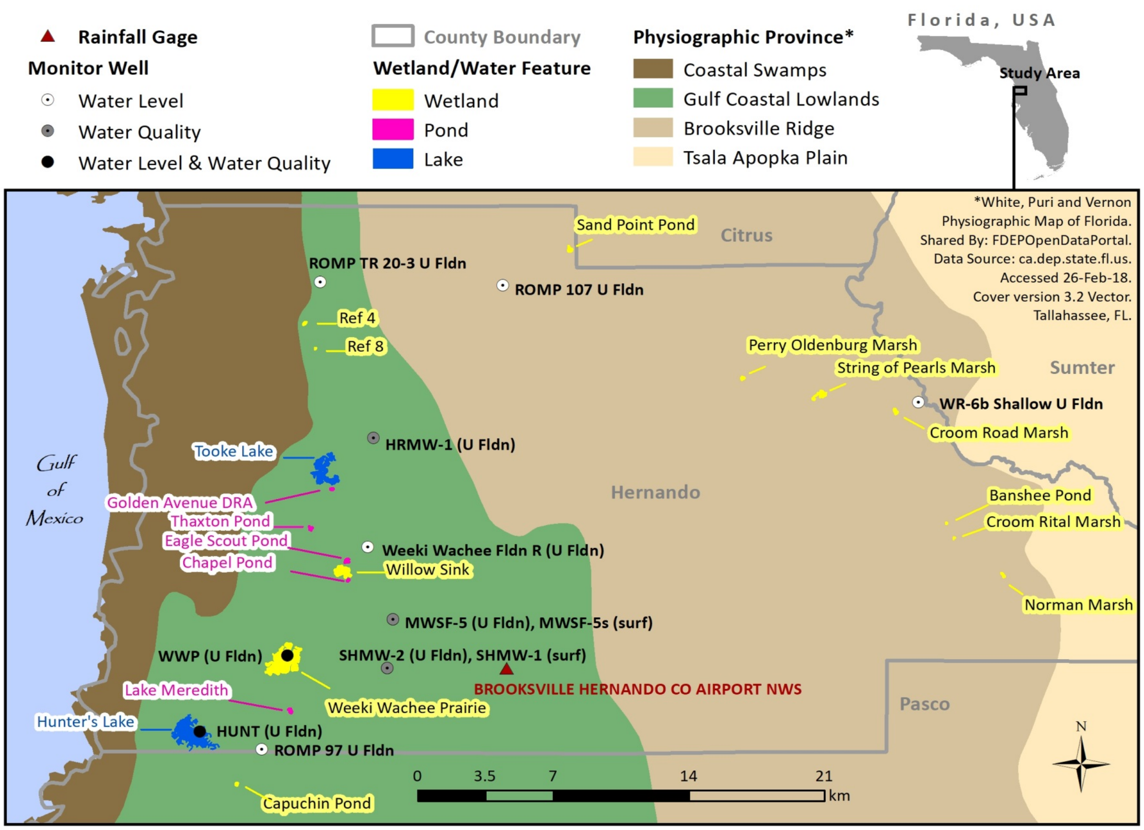


Figure 3-1. Project study area with monitoring site locations and physiographic provinces. Note, ponds and lakes, as presented here, include contiguous wetlands, which occur as a fringe or adjacent shallower pool(s).

Hydrogeologic Setting

In the Gulf Coastal Lowlands portion of the study area, the Upper Floridan aquifer occurs as a sequence of near-surface, highly transmissive karstic limestone that occasionally outcrops but is predominantly overlain by a thin overburden of unconsolidated sand with minor amounts of silt and clay (Arthur et al., 2008). Here the absence of significant low permeability sediments allow groundwater to move freely between the sand and limestone, and the Upper Floridan aquifer is considered unconfined. Because of the high permeability of the overburden, little surface runoff occurs, and recharge is relatively high. In the Brooksville Ridge portion of the study area, remnant low permeability clay sediments of Hawthorn Group origin separate the limestone from the mostly sand overburden (Arthur et al., 2008). This clay layer is thickest on and near the Ridge feature itself. While the clay is not expansive enough to confine the Upper Floridan aquifer regionally, it can produce locally perched water table conditions above it (Basso, personal comm. 2018). The clay layer thins westward towards the Gulf coast and along the Ridge's eastern flank, becoming discontinuous or altogether absent, resulting in unconfined conditions in these areas.

Subsidence is a characteristic feature of the karstic Upper Floridan aquifer in the project study area. As its limestone surface dissolves, pits are created that infill slowly with the sandy overburden. The infilled pits form the numerous wetlands, ponds and lakes seen today (Tihansky and Knochenmus, 2001). Because limestone dissolution may occur as small channels or large voids, and because these openings are infilled with sediment of varying depths and composition, a high degree of wetland hydrogeomorphologic variation is possible over a relatively small distance (Figure 3-2). Dissolution also occurs within the limestone, forming cavities and caverns that make the Upper Floridan aquifer in this region extremely transmissive and productive. Dissolution of near-surface carbonates can also concentrate insoluble clays within the limestone, leaving behind a clayey residuum cover over the

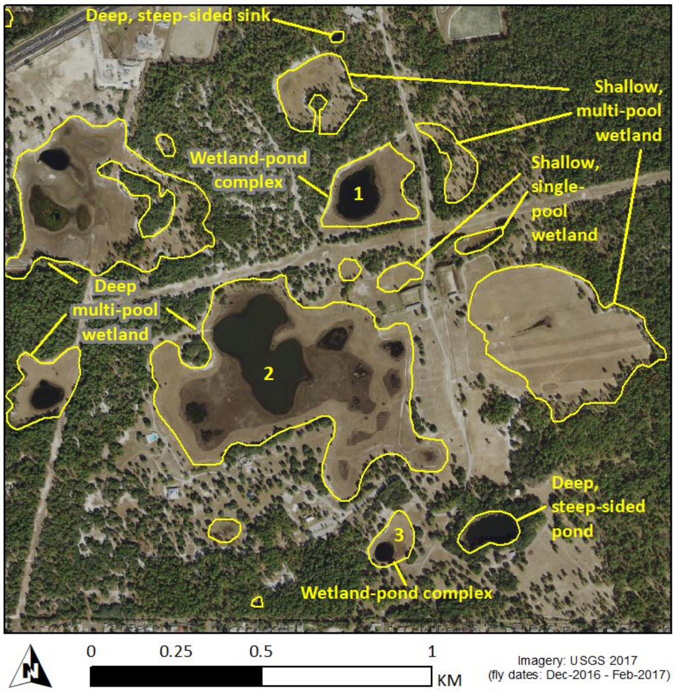


Figure 3-2. Aerial image of sandhill wetland and water features, Sandhill Scout Reserve, Brooksville, Florida, USA. Features evaluated in this study include: [1]Eagle Scout Pond, [2]Willow Sink, [3]Chapel Pond.

limestone surface (Miller, 1986). This layer of low permeability material is often laterally discontinuous and can vary in thickness from a thin veneer to more than 30 m thick and can create semi-confining (or perched) conditions above the limestone on a very local scale.

METHODS

Study Sites

Surface water from 12 wetlands, five ponds and two lakes were evaluated for water level elevation and geochemistry. As no standard definition exists for ponds, in this study they include those smaller, permanently inundated features with insufficient fetch to produce wave action. Groundwater from shallow wells constructed in the interior of 10 of the 12 wetlands and from 12 deeper monitor wells also were evaluated. Ten of these deeper wells were constructed within limestone of the U Fldn, and two were constructed in the overlying surficial sands. Five of the 10 wells were evaluated for their water level elevations, five for their water geochemistry and two for their water levels and geochemistry. All of the surface water features and all but five monitor wells were selected from a regulatory wetland monitoring program associated with local groundwater production (SWFWMD Water Use Permit #20005789, 2015) and are not evenly distributed among physiographic provinces (Figure 3-1). The other five monitor wells (constructed in limestone of the U Fldn) were included in this evaluation to compare with water levels of the wetlands, ponds and lakes. Unlike the other U Fldn monitor wells, these wells are not adjacent to groundwater production wells and have lengthier, more consistent water level elevation records. General site information, along with the type of analyses performed at each monitoring location, are presented in Table 3-1.

Table 3-1. General Site Information.

Site Type	Setting	Province		Station	Land Surface Elevation (m, NAVD88)	*Modeled Drawdown (m)	Area (h)	Perimeter (km)	Maximum Depth (m)	Cased Depth (m)	Analyses: Water Level			Analyses: Water Chemistry		
		Brooksville Ridge	Gulf Coastal Lowlands								SW	GW-ss	GW-ls	SW	GW-ss	GW-ls
Wetland		X^e		Banshee Pond	15	0.15	1	0.3	3	-	X			X		
		X^e		Croom Rital Marsh	16	0.15	1	0.3	2	-	X	X		X	X	
		X^e		Croom Road Marsh	14	0.12	4	0.9	1	-	X	X		X	X	
		X^e		Norman Marsh	17	0.09	2	0.8	1	-	X	X		X	X	
		X		Perry Oldenburg Marsh	15	0.12	2	0.6	2	-	X	X		X	X	
		X		Sand Point Pond	16	0.06	4	1	1	-	X	X		X		
		X^e		String of Pearls Marsh	14	0.15	11	3	1	-	X	X		X	X	
			X	Capuchin Pond	9	0.27	2	0.5	5	-	X			X		
			X	Ref 4	4	0.06	2	0.6	2	-	X	X		X	X	
			X	Ref 8	4	0.06	1	0.3	2	-	X	X		X	X	
			X	Weeki Wachee Prairie	7	0.24	144	13	3	-	X	X		X	X	
			X	Willow Sink	7	0.21	32	3	3	-	X	X		X	X	
Pond			X	Chapel Pond	7	0.21	1	0.5	6	-	X			X		
			X	Eagle Scout Pond	7	0.18	5	0.9	6	-	X			X		
			X	Golden Avenue DRA	6	0.12	2	0.5	5	-	X			X		
			X	Lake Meredith	9	0.46	4	0.8	5	-	X			X		
			X	Thaxton Pond	6	0.15	2	1	6	-	X			X		
Lake			X	Hunter's Lake	7	0.21	178	18	5	-	X			X		
			X	Tooke Lake	6	0.12	103	12	5	-	X			X		
Monitor Well	ASW		X	Hunter's Lake (HUNT)	6	0.21	-		37	20			X			X
			X	Weeki Wachee Prairie (WWP)	7	0.12	-		46	20			X			X
	Upland		X	ROMP 97 U Fldn	10	0.34	-	-	108	95			X			
		X		ROMP 107 U Fldn	35	0.06	-	-	73	43			X			
			X	ROMP TR 20-3 U Fldn	4	0.06	-	-	62	30			X			
			X	Weeki Wachee Fldn R (U Fldn)	18	0.18	-	-	76	45			X			
		X^e		WR-6b Shallow U Fldn	22	0.12	-	-	109	99			X			
			X	MWSF-5s (surf)	19	0.27	-	-	24	-					X	
			X	SHMW-1 (surf)	19	0.27	-	-	24	-					X	
			X	HRMW-1 (U Fldn)	12	0.09	-	-	122	46						X
			X	MWSF-5 (U Fldn)	19	0.27	-	-	162	78						X
			X	SHMW-2 (U Fldn)	19	0.27	-	-	91	43						X
											19	**10**	**7**	**19**	**11**	**5**

KEY: ASW: Adjacent to surface water feature; SW: surface water; GW-ss: groundwater from well constructed in surficial sands; GW-ls: groundwater from well constructed in limestone
^{e} eastern flank
* modeled drawdown value reflects all permitted users within model domain (Leggette, Brahsears & Graham, Inc. 2015)

Monitor Well Construction

Groundwater data were measured and/or sampled from wells constructed in four settings: 1) surficial sands within the wetland interiors, 2) surficial sands at upland locations; 3) limestone adjacent to surface water features; and 4) limestone at upland locations (i.e., not adjacent to surface water features). Wells set in the interior of wetlands were constructed of 5.1 cm PVC with solid casing 0.6 - 1 m below ground and the remainder comprised of slotted well screen. Well depths in these wells ranged

1 to 3 m below land surface. Wells set in the surficial sands at upland locations were constructed of 2.5 – 5.1 cm PVC at depths of 1.5 to 24 m below land surface (screen depths were not available). Wells constructed in limestone (adjacent to surface water features or at upland locations) were constructed of 2.4 – 3.2 cm PVC or steel. Solid casing was set just below the top of limestone (20 to 78 m below land surface) with open boreholes to depths of 36 to 162 m below land surface.

Water Level Data Collection & Analyses

Water level data obtained for most of the 19 surface water features include two periods of record (PORs) beginning in 2002 (Gulf Coastal Lowlands sites) or 2008 (Brooksville Ridge sites) and with both ending in 2018 (Hernando County Utilities Department [HCUD], unpublished data) (Table 3-2). Some sites had longer (or different) PORs, but because some data and/or survey accuracy could not be confirmed, not all data were included in the analyses. Data for the surface water features generally include twice monthly staff gage readings when surface water was present, or shallow monitor well readings when surface water was absent. Where both surface water and shallow monitor well readings were recorded, water levels from the monitor wells were selected for analysis (largely to rule out temporary ponding from recent rainfall during low water periods). Groundwater level data from the five U Fldn water level monitor wells were obtained for their PORs which began between 1967 and 2008 and ended in 2018 (HCUD, unpublished data; Southwest Florida Water Management District [SWFWMD], 2018; USGS, 2018)). Data consisted of hourly recordings from pressure transducers aggregated into daily averages. All data were provided in NAVD88 units feet and converted to metric for this study. Hydrograph and regression analyses were performed by pairing data from surface water features with data from nearby U Fldn water level monitor wells to examine the variation and correlation between them.

Table 3-2. Water level range of wetlands and waters in study area.

Site Type	Setting	Province: Brooksville Ridge	Province: Gulf Coastal Lowlands	Station	Period-of-Record	Start	End	Data Type: Surface Water	Data Type: Ground-water	Range (m)
Wetland		X[e]		Banshee Pond	*	Dec-08	Sep-18	x		2.76
		X[e]		Croom Rital Marsh	*	Dec-08	Sep-18	x	x	< 5.75
		X[e]		Croom Road Marsh	*	Dec-08	Sep-18	x	x	3.87
		X[e]		Norman Marsh	*	Dec-08	Sep-18	x	x	> 2.38
		X		Perry Oldenburg Marsh	*	Dec-08	Sep-15	x	x	> 3.80
		X		Sand Point Pond	*	Dec-08	Sep-18	x	x	> 3.16
		X[e]		String of Pearls Marsh	*	Dec-08	Sep-18	x	x	3.63
			X	Capuchin Pond		Nov-02	Sep-18	x		4.42
			X	Ref 4		Nov-02	Sep-18	x	x	2.28
			X	Ref 8	*	Apr-08	Sep-18	x	x	1.95
			X	Weeki Wachee Prairie		Nov-02	Sep-18	x	x	4.03
			X	Willow Sink		Oct-02	Sep-18	x	x	4.37
Pond			X	Chapel Pond		Nov-02	Sep-18	x		4.26
			X	Eagle Scout Pond		Nov-02	Sep-18	x		4.15
			X	Golden Avenue DRA		Nov-03	Sep-18	x		2.74
			X	Lake Meredith		Nov-02	Sep-18	x		5.02
			X	Thaxton Pond		Dec-02	Sep-18	x		3.63
Lake			X	Hunter's Lake		Jun-67	Sep-18	x		2.68
			X	Tooke Lake	*	May-06	Sep-18	x		2.31
Monitor Well	ASW		X	Hunter's Lake (HUNT)	*	Oct-12	Sep-18		x	1.59
			X	Weeki Wachee Prairie (WWP)	*	Oct-12	Sep-18		x	2.43
	Upland		X	ROMP 97 U Fldn		Oct-92	Sep-18		x	4.39
		X		ROMP 107 U Fldn	*	Oct-08	Sep-18		x	2.14
			X	ROMP TR 20-3 U Fldn		Oct-00	Sep-18		x	2.05
			X	Weeki Wachee Fldn R (U Fldn)		Oct-66	Sep-18		x	4.04
		X[e]		WR-6b Shallow U Fldn	*	May-08	Sep-18		x	3.91
			X	MWSF-5s (surf)	*	Oct-14	Sep-18		x	3.11
			X	SHMW-1 (surf)	*	Jan-07	Sep-18		x	4.64
			X	HRMW-1 (U Fldn)	*	May-11	Sep-18		x	3.11
			X	MWSF-5 (U Fldn)	*	Jan-15	Sep-18		x	2.88
			X	SHMW-2 (U Fldn)	*	Jan-07	Sep-18		x	4.58

KEY: ASW: Adjacent to surface water feature   [e] eastern flank

<: wetland flooded by non-contiguous river overflow; actual range is lower

>: minimum water levels not available due to shallow monitor well depth; actual range is higher

* Long-term range likely higher than shown due to shorter period-of-record which excludes minimum & maximum water levels as recorded at site with longest data record (Weeki Wachee Fldn R). Minimum water levels here occurred in 2009, 2012 and 2007 and maximum water levels occurred in 1982-1984, 1974 and 2003-2004.

Water Geochemistry Data Collection & Analysis

Water geochemistry data were collected once at the end of the 2015 dry and wet seasons, between May 29 and June 3, 2015 and October 5 and 10, 2015, respectively. Water sampling at each site was performed to evaluate water geochemistry along a vertical gradient (to the degree possible, given the availability of monitoring devices and depth of water at the sites) (Figure 3-3). For the wetlands, ponds and lakes, one or two surface water samples were collected based on the depth of water at the time of sampling. At sites where water depth was 2 m or less (all but one wetland), one *shallow* sample was

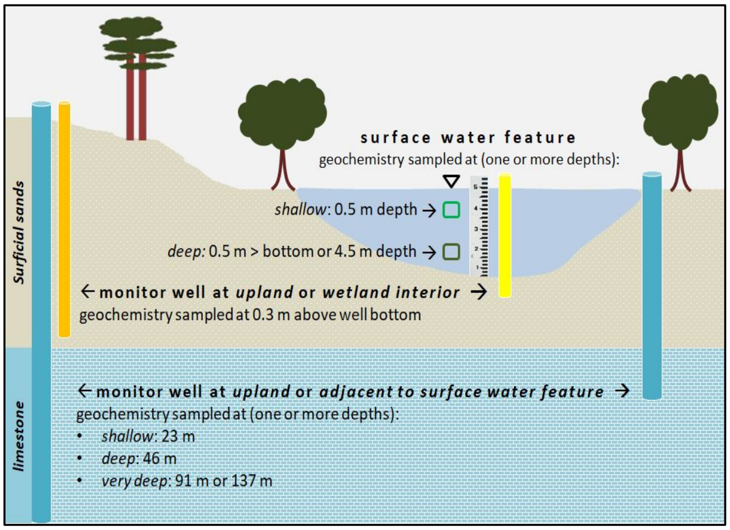


Figure 3-3. Water geochemistry sampling depths along vertical gradient at surface and groundwater monitoring locations.

collected at approximately 0.5 m below the top of the water column using the grab method. At the pond and lake sites (and one wetland) where water depth was 2 - 5 m, samples were collected at two depths—a *shallow* sample was collected as described above, and a *deep* sample was collected using a horizontal Van Dorn sampler at approximately 0.5 m above the bottom elevation. For the pond and lake sites where water depth was 5 m or more, the *shallow* sample was collected as above, and the *deep* sample was collected using the horizontal Van Dorn sampler at approximately 4.5 m below the water level surface. Grab samples were collected in a 500 mL high-density plastic (hdp) container with a screw on cap; Van Dorn samples were transferred to hdp containers upon retrieval.

At the wetland sites where shallow monitor wells were installed, groundwater samples were extracted using either a peristaltic pump and 1.3 cm tubing or by using a 2.5 cm PVC bailer or 1.3 cm steel bailer (well-width dependent) attached to a rope and inserted to a depth of approximately 0.3 m above the well bottom. At the other monitor wells, groundwater samples were extracted at various depths (depending on the depth of the well) using a 2.5 cm PVC bailer attached to a rope. For monitor wells in the surficial sands, the bailer was inserted to a depth of approximately 0.3 m above the well bottom. For monitor wells constructed in limestone, the bailer was inserted to multiple depths—approximately 23 m, 46 m and 91 m or 137 m—referenced herein as *shallow, deep or very deep* samples (respectively) to identify any variation along the vertical gradient. Pumped samples were collected directly into 500 mL hdp containers; bailed samples were immediately transferred to 500 ML hdp containers upon retrieval. Field parameters—pH, specific conductance and temperature—for both surface and groundwater samples were measured by inserting the multi-meter probe (calibrated on the day of use) (YSI Inc. Yellow Springs, Ohio, USA) into the sample and recording the parameter values as soon as parameter-equilibrium was achieved. Samples were then sealed and transferred to the mobile staging area, filtered with a 0.45 micron filter (where algal content was dense) and then transferred to separate 50 mL or 30 mL hdp containers and placed on ice until refrigerated. Samples submitted for cation analysis were treated with nitric acid within 1 week of collection. The multi-meter probe and hdp sample containers and caps were thoroughly rinsed between samples.

Cation (Ca^{2+}, Mg^{2+}, K^+ and Na^+) samples for the dry and wet seasons and Ca^{2+} and Mg^{2+} samples for the dry season were analyzed at the University of South Florida's (USF) Geochemical Research Laboratory in Tampa, Florida using a Perkin Elmer Optima 2000 DV ICP-OES. Anion (Cl^-, SO_4^{2-}) samples for the dry and wet season and cation (K^+ and Na^+) samples for the wet season were analyzed at Advanced Environmental Laboratories, Inc. in Tampa, Florida. Isotopic analysis was performed at USF's Stable Isotope Laboratory using the Picarro Cavity Ringdown Spectrometer.

Rainfall Data

Rainfall data (daily and 1980-2010 monthly normals) were obtained for the Brooksville Hernando County Airport gage located in the center of the study area (Figure 3-1) (Arguez et al., 2010).

RESULTS

Water Level Analyses

The hydrographs in Appendices 3-A1 and 3-A2 depict the widely ranging water levels characteristic of sandhill wetlands and waters (for clarity, only the most recent 10 years of the 6 to 52-year PORs are shown). Calculated water level ranges (maximum water level minus minimum water level) for the full, available PORs are presented in Table 3-2. Water levels range between 2 and 5 m for both the features and monitor wells and (where adequate PORs are available for analysis) generally increase north to south along topographic and hydraulic gradients.

The close and consistent tracking between water levels of sandhill wetland and water features and those of the nearby U Fldn monitor wells also are characteristic (Appendices 3-A1 and 3-A2). Water level deviations between features and monitor wells do occur and may generally be characterized as

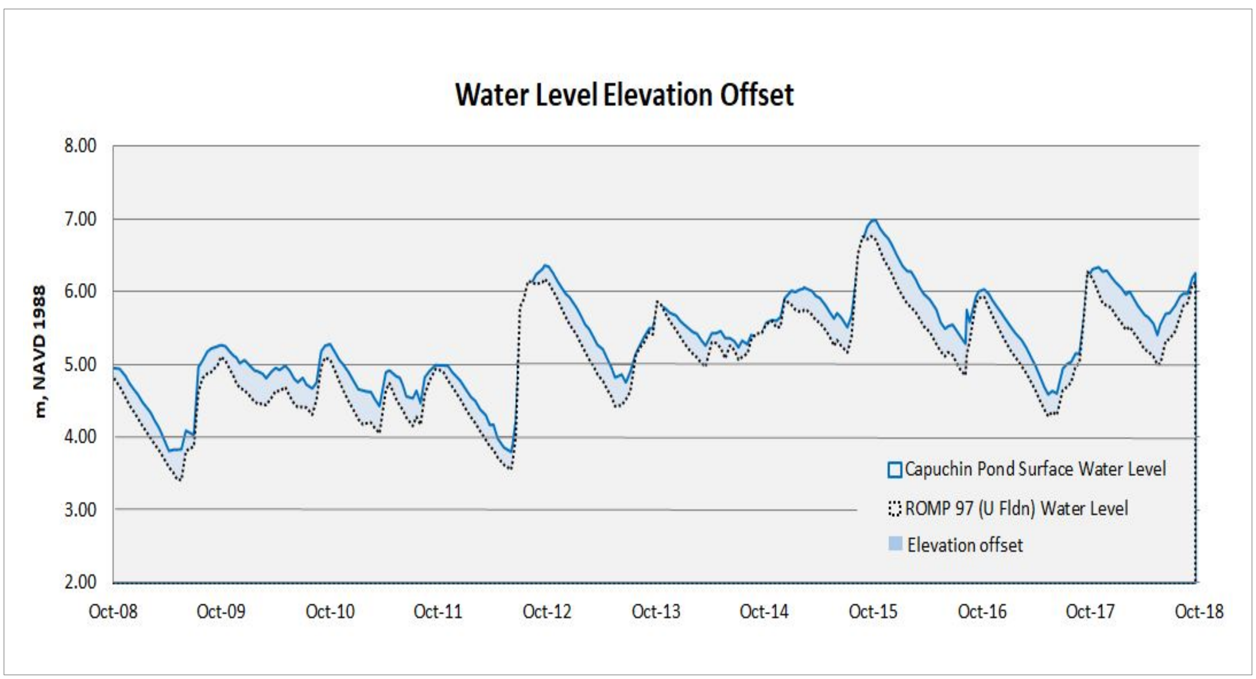


Figure 3-4a. Example of an elevation offset between a sandhill wetland and water feature (Capuchin Pond) and a nearby monitor well (ROMP 97 U Fldn). Note the offset is fairly consistent over time.

either elevation offset or behavioral response. An elevation offset is fairly consistent over a feature's POR and may range from negligible (Croom Road Marsh) to more than 3 m (Norman Marsh) depending on their relative positions along the regional hydraulic gradient (Figure 3-4a). The offsets are generally small for wetlands and wells in close proximity and during periods of low recharge (i.e., when the gradient flattens). Behavioral responses are numerous and vary in their magnitude, rate and/or timing in response to rainfall events or lack thereof. When an elevation offset is adjusted (by vertically shifting the axis of the monitor well so its water levels vary at the elevation of the wetland water level), the behavioral responses are more apparent (Figure 3-4b). In general, differences in behavioral responses between features and monitor wells displayed the following patterns:

- lower *magnitude* of rainfall responses at the features;
- similar *rate of water level incline* (or similar then tapering) at the features;
- similar *onset of water level decline* at the features, except during hydrologic highs (then lagging); and
- slower *rate of water level decline* at the features except during hydrologic highs (then similar).

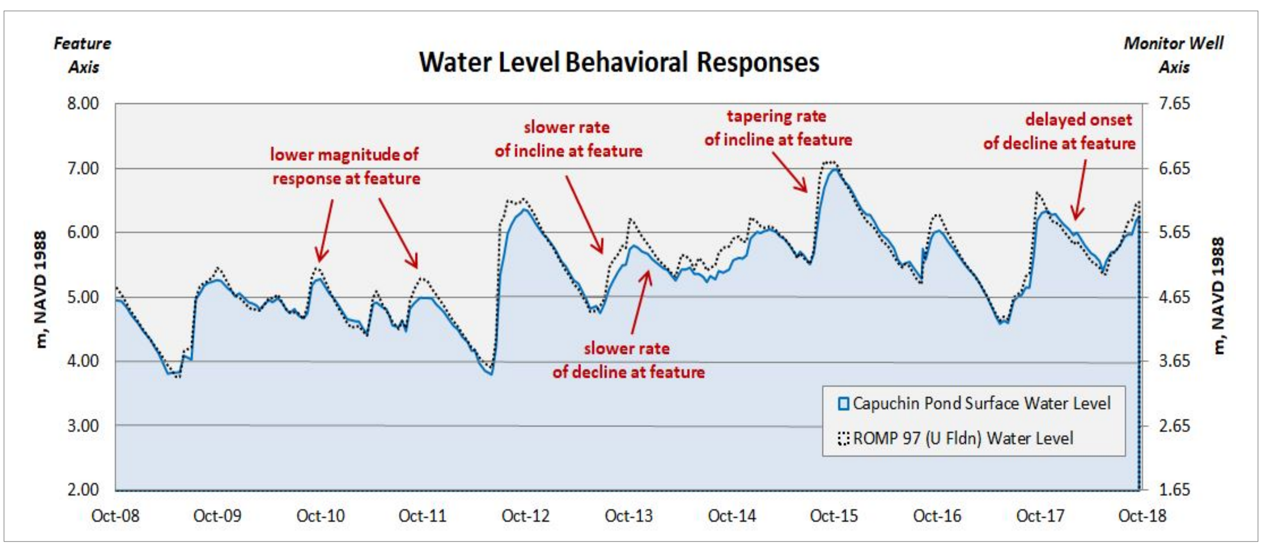


Figure 3-4b. Example of behavioral response deviations between a sandhill wetland and water feature (Capuchin Pond) and a nearby monitor well (ROMP 97 U Fldn). For illustrative purposes, the elevation offset shown in Figure 3-5a has been removed (by adjusting the right axis) to highlight these deviations. Note that while numerous deviations may occur for a given site, the general patterns are consistent across the POR.

Linear regression of the paired surface water feature and U Fldn monitor well water level elevations was performed using XLSTAT software (Addinsoft, 2019). Correlation coefficients (R^2) are included in the hydrographs (Appendices 3-A1 and 3-A2) and in Table 3-3, which lists the features in descending order by their coefficients (along with other information for comparison). At all but two features, coefficients are high (R^2 = 0.84 - 0.99), suggesting most to all of the variation in the wetland, pond and lake water levels are explained by U Fldn water levels at the monitor wells. Coefficients at the other two features are low (R^2 = 0.43 and 0.48), suggesting some other factor(s) explains most of the variation in their water levels. The data show features whose water levels are most highly correlated with those of the U Fldn are generally:

- distributed across both physiographic provinces;
- proximal to the monitor wells (generally within 3 km);
- smaller in area (generally 5 h or less); and represented by all three feature types (wetland, pond and lake), although ponds as a group are more highly correlated (R^2 = 0.94 - 0.99) than wetlands or lakes (R^2 = 0.84 - 0.99).

Site-specific hydrographs for three exemplar features and three exceptional features are presented in greater detail for closer examination (Figures 3-5a-c and 3-5d-f, respectively). Each hydrograph includes: surface water and/or shallow groundwater levels, historical (i.e., pre-development) wetland edge and bottom elevations, water levels for the nearby U Fldn monitor well and monthly rainfall (POR and 1980-2010 normals). U Fldn water level elevations (right axis) are offset (as needed) to align with those of the features (left axis) to highlight differences in feature-well behavioral responses.

Table 3-3. Results of linear regression of paired water level data for wetland and water features (dependent variable) and Upper Floridan aquifer (explanatory variable).

	Physiographic Province				Station Information		Data Composition		Descriptive Statistics*						
Station	Brooksville Ridge	Gulf Coastal Lowlands	Station Type	Upper Floridan AquiferMonitor Well	distance to well	surface area	surface water	ground water	Obs.	Range	Min.	Max.	Mean	Std. dev.	R^2
					km	h	% of data			m	m, NAVD 1988				
Croom Road Marsh	X[e]		wetland	WR-6b Shallow	1	4	8%	92%	231	3.7	10.2	13.9	11.9	0.8	0.99
Chapel Pond		X	pond	Weeki Wachee Fldn R	2	1	100%		380	4.3	3.0	7.3	4.7	0.9	0.99
Hunter's Lake		X	lake	HUNT	0	178	100%		74	0.5	1.2	1.7	1.4	0.1	0.98
Golden Ave DRA		X	pond	Weeki Wachee Fldn R	4	2	100%		244	2.7	2.9	5.6	4.2	0.6	0.98
Thaxton Pond		X	pond	Weeki Wachee Fldn R	3	2	100%		376	3.6	2.4	6.0	4.0	0.6	0.98
Lake Meredith		X	pond	ROMP 97	3	4	100%		343	5.0	3.8	8.8	5.4	0.9	0.97
Capuchin Pond		X	wetland	ROMP 97	2	2	100%		346	4.4	3.8	8.2	5.3	0.8	0.97
Ref 8		X	wetland	ROMP TR 20-3	3	1	58%	42%	251	2.0	1.7	3.6	2.6	0.4	0.95
Eagle Scout Pond		X	pond	Weeki Wachee Fldn R	1	5	100%		376	4.1	3.0	7.1	4.6	0.9	0.94
String of Pearls Marsh	X[e]		wetland	WR-6b Shallow	5	11	18%	82%	233	3.6	10.2	13.8	12.1	0.8	0.92
Ref 4		X	wetland	ROMP TR 20-3	2	2	53%	47%	279	2.2	1.5	3.6	2.4	0.4	0.92
Willow Sink		X	wetland	Weeki Wachee Fldn R	1	32	55%	45%	384	4.4	3.1	7.5	4.8	0.8	0.91
Croom Rital Marsh	X[e]		wetland	WR-6b Shallow	7	1	18%	82%	224	4.2	11.6	15.7	13.6	1.0	0.91
Weeki Wachee Prairie		X	wetland	WWP	0	144	56%	44%	26	1.7	4.7	6.5	5.4	0.4	0.88
Norman Marsh	X[e]		wetland	WR-6b Shallow	10	2	28%	72%	142	2.0	15.1	17.1	15.7	0.5	0.86
Banshee Pond	X[e]		wetland	WR-6b Shallow	7	1	100%		230	2.7	12.4	15.1	13.4	0.5	0.84
Tooke Lake			lake	WR-6b Shallow	4	103	100%		328	2.3	3.0	5.3	4.1	0.5	0.84
Perry Oldenburg Marsh	X		wetland	WR-6b Shallow	9	2	18%	82%	121	3.8	11.1	14.9	12.4	1.0	0.48
Sand Point Pond	X		wetland	ROMP 107	4	4	53%	47%	203	3.2	13.5	16.7	15.6	0.7	0.43

NOTES: *Where both surface and shallow groundwater data observations were available for a given date, groundwater data were selected for analyses.*

[e] eastern flank

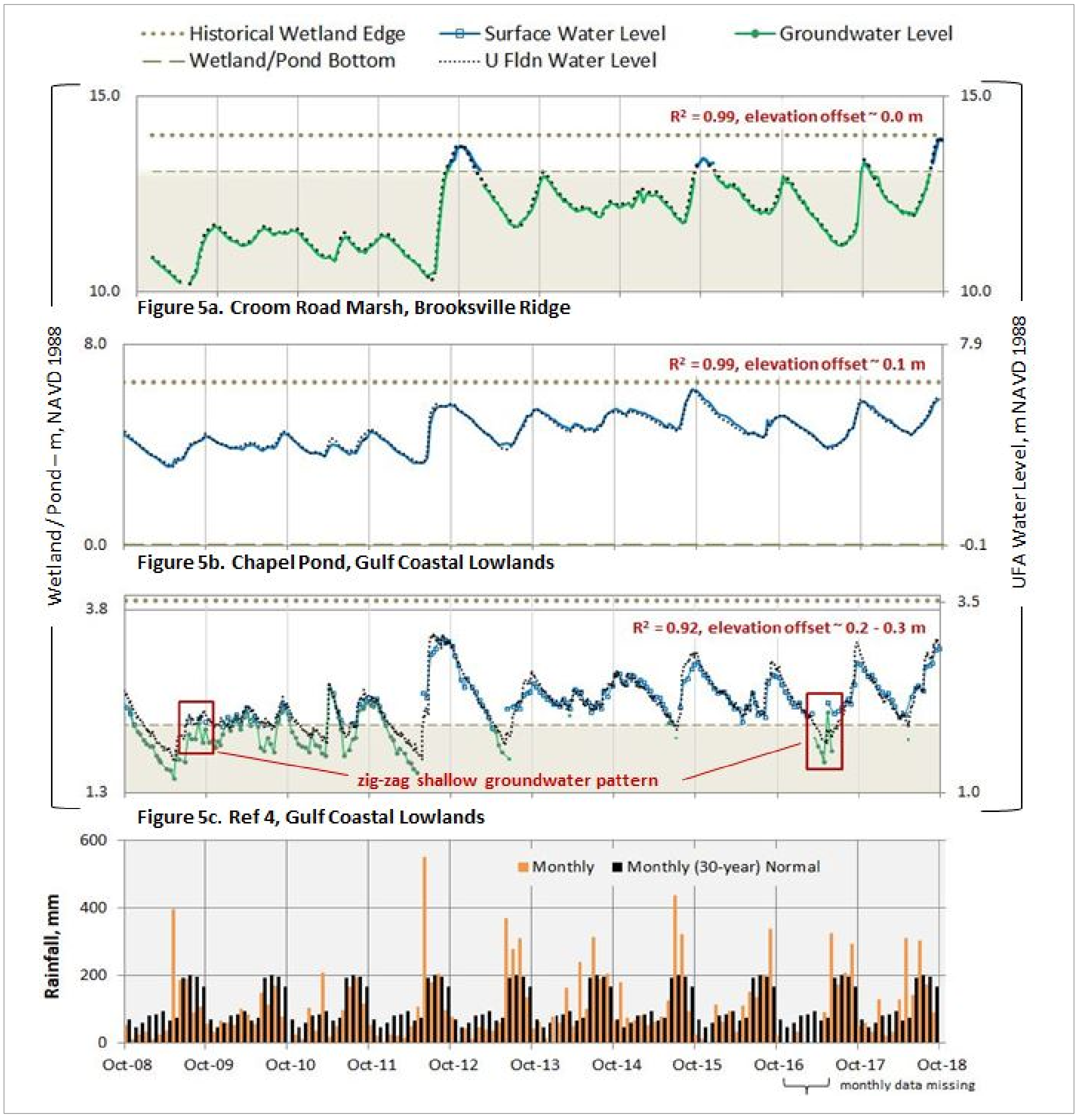
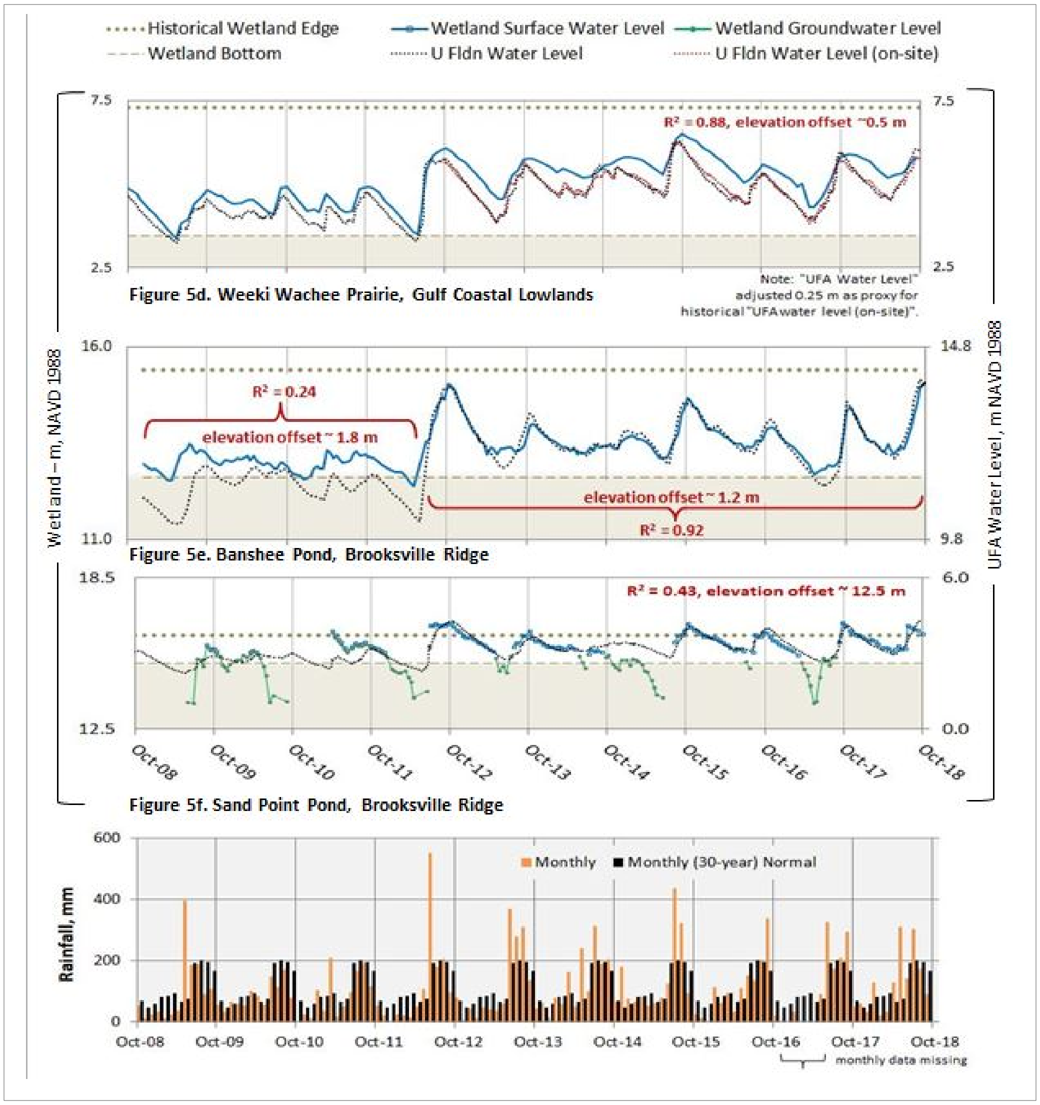


Figure 3-5a-f. Hydrographs of wetland & water features with U Fldn monitor well water levels and monthly and monthly normal (30-year) rainfall for 10-year POR. Note monitor well water level elevations (right axis) are offset relative to wetland water level elevations (left axis) to remove elevation offsets (where present) and highlight behavioral responses.

3-5a: Shallow, intermittently inundated sandhill wetland (*Croom Road Marsh*) and nearby U Fldn monitor well (*WR-6*). Note the elevation offset is negligible, and behavioral response deviations are not apparent.

3-5b: Deep, permanently inundated sandhill pond (*Chapel Pond)* and nearby U Fldn monitor well (*WW FLDN*). Note the elevation offset is small (i.e., 0.1 m difference between vertical axes), and behavioral response deviations are small and follow the general patterns noted at other features.

3-5c. Seasonally inundated sandhill wetland (*Ref 4*) and nearby U Fldn monitor well (*ROMP TR20-3*). Elevation offsets average 0.2 – 0.3 m (surface water and shallow groundwater, respectively) and behavioral responses are similar to other features, except for the periodic zig-zag pattern of the shallow groundwater levels during hydrologic low periods (see detailed insets provided in Figure 3-5g).



3-5d. Large, multi-pool sandhill wetland (*Weeki Wachee Prairie)* with on-site U Fldn monitor well (*WWP*) and nearby U Fldn monitor well (*WW Fldn*). Here, an unexpected elevation offset (0.5 m) exists between surface water and on-site U Fldn water levels. Despite the offset, behavioral responses follow the general patterns noted for other features. (Note, because the POR for the wetland precedes that of the on-site (WWP) monitor well, water levels from the nearby (Weeki Wachee Fldn R) well were adjusted 0.25 m to align with those of the on-site well to serve as its historical proxy (because of this adjustment, the elevation offset has not been removed).

3-5e. Deep, semi-permanently inundated sandhill wetland (*Banshee Pond)* and nearby U Fldn monitor well (*WR-6*). Note the dichotomous wetland-well water level elevation offset and behavioral response deviations during its low and high water level periods.

3-5f. Shallow, seasonally inundated wetland (*Sand Point Pond*) and nearby U Fldn monitor well (*ROMP 107*). Note the extremely high elevation offset, poor tracking, poor correlation (R^2 = 0.43) and behavioral responses that do not follow the general patterns noted for the other features.

Water levels at two of the exemplars exhibited near-perfect correlation (R^2 = 0.99) with those of the nearby U Fldn monitor wells, despite the features' stark hydrogeomorphic (and physiographic) differences. Croom Road Marsh is a very shallow wetland located along the eastern flank of the Brooksville Ridge that inundates intermittently, and Chapel Pond is a deep pond located in the Gulf Coastal Lowlands, which is permanently inundated (Figure 3-1, Table 3-1). Water levels from both features rise and fall closely in sync with those of the nearby U Fldn monitor wells (Figures 3-5a and 3-5b, respectively). At Croom Road Marsh, water levels appear coincident with those of the WR-6b shallow U Fldn monitor well, owing to a negligible elevation offset and minimal difference in behavioral responses (Figure 5a). At Chapel Pond, water levels deviate some from those of the Weeki Wachee Fldn R monitor well, both in elevation offset (which is small, 0.1 m, compared to most other sites) and in behavioral responses (Figure 5b), which also are small and similar to those described previously (Figure 4b). Water levels at the five other features with extremely high correlation coefficients ($0.97 \geq R^2 \leq 0.98$, Table 3-3) show similar behavioral responses as their nearby monitor wells, but with greater elevation offsets (0.2 - 0.6 m) (Appendix 3-A1).

Eight other features exhibit water levels closely tracking those of the U Fldn, but with lower correlation coefficients ($0.84 \leq R^2 \leq 0.95$), suggesting factor(s) other than the U Fldn contribute to their variation (albeit to a lesser degree) (Table 3-3). One feature (Ref 4) is exemplary among the group and is discussed here in greater detail. Ref 4 is a shallow, seasonally inundated wetland in the Gulf Coastal Lowlands (Figure 3-1, Table 3-1). Surface water and shallow groundwater levels at Ref 4 show close tracking with U Fldn water levels at the ROMP TR20-3 monitor well, with elevation offsets averaging 0.2 m - 0.3 m, respectively (Figure 3-5c). Behavioral responses follow the typical patterns for sandhill wetlands and waters (Figure 3-4b), but with slightly more deviation than those described for the prior group. Also, the shallow groundwater levels exhibit an interesting, periodic zig-zag pattern during hydrologic lows (Figure 3-5g). This pattern was noted at two other wetlands (Ref 8 and String of Pearls

Marsh) that share a similar hydrogeomorphology. The pattern is consistent with a rarely noted phenomenon known as the Lisse effect (Weeks, 2002; Heliotis et al., 1987). The Lisse effect occurs when intense rains seal the wetland surface, trapping air beneath the advancing wetting front. Pressure builds which raises the head in the shallow monitor well beyond that due to recharge; this appears as a sharp spike in the groundwater level. When the pressure is released (usually after a few days), the groundwater level equilibrates with the water table, exhibiting a drop in water level that reflects the actual recharge that occurred from the rainfall event.

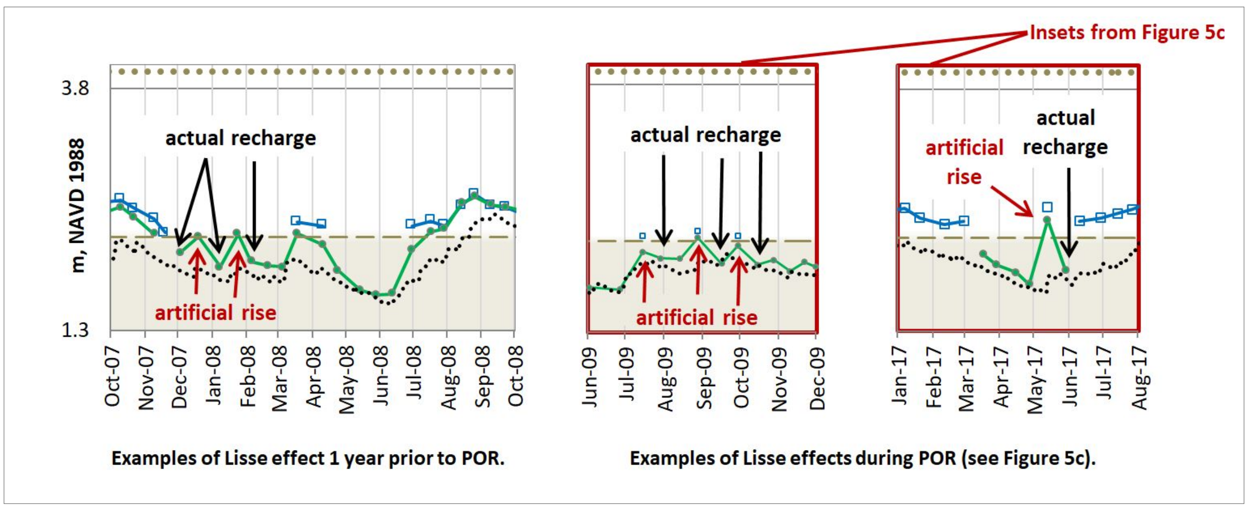


Figure 3-5g. Apparent Lisse effect in shallow groundwater levels at wetland Ref 4. Note the zig-zag pattern, representing a spike and dip in the shallow groundwater levels during a hydrologic low period. Lisse effects occur following intense rainfall which seals the surface, trapping air, which builds up pressure and raises the head in the shallow monitor well beyond that due to recharge. When the pressure is released, the water level in the monitor well equilibrates with the water table, reflecting the actual recharge that occurred from the rainfall event (Weeks, 2002; Heliotis et al., 1987).

Four wetlands were exceptional, exhibiting uncharacteristic water level deviations and/or poor tracking and correlation relative to water levels of the nearby U Fldn monitor wells. Hydrographs for the three representative features are presented in Figures 3-5d-f. The first is a large multi-pool wetland in the Gulf Coastal Lowlands (Weeki Wachee Prairie, Figure 3-1, Table 3-1) with an unexpected hydrologic condition. While surface and shallow groundwater levels were highly correlated to those of the WWP monitor well (R^2 = 0.88, Table 3-3), and behavioral responses followed the general patterns noted at other features (Figures 3-4b, 3-5a-c), an elevation offset of 0.5 m is apparent (Figure 3-5d). While offsets at least this large were noted for other features, the offset here is unexpected given the U Fldn well is located on-site at the wetland's edge, where the wetland-well hydraulic gradient would expectedly be minimal.

Also exceptional is the hydrograph for Banshee Pond, a relatively deep, semi-permanently inundated wetland along the eastern flank of the Brooksville Ridge (Figure 3-1, Table 3-1). Wetland surface water levels exhibited a dichotomous water level relationship with those of the WR-6b U Fldn monitor well (Figure 3-5e). In the early part of the POR between October 2008 and May 2012 (a period of sustained low rainfall), a 2 m elevation offset was apparent and wetland-U Fldn water levels did not rise and fall in sync, resulting in an extremely low correlation (R^2 = 0.24). In the period after May 2012: the elevation offset was notably less (1.2 m); wetland-well water levels were in sync; and correlation was very high (R^2 = 0.92). The two periods are separated by Tropical Storm Debby, which brought 320 mm rainfall to the area in June 2012 and raised water levels markedly in both the wetland and monitor well (Arguez et al., 2018). Higher overall rainfall in the latter period sustained these higher water levels and their close correlation for the remainder of the POR.

Most exceptional of all hydrographs are those of the two wetlands in the Brooksville Ridge physiographic province that are located along the Ridge feature (Figure 3-1, Table 3-1). Of the two, Sand Point Pond exhibited more extreme deviations and less correlation and is discussed here in greater detail. Sand Point Pond is a shallow, seasonally inundated wetland whose water levels exhibited a very high elevation offset (approximately 12.5 m), poor tracking and low correlation (R^2 = 0.43) relative to water levels of the nearby ROMP 107 U Fldn monitor well (Figure 3-5f, Table 3-3). Many behavioral response deviations are apparent in the hydrograph, particularly in the wetland groundwater levels that differ notably from those of the U Fldn in their timing, magnitude and rates of incline and declines. These differences do not follow the general pattern of behavioral responses noted for the other features.

Water Geochemistry Analyses

Field and laboratory results from the dry and wet season water sampling events are presented in Tables 3-4a and 3-4b, respectively. Data for each parameter are provided in color scales for easy comparison of values between feature types (wetland, pond, lake, monitor well) and sample types (surface, surficial

Table 3-4a. Geochemical sampling results, dry season.

STATION: Feature Type		Name / Abbreviation		Physiographic Province: Brooksville Ridge	Physiographic Province: Gulf Coastal Lowlands	Water Level vs. land surface (m)	SAMPLE: Type		Depth (m)	Temp (C)	pH (std.)	Spec. Cond. (uS/cm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	$SO4^{2-}$ (mg/L)	$HCO3^{-}$ (mg/L)	^{2}H δ (0/00)	^{18}O δ (0/00)
Wetland		Banshee Pond	BP	X		0.6	Surface Water	Shallow	0.3	28	5.1	48	1.9	1.0	4.6	1.9	4.1	0.5	18.1	25.5	6.1
Wetland		Capuchin Pond	CaPo		X	2.4	Surface Water	Shallow	0.3	28	7.3	48	1.5	0.9	4.2	1.1	4.5	0.5	13.5	17.1	3.5
Wetland		Ref 4	R4		X	0.2	Surface Water	Shallow	0.3	26	5.4	67	1.8	0.6	6.7	1.1	5.4	0.8	17.8	19.3	3.2
Wetland		Ref 8	R8		X	0.3	Surface Water	Shallow	0.3	29	4.7	59	2.2	0.7	4.0	1.2	4.5	0.5	14.3	34.6	7.9
Wetland		Weeki Wachee Prairie	WWP		X	0.9	Surface Water	Shallow	0.3	31	7.0	188	14.2	1.3	6.1	1.2	8.3	1.0	52.2	28.9	4.7
Wetland		Willow Sink	WS		X	1.0	Surface Water	Shallow	0.3	34	4.9	30	1.4	0.4	1.7	0.9	3.3	0.6	5.8	24.3	4.3
Pond		Chapel Pond	ChPo		X	4.9	Surface Water	Shallow	0.3	31	5.6	57	4.6	1.0	4.6	1.2	3.6	0.5	26.2	14.8	3.1
Pond		Eagle Scout Pond	ESP		X	3.7	Surface Water	Shallow	0.3	33	4.4	60	1.9	0.7	2.2	1.0	4.0	3.4	5.4	19.4	3.9
Pond		Golden Avenue DRA	GA		X	3.0	Surface Water	Shallow	0.3	30	6.9	264	25.5	1.1	4.5	1.3	4.5	0.9	88.4	16.0	2.9
Pond		Lake Meredith	LM		X	2.7	Surface Water	Shallow	0.3	27	6.8	145	11.6	1.3	5.2	1.3	5.5	0.5	47.4	15.8	3.3
Pond		Thaxton Pond	TP		X	4.3	Surface Water	Shallow	0.3	28	7.2	205	20.7	0.8	3.0	1.2	2.5	0.1	72.1	1.7	1.2
Lake		Hunter's Lake	HL		X	3.0	Surface Water	Shallow	0.3	28	7.8	206	13.3	1.2	7.9	0.9	14.0	2.2	42.3	18.9	2.4
Lake		Tooke Lake	TL		X	1.8	Surface Water	Shallow	0.3	33	7.5	104	5.9	0.9	7.0	1.4	8.1	4.5	23.7	24.4	4.4
Wetland		Capuchin Pond	CaPo		X	0.0	Surface Water	Deep	2.0	28	7.0	48	1.6	0.9	4.7	1.1	4.5	0.7	15.3	19.6	3.7
Pond		Chapel Pond	ChPo		X	4.9	Surface Water	Deep	4.3	21	4.8	90	7.7	1.1	4.5	1.3	3.5	0.3	36.6	1.6	1.3
Pond		Eagle Scout Pond	ESP		X	3.7	Surface Water	Deep	2.9	28	7.1	64	2.6	0.7	4.6	1.4	4.5	3.3	13.8	18.5	3.7
Pond		Golden Avenue DRA	GA		X	3.0	Surface Water	Deep	3.0	28	7.2	294	26.0	1.1	4.3	1.3	4.5	1.0	89.1	10.8	2.5
Pond		Lake Meredith	LM		X	2.7	Surface Water	Deep	2.7	25	6.3	274	12.2	1.3	5.4	1.3	5.5	0.5	50.0	13.7	3.0
Pond		Thaxton Pond	TP		X	4.3	Surface Water	Deep	4.3	25	6.7	281	28.8	1.0	2.0	1.1	3.7	0.2	93.0	2.6	0.4
Lake		Hunter's Lake	HL		X	0.0	Surface Water	Deep	2.8	27	7.3	239	13.2	1.2	6.8	0.8	14.0	2.0	39.0	11.5	2.2
Monitor Well	Wetland Interior	Croom Rital Marsh	CrRi	X		-1.0	Surficial Sands		3.7	23	4.8	32	1.9	0.3	0.7	0.8	0.7	1.5	7.2	-3.5	-2.2
Monitor Well	Wetland Interior	Croom Road Marsh	CrRo	X		-1.0	Surficial Sands		3.4	26	4.2	67	2.0	0.2	2.3	0.8	3.3	2.8	5.2	-9.1	-2.2
Monitor Well	Wetland Interior	Perry Oldenburg Mars	POM	X		-1.6	Surficial Sands		2.6	26	5.1	48	2.7	0.7	2.8	1.0	2.9	1.2	14.0	-14.3	-3.2
Monitor Well	Wetland Interior	Ref 4	R4		X	0.2	Surficial Sands		4.1	26	5.0	87	2.8	1.3	4.2	1.1	4.0	1.3	19.3	4.6	0.9
Monitor Well	Wetland Interior	Ref 8	R8		X	0.3	Surficial Sands		3.7	27	5.2	87	2.3	1.0	8.2	2.4	0.6	0.6	35.8	2.4	0.5
Monitor Well	Wetland Interior	String of Pearls Marsh	SOP	X		-0.9	Surficial Sands		3.5	25	4.4	61	3.9	0.4	1.5	0.9	2.4	0.7	14.0	-11.3	-2.5
Monitor Well	Wetland Interior	Willow Sink	WS		X	1.0	Surficial Sands		2.7	27	5.7	181	16.7	1.0	2.0	2.6	1.8	0.6	61.6	18.4	1.5
Monitor Well	Upland	SHMW1	SH		X	-12.2	Surficial Sands		24.1	25	6.0	208	19.1	0.7	1.8	1.3	2.7	4.1	58.7	-11.3	-3.3
Monitor Well	Upland	MWSF5s	M5		X	-13.7	Surficial Sands		14.0	26	5.5	122	6.6	2.0	1.6	1.2	1.9	13.0	16.2	-16.4	-3.6
Monitor Well	ASW	Hunter's Lake	HL		X	-1.4	Limestone	Shallow	22.9	24	8.8	176	8.6	1.0	6.4	1.8	11.0	0.7	31.0	-16.5	-3.5
Monitor Well	ASW	Weeki Wachee Prairie	WWP		X	-2.1	Limestone	Shallow	22.9	25	8.7	164	6.8	0.5	8.2	6.6	4.5	0.5	47.0	-12.6	-2.9
Monitor Well	ASW	Hunter's Lake	HL		X	-1.4	Limestone	Deep	45.7	26	8.4	237	13.5	1.1	8.0	1.9	11.0	1.1	50.4	-16.4	-3.6
Monitor Well	ASW	Weeki Wachee Prairie	WWP		X	-2.1	Limestone	Deep	45.7	25	8.8	205	12.5	0.6	8.3	6.4	4.6	0.5	64.7	-12.9	-2.9
Monitor Well	Upland	HRMW1	HR		X	-8.1	Limestone	Shallow	22.9	25	6.5	562	42.4	11.3	4.0	1.1	5.8	14.0	170.3	-19.2	-4.0
Monitor Well	Upland	MWSF5	M5		X	-13.7	Limestone	Shallow	22.9	26	5.6	302	23.5	2.3	4.8	1.8	5.9	12.0	73.2	-17.3	-3.9
Monitor Well	Upland	HRMW1	HR		X	-8.1	Limestone	Deep	45.7	25	7.0	562	39.6	10.2	4.8	1.2	5.8	14.0	158.9	-15.5	-3.7
Monitor Well	Upland	MWSF5	M5		X	-13.7	Limestone	Deep	45.7	26	6.2	305	23.5	2.3	6.9	2.1	5.9	12.0	79.5	-17.5	-3.9
Monitor Well	Upland	SHMW2	SH		X	-12.2	Limestone	Deep	45.7	25	6.4	188	11.7	3.1	6.2	1.3	6.8	0.4	57.1	-14.9	-3.2
Monitor Well	Upland	MWSF5	M5		X	-13.7	Limestone	Very Deep	122.0	26	6.2	310	23.8	2.3	7.4	2.2	6.2	11.0	82.7	-17.5	-3.8
Monitor Well	Upland	SHMW2	SH		X	-12.2	Limestone	Very Deep	91.5	25	6.7	173	16.4	3.3	7.1	1.4	6.9	1.1	74.1	-11.9	-3.0
								Min	**0.3**	**21**	**4.2**	**30**	**1.4**	**0.2**	**0.7**	**0.8**	**0.6**	**0.1**	**5.2**	**-19.2**	**-4.0**
								Max	**122.0**	**34**	**8.8**	**562**	**42.4**	**11.3**	**8.3**	**6.6**	**14.0**	**14.0**	**170.3**	**34.6**	**7.9**

ASW - adjacent to surface water

Table 3-4b. Geochemical sampling results, wet season.

STATION							SAMPLE		FIELD PARAMETERS				CATIONS				ANIONS			ISOTOPES	
Feature Type		Name / Abbreviation		Physiographic Province: Brooksville Ridge	Physiographic Province: Gulf Coastal Lowlands	Water Level vs. land surface (m)	Type		Depth (m)	Temp (C)	pH (std.)	Spec. Cond. (uS/cm)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	$SO4^{2-}$ (mg/L)	$HCO3^{-}$ (mg/L)	^{2}H δ (0/00)	^{18}O δ (0/00)
Wetland		Banshee Pond	BP	X		2.1	Surface Water	Shallow	0.3	28	5.1	18	2.5	0.5	1.0	1.3	2.5	3.1	6.9	-6.89	-1
Wetland		Capuchin Pond	CaPo		X	3.7	Surface Water	Shallow	0.3	25	4.3	23	1.9	1.0	1.7	0.4	5.5	3.1	2.6	1.48	0.5
Wetland		Croom Rital Marsh	CrRi	X		0.7	Surface Water	Shallow	0.3	25	4.1	26	2.9	0.8	8.0	0.3	9.3	3.7	14.2	-19.4	-4
Wetland		Croom Road Marsh	CrRo	X		0.3	Surface Water	Shallow	0.3	27	4.2	22	0.8	0.3	0.9	0.3	3.2	2.5	-2.0	-13.5	-2
Wetland		Norman Marsh	NM	X		1.0	Surface Water	Shallow	0.3	27	4.7	22	3.8	1.1	0.8	0.4	3.4	3.1	10.1	-12.2	-2
Wetland		Perry Oldenburg Mars	POM	X		0.7	Surface Water	Shallow	0.3	24	5.2	27	3.1	0.9	1.4	0.6	3.6	3.1	8.4	-14.7	-3
Wetland		Ref 4	R4		X	0.9	Surface Water	Shallow	0.3	25	4.2	22	0.5	0.4	0.3	0.3	3.6	3.1	-5.1	-5.57	-1
Wetland		Ref 8	R8		X	1.1	Surface Water	Shallow	0.3	25	4.2	20	0.6	0.4	0.5	0.3	3.2	3.1	-3.9	-0.29	0.6
Wetland		Sand Point Pond	SPP	X		1.2	Surface Water	Shallow	0.3	23	6.6	118	24.4	2.0	0.7	4.6	3.9	3.3	82.2	-19.7	-4
Wetland		String of Pearls Marsh	SOP	X		0.6	Surface Water	Shallow	0.3	24	4.3	18	2.3	0.8	1.1	0.4	3.4	2.5	5.4	-16.7	-3
Wetland		Weeki Wachee Prairie	WWP		X	2.0	Surface Water	Shallow	0.3	27	7.7	101	18.3	1.7	4.2	0.7	9.5	4	55.0	-0.2	0.2
Wetland		Willow Sink	WS		X	2.0	Surface Water	Shallow	0.3	27	4.3	15	1.2	0.2	12.0	0.6	4.3	3.2	25.9	0.61	0.4
Pond		Chapel Pond	ChPo		X	6.1	Surface Water	Shallow	0.3	26	5.3	30	4.5	1.1	1.4	0.6	4.4	3.2	12.2	1.39	0.4
Pond		Eagle Scout Pond	ESP		X	4.6	Surface Water	Shallow	0.3	28	4.9	25	2.8	0.8	1.8	1	5.2	4.6	3.9	4.94	1.1
Pond		Golden Avenue DRA	GA		X	4.3	Surface Water	Shallow	0.3	29	6.9	185	37.8	1.6	2.1	1.3	6.1	3.5	115.6	5.82	1.3
Pond		Lake Meredith	LM		X	4.3	Surface Water	Shallow	0.3	26	6.4	123	26.3	2.2	3.3	0.9	4.2	3.1	90.1	-1.26	-0
Pond		Thaxton Pond	TP		X	4.6	Surface Water	Shallow	0.3	26	6.3	101	23.5	1.0	1.3	0.5	3.6	2.5	71.4	-0.82	-0
Lake		Hunter's Lake	HL		X	3.7	Surface Water	Shallow	0.3	27	6.1	188	15.5	1.4	6.2	0.4	13	4.2	43.5	-13	-3
Lake		Tooke Lake	TL		X	2.4	Surface Water	Shallow	0.3	27	6.3	49	7.2	1.0	3.1	0.5	7.3	5.5	16.2	9.07	2
Wetland		Capuchin Pond	CaPo		X	3.6	Surface Water	Deep	3.4	25	4.3	30	2.2	1.0	1.6	0.6	5.4	3.1	3.7	3.18	0.8
Pond		Chapel Pond	ChPo		X	6.1	Surface Water	Deep	4.6	25	4.4	33	12.3	1.4	1.8	0.9	4.9	3.4	37.9	2.65	0.6
Pond		Eagle Scout Pond	ESP		X	4.6	Surface Water	Deep	4.6	26	4.4	26	2.3	0.7	1.6	0.5	5	4.5	1.4	5.33	1.2
Pond		Golden Avenue DRA	GA		X	4.3	Surface Water	Deep	4.6	26	6.5	193	34.8	1.5	2.5	1.6	6.7	3.6	106.7	4.34	1
Pond		Lake Meredith	LM		X	4.3	Surface Water	Deep	4.3	26	5.8	130	23.5	1.9	3.5	0.9	9	3.6	71.8	-1.47	-0
Pond		Thaxton Pond	TP		X	4.6	Surface Water	Deep	4.6	25	5.5	124	65.0	1.8	1.4	1	5.5	3.1	198.7	0.84	0.1
Lake		Hunter's Lake	HL		X	3.4	Surface Water	Deep	1.8	26	6.4	188	16.9	1.5	4.6	0.5	13	4.4	44.1	6.68	1.2
Monitor Well	Wetland Interior	Croom Rital Marsh		X		0.7	Surficial Sands		3.7	24	3.1	25	2.2	0.5	2.7	0.4	7.2	5.4	-2.0	-12.8	-3
Monitor Well	Wetland Interior	Croom Road Marsh		X		0.3	Surficial Sands		3.4	26	4.4	27	2.5	0.4	3.8	0.3	7.1	7.2	-1.1	-8.71	-3
Monitor Well	Wetland Interior	Norman Marsh	NM	X		1.0	Surficial Sands		1.5	25	4.5	47	10.3	0.3	0.3	0.4	2.9	7.1	20.2	-15.5	-4
Monitor Well	Wetland Interior	Perry Oldenburg Mars	POM	X		0.7	Surficial Sands		2.7	25	4.7	88	9.0	1.8	3.2	1.4	5	3.7	33.5	-8.37	-2
Monitor Well	Wetland Interior	String of Pearls Marsh	SOP	X		0.6	Surficial Sands		3.7	24	5.7	102	21.6	3.4	19.0	1.3	37	6	63.8	-8.58	-2
Monitor Well	Upland	MWSF5s	M5		X	-11.9	Surficial Sands		13.7	26	5.9	99	5.8	1.9	2.6	0.6	2.8	13	13.5	-10.9	-3
Monitor Well	Upland	SHMW1	SH		X	-10.1	Surficial Sands		24.1	26	5.6	52	6.2	0.3	1.4	0.9	10	16	-12.1	-10.4	-3
Monitor Well	ASW	Hunter's Lake	HL		X	-0.7	Limestone	Shallow	22.9	25	8.4	185	11.8	1.2	9.2	1.8	13	3.2	42.5	-14.2	-3
Monitor Well	ASW	Weeki Wachee Prairie	WWP		X	-0.9	Limestone	Shallow	22.9	26	6.9	225	9.3	0.4	5.9	8.4	6.8	3.3	43.4	5.1	0.9
Monitor Well	ASW	Hunter's Lake	HL		X	-0.7	Limestone	Deep	45.7	27	8.5	191	12.8	1.2	6.3	1.5	13	3.3	37.6	-16.3	-4
Monitor Well	ASW	Weeki Wachee Prairie	WWP		X	-0.9	Limestone	Deep	45.7	26	7.7	158	17.9	0.6	4.7	6.7	6.9	3.4	63.8	-12.1	-3
Monitor Well	Upland	HRMW1	HR		X	-6.9	Limestone	Shallow	22.9	25	7.4	571	47.7	10.0	4.3	0.6	7.7	17	173.1	-17.7	-4
Monitor Well	Upland	MWSF5	M5		X	-11.9	Limestone	Shallow	22.9	26	6.9	321	30.7	3.2	7.0	1.7	7	14	100.7	-17.1	-4
Monitor Well	Upland	HRMW1	H5		X	-6.9	Limestone	Deep	45.7	24	7.3	570	47.7	2.5	3.6	0.5	7.5	16	134.6	-18.6	-4
Monitor Well	Upland	MWSF5	M5		X	-11.9	Limestone	Deep	45.7	26	6.9	330	31.8	3.3	4.7	1.6	7.5	14	97.7	-16.7	-4
Monitor Well	Upland	SHMW2	SH		X	-10.2	Limestone	Deep	45.7	25	8.4	93	13.5	4.2	4.1	0.5	6.8	3.1	58.0	-16.3	-3
Monitor Well	Upland	MWSF5	M5		X	-11.9	Limestone	Very Deep	91.5	25	7.1	282	33.9	3.4	4.8	1.8	7	14	105.8	-17.6	-4
Monitor Well	Upland	SHMW2	SH		X	-10.2	Limestone	Very Deep	91.5	25	8.8	91	10.5	3.4	4.5	0.6	8.3	3.1	43.9	-13.5	-3
								Min	**0.3**	**23**	**3.1**	**15**	**0.5**	**0.2**	**0.3**	**0.3**	**2.5**	**2.5**	**-12.1**	**-19.7**	**-4.0**
								Max	**91.5**	**29**	**8.8**	**571**	**65.0**	**10.0**	**19.0**	**8.4**	**37.0**	**17.0**	**198.7**	**9.1**	**2.0**

ASW - adjacent to surface water

sand and limestone). As shown, pH, specific conductance and calcium ion (Ca^{2+}) are generally highest for limestone water samples, although several surface water samples have comparable values. This overlap is more visible in scatterplots, which delineate the limestone water chemistry domains for these parameters (Figures 3-6 and 3-7). The scatterplots also estimate the domains representative of rainwater chemistry. Inter-domain samples are suggestive of endmember mixing (it is presumed surface water samples occurring within limestone water domains also represent a mixed, rather than strict limestone water chemistry given their direct receipt of rainwater).

Scatterplots for both specific conductance and Ca^{2+} show rainwater domains are comprised primarily of wetland surface water and surficial sand water samples, while limestone water domains (and those suggestive of endmember mixing) include all sample types (Figures 3-6 and 3-7). The pH values for samples in the rainwater domains are generally low, less than 5.6 (with the exception of one deep wetland and one pond where pH was notably higher, 7.0 – 7.3 in the dry season). The pH values for samples in the limestone water domain are higher, 5.6 or more. Between seasons, pH increased notably for limestone water samples and decreased for most surface water samples. Specific conductance decreased at most wetland, pond and lake samples between seasons, but was generally unchanged for the (upland well) limestone water samples, decreasing notably at only one well between seasons (Figure 3- 6). Ca^{2+} increased for most features between seasons, particularly at one pond where it more than doubled (29 – 65 mg/L), exceeding the concentration of the highest limestone endmember (Figure 3-7).

The Piper plots in Figure 3-8 (Waterloo Hydrogeologic, 2017) show most of the surface water and limestone water samples in the dry and wet seasons reflect a calcium-bicarbonate chemistry, which is typical of shallow fresh groundwater. Changes in water chemistry between seasons were minor and generally included a decrease in the number of samples with elevated sodium and an increase in the number with elevated chloride *(*Table 3-5*).*

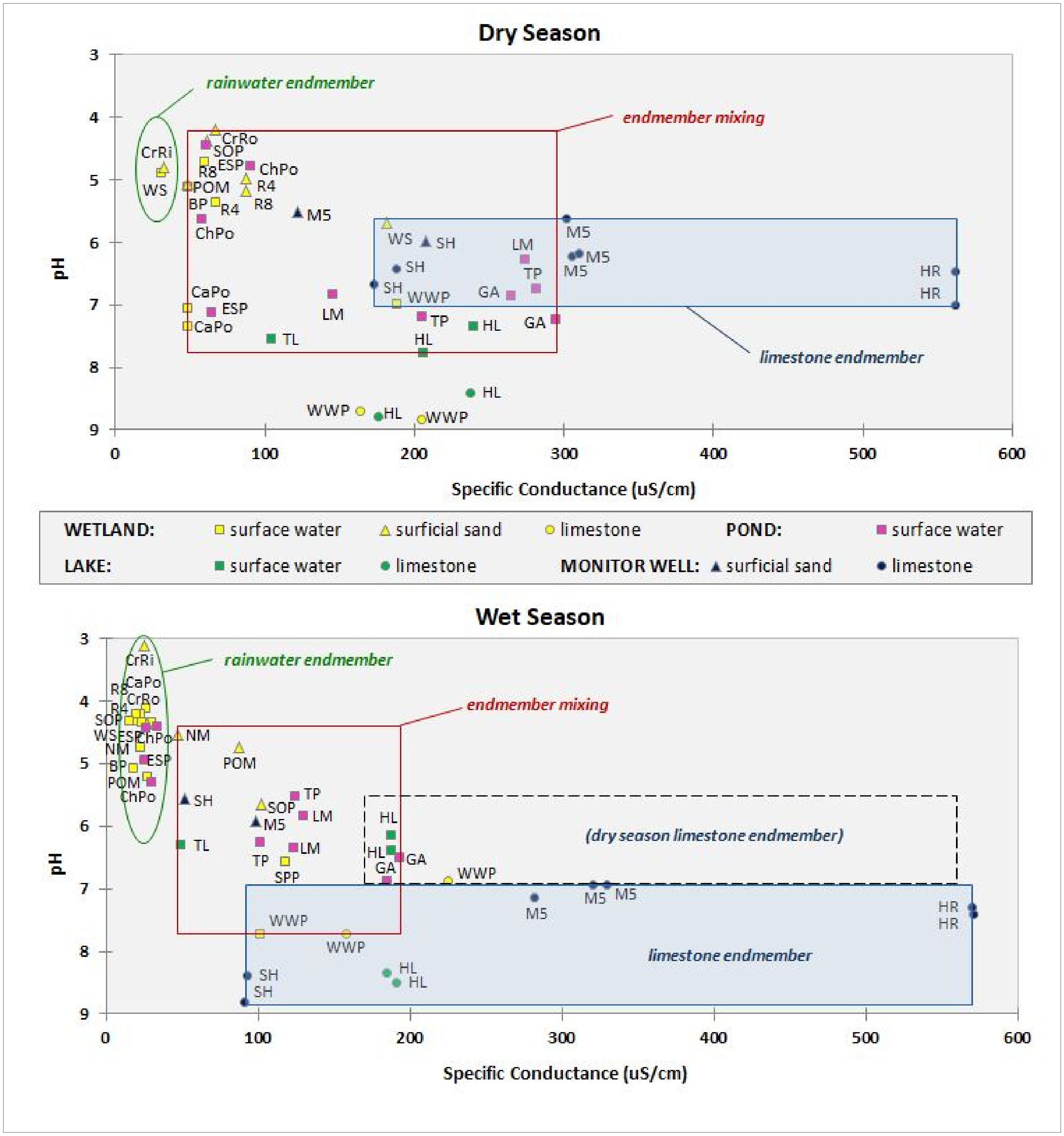


Figure 3-6. Scatterplot of field pH & specific conductance for dry and wet season water samples. Note the numerous surface water samples occurring within the limestone endmember domains and in the area designated as endmember mixing. (Note, samples collected in limestone from wells adjacent to surface water features at WWP and HL were not included in the domain delineation because these wells were not designed for water chemistry sampling and may have been contaminated with drilling muds or bentonite.)

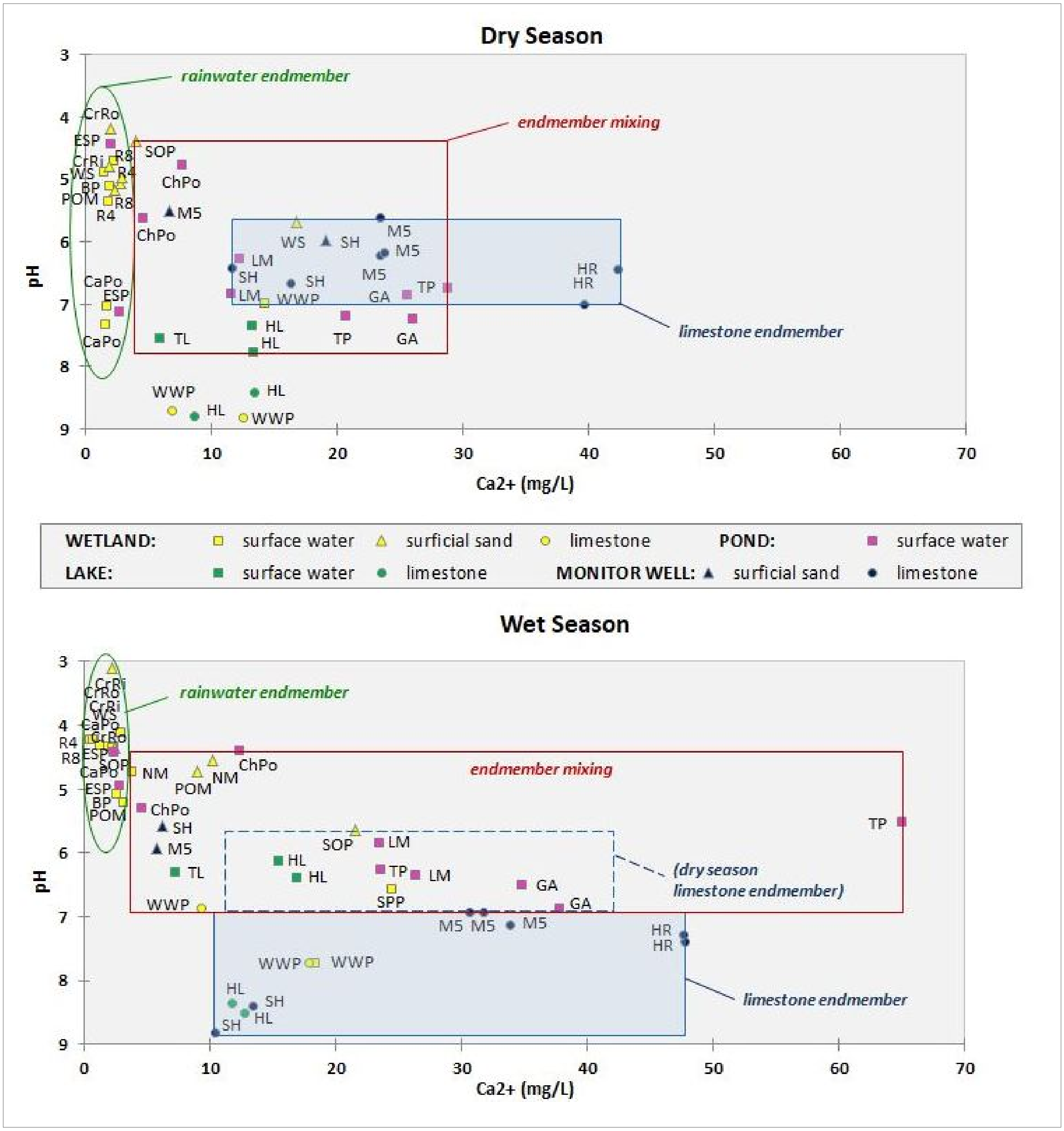


Figure 3-7. Scatterplot of field pH & calcium ion (Ca2+) for dry and wet season water samples. Note the numerous surface water samples occurring within the limestone endmember domains and in the area designated as endmember mixing.

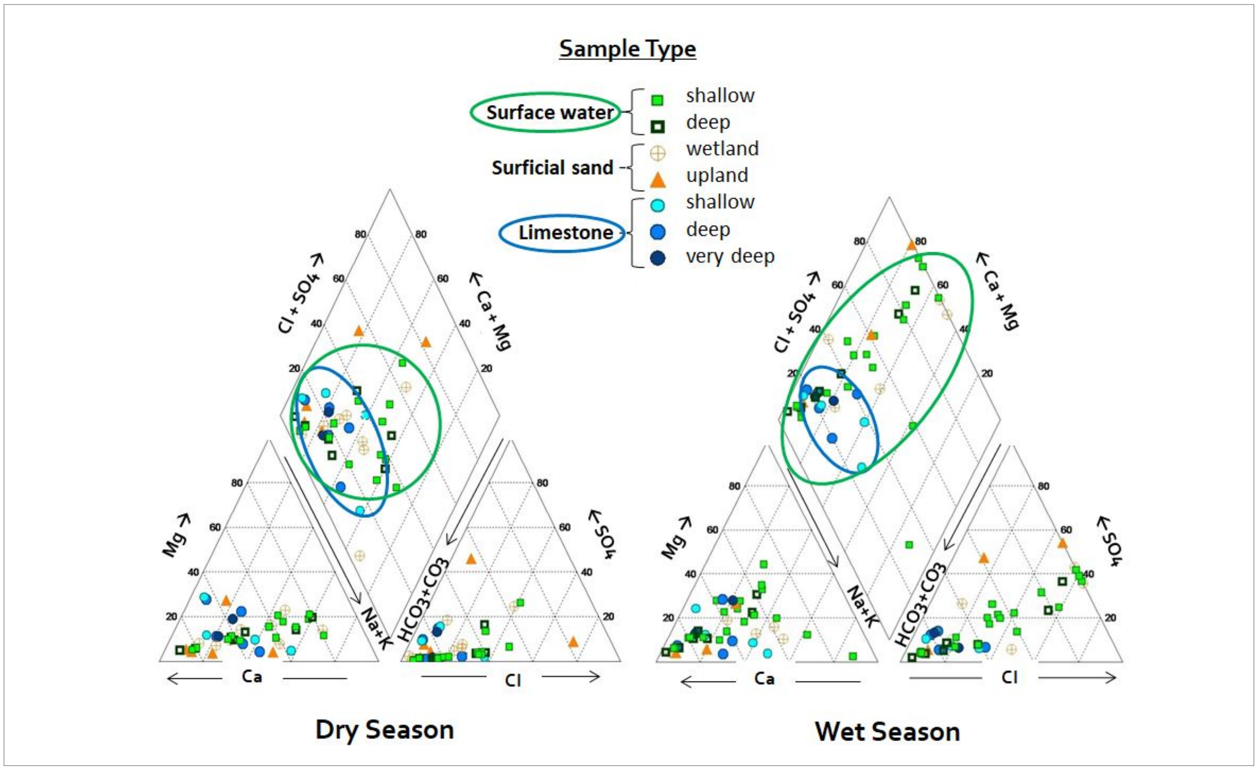


Figure 3-8. Piper diagrams for dry and wet season water samples along vertical gradient. (Waterloo Hydrogeologic, 2017)**.** Note most samples reflect a calcium-bicarbonate water type.

Results from the heavy isotope analyses for hydrogen (^{2}H, deuterium) and oxygen (^{18}O) are presented for the dry and wet seasons in Tables 3-4a and 3-4b, respectively. Values are reported according to the following equation, where R is the ratio between heavy and light isotopes:

$$\delta\ (^{o}/_{oo}) = R_{sample}/R_{standard} - 1) \times 1000$$

Samples with positive values indicate an isotopic composition with a higher proportion, or enrichment, of heavy isotopes relative to the standard (Vienna-SMOW, Craig, 1961). Samples with negative values contain a lower proportion, or depletion, of heavy isotopes relative to the standard. For the dry season, a clear demarcation is apparent between sample types enriched (blue color scale) and depleted (red color scale) in heavy isotopes—surface water samples are all enriched (^{2}H = +2.6 to +34.6, ^{18}O = +0.4 to

+7.9), and limestone water samples are all depleted (δ^2H = -19.2 to -11.9, δ^{18}O = -4.0 to -2.9) (Table 3-4a). Surficial sand water samples were variable (δ^2H = -16.4 to +13.4, δ^{18}O = -3.6 to +2.5), showing enrichment when collected from features inundated at the time of sampling (Ref 4, Ref 8 and Willow Sink) and depletion when collected from features without inundation at the time of sampling (Croom Rital, Croom Road, Perry Oldenburg and String of Pearls Marshes). For the wet season, results were more variable (Table 3-4b). All groundwater samples—both limestone and surficial sand—were depleted in heavy isotopes (δ^2H = -18.6 to -12.1, δ^{18}O = -3.9 to -2.8) except for one anomaly, WWP, which was enriched (δ^2H = +5.1, δ^{18}O = +0.93). Surface water samples varied (δ^2H = -19.7 to +9.1, δ^{18}O = -4.0 to +2.0)—those depleted in heavy isotopes were collected from (Brooksville Ridge) features which were inundated for a much shorter period prior to sampling, while samples enriched in heavy isotopes were collected from (Gulf Coastal Lowlands) features which were inundated longer.

Isotope composition data for feature and sample types are presented graphically alongside the Global Meteoric Water Line (MWL), which represents isotope composition of unevaporated global precipitation (Figure 3-9). The global MWL is based on values of ^{2}H and ^{18}O, which are linearly related as $\delta\,^2H = 8\,\delta^{18}O + 10$ (Craig, 1961). An evaporation line was added for samples plotting below the MWL, which are indicative of evaporated water. Overall, these graphics reiterate the contrast in heavy isotope composition between sample types—enrichment in most surface water samples and depletion in most groundwater samples (surficial sand and limestone), and an overall reduction of heavy isotope enrichment between seasons.

Table 3-5. Water type comparison by season. Seasonal changes in water chemistry were minor and generally included a decrease in the number of samples with elevated sodium and an increase in the number with elevated chloride.

Physiographic Province	Feature Type	Station	Abbrev.	Sample Type	Vertical Profile	Dry	Wet
Brooksville Ridge	Wetland	Banshee Pond	BP	Surface Water	Shallow	Na-Ca-HCO3-Cl	Ca-HCO3-Cl-SO4
		Croom Rital Marsh	CrRi	Surface Water	Shallow	--	Na-Ca-Cl-HCO3
				Surficial Sands		Ca-HCO3	Na-Ca-Cl-SO4
		Croom Road Marsh	CrRo	Surface Water	Shallow		Na-Ca-Cl-SO4
				Surficial Sands		Na-Ca-Cl-HCO3-SO4	Na-Ca-Cl-SO4
		Norman Marsh	NM	Surface Water	Shallow	--	Ca-Mg-HCO3-Cl
				Surficial Sands		--	Ca-HCO3-SO4
		Perry Oldenburg Marsh	POM	Surface Water	Shallow	--	Ca-Mg-Na-HCO3-Cl-SO4
				Surficial Sands		Ca-Na-HCO3-Cl	Ca-HCO3
		Sand Point Pond	SPP	Surface Water	Shallow	--	Ca-HCO3
		String of Pearls Marsh	SOP	Surface Water	Shallow	--	Ca-Mg-Na-Cl-HCO3-SO4
				Surficial Sands		Ca-Na-HCO3-Cl	Ca-Na-HCO3-Cl
Gulf Coastal Lowlands		Capuchin Pond	CaPo	Surface Water	Shallow	Na-Ca-Mg-HCO3-Cl	Ca-Mg-Na-Cl- SO4
					Deep	Na-Ca-HCO3-Cl	Ca-Mg-Na-Cl-SO4-HCO3
		Ref 4	R4	Surface Water	Shallow	Na-HCO3-Cl	Mg-Cl-SO4
				Surficial Sands		Na-Ca-Mg-HCO3-Cl	--
		Ref 8	R8	Surface Water	Shallow	Na-Ca-HCO3-Cl	Ca-Mg-Cl-SO4
				Surficial Sands		Na-HCO3	--
		Weeki Wachee Prairie	WWP	Surface Water	Shallow	Ca-Na-HCO3-Cl	Ca-HCO3-Cl
				Limestone	Shallow	Na-Ca-HCO3	Ca-Na-K-HCO3
					Deep	Ca-Na-HCO3	Ca-HCO3
		Willow Sink	WS	Surface Water	Shallow	Na-Ca-HCO3-Cl	Na-HCO3
				Surficial Sands		Ca-HCO3	--
	Pond	Chapel Pond	ChPo	Surface Water	Shallow	Ca-Na-HCO3	Ca-Mg-HCO3-Cl
					Deep	Ca-Na-HCO3	Ca-HCO3
		Eagle Scout Pond	ESP	Surface Water	Shallow	Ca-Na-Mg-Cl-HCO3-SO4	Ca-Na-Mg-Cl-SO4-HCO3
					Deep	Na-Ca-HCO3-Cl	Ca-Na-Mg-Cl-SO4
		Golden Avenue DRA	GA	Surface Water	Shallow	Ca-HCO3	Ca-HCO3
					Deep	Ca-HCO3	Ca-HCO3
		Lake Meredith	LM	Surface Water	Shallow	Ca-Na-HCO3	Ca-HCO3
					Deep	Ca-Na-HCO3	Ca-HCO3
		Thaxton Pond	TP	Surface Water	Shallow	Ca-HCO3	Ca-HCO3
					Deep	Ca-HCO3	Ca-HCO3
	Lake	Hunter's Lake	HL	Surface Water	Shallow	Ca-Na-HCO3-Cl	Ca-Na-HCO3-Cl
					Deep	Ca-Na-HCO3-Cl	Ca-HCO3-Cl-SO4
				Limestone	Shallow	Ca-Na-HCO3-Cl	Ca-Na-HCO3-Cl
					Deep	Ca-Na-HCO3-Cl	Ca-Na-HCO3-Cl
		Tooke Lake	TL	Surface Water	Shallow	Na-Ca-HCO3-Cl	Ca-Na-HCO3-Cl
	Upland Monitor Well	HRMW1	HR	Limestone	Shallow	Ca-Mg-HCO3	Ca-Mg-HCO3
					Deep	Ca-Mg-HCO3	Ca-HCO3
		MWSF5	M5	Surficial Sands		Ca-Mg-SO4-HCO3	Ca-Mg-SO4-HCO3
				Limestone	Shallow	Ca-HCO3	Ca-HCO3
					Deep	Ca-HCO3	Ca-HCO3
					Very Deep	Ca-HCO3	Ca-HCO3
		SHMW	SH	Surficial Sands		Ca-HCO3	Ca-SO4-Cl
				Limestone	Deep	Ca-Na-Mg-HCO3	Ca-Mg-HCO3
					Very Deep	Ca-Na-HCO3	Ca-Mg-HCO3-Cl

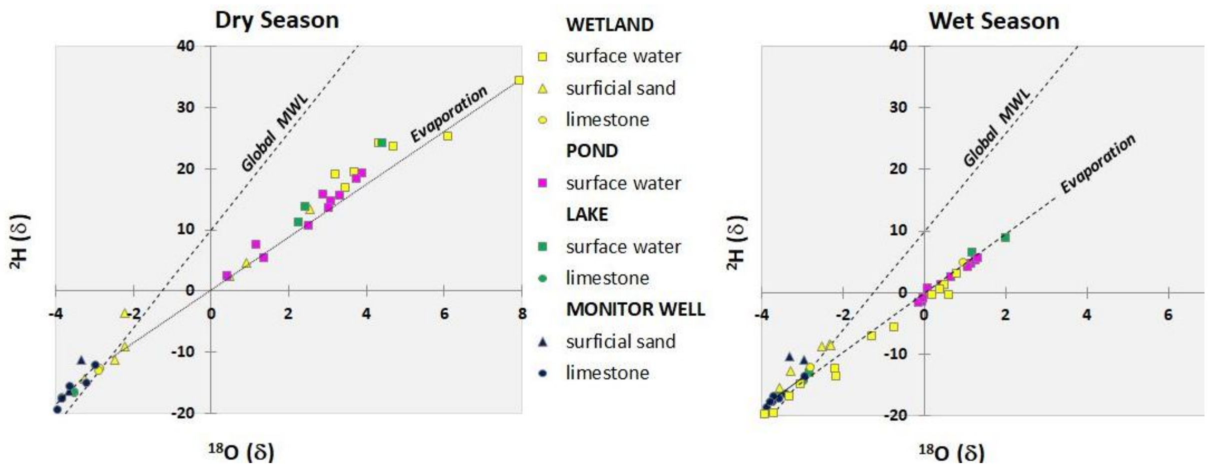


Figure 3-9. Local and Global Meteoric Water Lines (MWLs) for dry and wet season water samples. Note the general pattern of enrichment in heavy isotopes (relative to the VMOW standard) for surface water samples and depletion in heavy isotopes for groundwater samples (surficial sand and limestone). Between seasons, a decrease in overall enrichment of heavy isotopes is apparent, with some wet season surface water samples reflecting depletion due to dilution by fresh (unevaporated) rainwater.

Agglomerative Hierarchical Cluster (AHC) analysis was selected as a final, more exploratory analysis to examine the similarity/dissimilarity between water samples using both the geochemical and isotopic data. AHC is an iterative, "bottom up" hierarchical approach that begins by classifying each sample as its own cluster (Reddy, 2018). Pairs of samples are then clustered based on their least dissimilarity for the variables selected, until one cluster containing all samples is produced. A hierarchical tree is produced whose branches can be truncated automatically (by the algorithm) or manually based on a predetermined number of classes. For this study. classes were not predetermined, dissimilarity was measured as the Euclidian distance between objects, and Ward's method was selected as the parameters in the agglomeration method (Ward, 1963). Variables used in the analyses include: specific conductance, ^{2}H, ^{18}O, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Cl^{-} and SO^{2-}_{4}. Results from the AHC analysis show agglomeration of the dry and wet season data into three and four classes, respectively Figure 3-10 (Addinsoft, 2019). Classification for both seasons is similar, with Class 1 representing only surface and

Variance decomposition for the optimal classification:	Dry Season Absolute	Dry Season Percent	Wet Season Absolute	Wet Season Percent
Within-class	1,946	12%	1198	7%
Between-classes	14,695	88%	16230	93%
Total	16,641	100%	17428	100%

*Results by Class:	Dry 1	Dry 2	Dry 3	Wet 1	Wet 2	Wet 3	Wet 4
Objects	19	19	2	20	19	2	3
Sum of weights	19	19	2	20	19	2	3
Within-class variance	1149	2851	12	217	2359	30	656
Minimum distance to centroid	10	17	2	5	13	4	10
Average distance to centroid	29	48	2	13	45	4	19
Maximum distance to centroid	76	81	2	28	86	4	29
	BP	GA	HR	BP	GA	HR	M5
	CaPo	HL	HR	CaPo	HL	HR	M5
	ChPo	TP		ChPo	LM		M5
	ESP	WWP		CrRi	SPP		
	LM	GA		CrRo	TP		
	R4	HL		ESP	WWP		
	R8	LM		NM	GA		
	TL	TP		POM	HL		
	WS	SH		R4	LM		
	CaPo	WS		R8	TP		
	ChPo	HL		SOP	M5		
	ESP	M5		TL	POM		
	CrRi	WWP		WS	SOP		
	CrRo	HL		CaPo	HL		
	M5	M5		ChPo	WWP		
	POM	SH		ESP	HL		
	R4	WWP		CrRi	SH		
	R8	M5		CrRo	WWP		
	SOP	SH		NM	SH		
				SH			

Sample Types
- surface water - shallow
- surface water - deep
- surficial sand - wetland
- surficial sand - upland
- limestone - shallow
- limestone - deep
- limestone - very deep

Note: Central objects (i.e,. those nearest the centroid) are underscored.

*Profile Plots

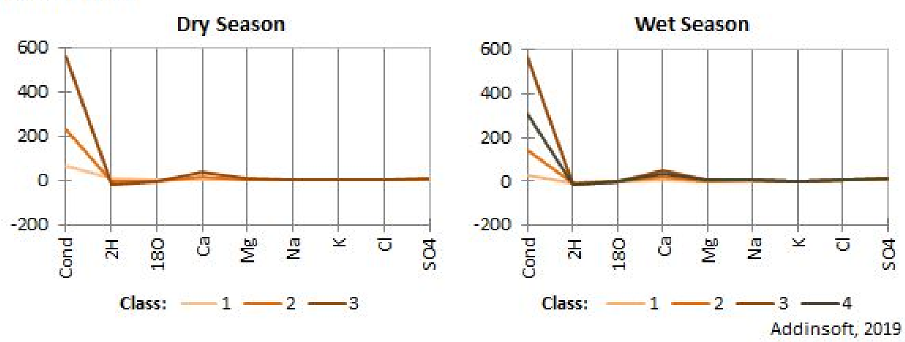


Figure 3-10. Cluster Analysis & Profile Plots for dry and wet season water samples, by sample type and depth profile. Sample waters were automatically grouped into three dry season classes and four wet season classes: Class 1 consists mostly of wetland surface and shallow groundwater (surficial sand) samples indicating a common rainwater chemistry; Class 3 and 4 consist only of limestone samples indicating a clear limestone water chemistry; and Class 2 includes a mix of surface water, shallow groundwater and shallow and deep limestone water chemistry, suggesting a shared chemistry of rainwater-limestone endmember mixing. The profile plots identify specific conductance and calcium ions (Ca^{2+}) as the most influential parameters in generating these groupings, followed by ^{2}H and SO^{2-}_{4}.

surficial sand water samples (i.e., rainwater endmember class) and Class 3 and 4 representing only limestone water samples (i.e., limestone endmember classes). For both seasons, Class 2 includes waters of all three sample types, including both shallow surface water samples and very deep limestone water samples (i.e., endmember mixing class). Profile plots show specific conductance and calcium ion (Ca^{2+}) as the most influential parameters in the agglomeration of these groupings, followed by deuterium (^{2}H) and sulfate (SO^{2-}_{4}). Results here are consistent with the scatterplot analyses, which show overlap in water geochemistry between surface water and limestone water sample types as indicated primarily by specific conductance and Ca^{2+}

DISCUSSION

From raised bogs (Large et al., 2007) and vernal pools (Rains et al., 2006; Schlising and Saunders, 1982) to fens (Wilcox et al., 1986) and Carolina bays, studies of geographically isolated wetlands (GIWs) have long characterized hydrologic control along a continuum of local forces from precipitation to groundwater of a surficial aquifer. The sandhill wetland and water features of west-central Florida expand this continuum to include hydrologic control by a regional force, that of an expansive water-supply aquifer (Figure 3-11). Physical and chemical evidence presented here show that these features are hydraulically connected to the Upper Floridan aquifer (U Fldn), part of the expansive Floridan aquifer system, which is one of the most productive in the world (Miller, 1990). This connection distinguishes the sandhill wetlands and waters of west-central Florida from most other GIWs. These findings are important both to the field of ecohydrology and to the proper identification, management and protection of these unique natural resources, particularly given increased groundwater demands, a changing climate and potential losses in federal protections for isolated wetlands and waters.

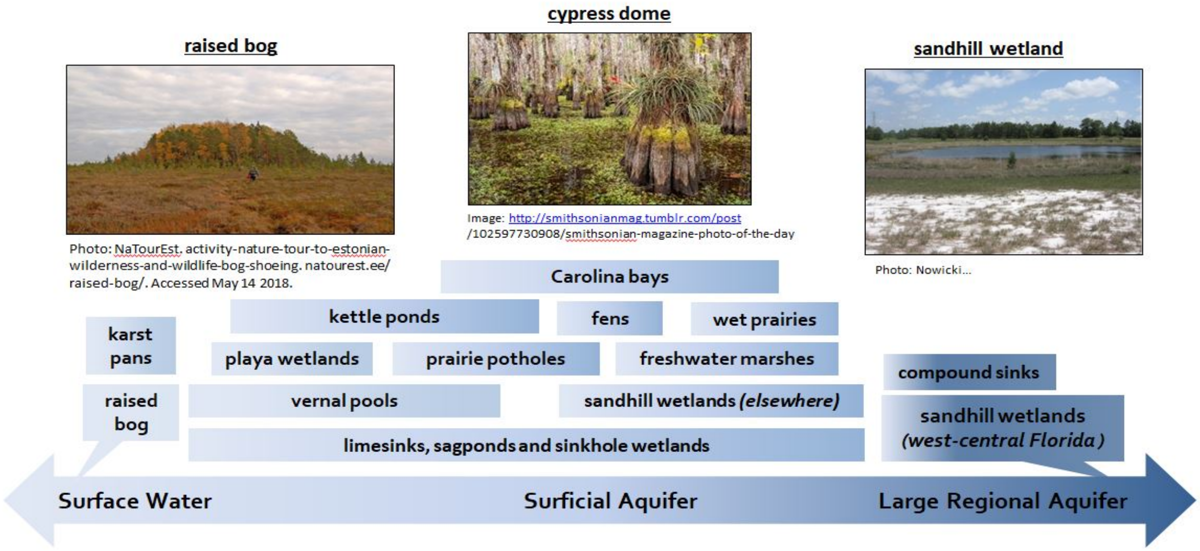


Figure 3-11. Sandhill wetlands as regional groundwater endmembers along an isolated wetland hydrologic continuum.

This study examines water levels and water geochemistry to: 1) document the characteristic (and certain exceptional) hydrologic attributes of sandhill wetlands and waters in west-central Florida; and 2) compare these attributes to those of the U Fldn as evidence (where applicable) of a hydraulic connection. The characteristic sandhill wetland and water hydrology is widely ranging (water levels vary 2 - 5 m at the study sites), with lengthy periods of no surface water at some sites. Water levels fluctuate in sync with those of the U Fldn with consistent, predictable deviations (i.e., an elevation offset and four general types of behavioral responses) and as a result are very highly correlated. At many features, the water type is calcium-bicarbonate; and elevated specific conductance, calcium [Ca^{2+}] and/or pH reflects rainwater mixed with water residing in limestone. At other features, greater depth to limestone likely precludes exchange with the water residing in it. Instead water chemistry reflects rainwater in contact with the overlying surficial sands and feature substrate; other ions (e.g., Na^{+}, Cl^{-} and SO_4^{2-}) predominate, and pH is lower (particularly for wetlands that accumulate acidic organic materials).

These attributes define the hydrology of 17 of the 19 wetland and water features in the study area and indicate a definitive hydraulic connection with the U Fldn. This finding is consistent with a study by Henderson (1986) that documents the hydraulic connection of a sandhill lake (Hunter's Lake, one of the features in this study) to the regional groundwater system and is supported by Part 2 of this study which describes the mechanisms by which Florida's sandhill wetlands and waters connect to the U Fldn (Nowicki et al., in prep.).

The two remaining wetlands share some of these hydrologic attributes (e.g., widely ranging water levels and a calcium-bicarbonate water chemistry), but their water levels do not fluctuate in sync with those of the U Fldn and are consequently poorly correlated (R^2 = 0.43 and 0.48). Both wetlands (Sand Point Pond and Perry Oldenburg Marsh) are located in the Brooksville Ridge physiographic province, along the ridge feature itself. Here, remnant low permeability clay sediments of the Hawthorn Formation result in perched (or semi-perched, respectively) water table conditions. These conditions are reflected in the wetlands' behavioral responses which deviate markedly from those of the U Fldn (Appendix 3-A2, Figure 3-5f). Also, the elevation offset at Sand Point Pond is noteworthy at 12.5 m, precluding a hydraulic connection with the U Fldn. The wetland's calcium bicarbonate water chemistry may be explained by its adjacency to a nursery irrigated with water likely pumped from limestone (an overflow culvert connects the wetland to a pond receiving drainage from the nursery). At Perry Oldenburg Marsh, the elevation offset is much less, and the wetland is in closer proximity to limestone. This may allow mineralized water to enter the wetland, resulting in its bicarbonate water chemistry. The clear lack of synchronization with U Fldn water levels and its location along the ridge, however, suggest that while the U Fldn may influence the water levels at Perry Oldenburg Marsh, it is geology (i.e., clay) that controls them. Given the lack of hydrologic control by or hydraulic connection to the U Fldn, neither of these two wetlands is considered a sandhill wetland.

Water levels of the 17 features that are considered sandhill wetlands and waters synchronize well with those of the U Fldn, but vary in the degree of their elevation offsets and behavioral response deviations, the latter of which is reflected in their correlation coefficients ($0.84 \leq R^2 \leq 0.99$). While the elevation offsets are attributed to the relative feature-well positions along the hydraulic gradient, the consistent and predictable patterns of the behavioral responses suggest site-specific factors produce much of their residual variation; although antecedent conditions and rainfall intensity and duration likely influence these responses. The four general types of behavioral responses characteristic to sandhill wetlands and waters (and two unexpected types of deviations), as outlined previously, are discussed here in the context of the factors that may cause them.

Lower *magnitude* of rainfall responses at the features: For most of the features, rainfall responses were generally lower in magnitude than those of the monitor wells. This may be related to the inherent differences between open depressions and matrices. Specific yield (Sy) at the open depressions of the features is an order of magnitude higher (Sy = 1.0) than the limestone matrix of the monitor wells (Sy = 0.2, Heath, 1983). A higher specific yield at the features requires more water to achieve the same rise in water level as at the monitor wells whose matrices have less pore space to fill. Groundwater contribution to the features from the adjacent uplands may lessen the effect of specific yield, while other factors (e.g., evaporation) may enhance it, and others still (e.g., rainfall intensity and duration) may overcome it. This appears to have happened at several features during periods of intense rainfall, such as occurs during tropical storms or El Nino events (e.g., 2012 and 2015). In these cases, overland flow (which is generally low in sandhill) may have been generated, sending volumes of water directly into the features that would have otherwise percolated into the adjacent uplands. The response was especially high in features located in residential areas (e.g., Lake

Meredith and Golden Avenue) where impervious surfaces and stormwater swales would have contributed even more runoff.

Similar or tapering *rate of water level incline* at the features*:* Rainfall responses at the features were generally similar to those of the monitor wells or tapered—responding initially at the same rate, but then slowing. This may be related to their inherent differences (as noted above) and to antecedent water level elevations at the features. Because the features are broader at the top, water level rise is not linear as in a column—the more water that is added, the more that is needed to maintain the same rate of incline as the features' peripheries expand. Also, the broader the area of inundation, the greater the opportunity for evaporation (and groundwater exchange) to affect water level incline. At the monitor wells, the rate of water level rise through the matrices would generally be more even and would not be subject to evaporation (or surface water exchange).

Similar *onset of water level decline* at the features, except during hydrologic highs (then lagging)*:* Water levels at the features and monitor wells generally begin to decline at the same time, except during high water conditions when feature water levels lag behind. The lag may be due to discharge of groundwater to the features from bank storage following rainfall events. If so, the extra input may counter losses to evaporation and leakage. Once the inputs dwindled or stopped (and no new rain fell), the water levels in the features began to decline. Water levels at the monitor wells would not receive input of this kind and would begin to drain more readily.

Slower *rate of water level decline* at the features except during hydrologic highs (then similar): Water levels at the features generally declined at a slower rate than at the monitor wells, except during high water periods when the rates were similar. The slower rates may be due to reduced leakage by lower permeability materials (e.g., accumulated organics or eroded-in silt) which would be more effective when not acting against the full force of the inundation above them. During high water periods, higher heads may overcome the effect of substrate, resulting in faster water level declines, similar to rates at the monitor wells.

More detailed analysis with more numerous and more frequent monitoring (e.g., rainfall, evaporation, surface water and shallow and deep groundwater levels) would be needed to confirm and quantify the effects of these factors on feature and monitor well water level responses. Also, except in two cases where U Fldn monitor wells were constructed adjacent to surface water features (Weeki Wachee Prairie and Hunter's Lake), U Fldn water levels are monitored at wells 1 – 10 km from the features. Water levels at these more distant wells reflect the regional groundwater flow system and are not subject to the local complexities or vertical gradients experienced by those adjacent to surface water features; complexities which may locally bulge, deflate or even maintain the U Fldn water table in notable ways. For example, Henderson (1986) describes a condition of static stage at Hunter's Lake (lasting nearly 3 months) for which the "ground-water system had to provide more than 200 acre-ft of water to Hunters Lake" (25 hectare-m) averaging 1 ft^3/sec (1.7 m^3/minute), and that were it not for slight changes in lake stage relative to groundwater levels (which generated significant groundwater exchange to and from the lake), the static stage would not have been possible. He characterized Hunter's Lake as a groundwater flow-through feature and suggested the same for others in the area (including Weeki Wachee Prairie, although specific results were not provided).

Henderson's findings may help explain the higher than expected elevation offset (0.5 m) between the water level at Weeki Wachee Prairie and that of the U Fldn as measured on-site. Weeki Wachee Prairie appears similar in its geologic construct as Hunter's Lake, occurring within a large depression at the base of a relict sand dune. The higher topography of the dune and regional hydraulic gradient suggest it, too, is a flow-thru system. The U Fldn well is located on the down-gradient side of Weeki Wachee Prairie (opposite the relict sand dune) where the gradient may be steepest (similar to Hunter's Lake). A steep vertical hydraulic gradient at the U Fldn well would offer a plausible explanation for the 0.5 m offset between water levels at the surface and in the U Fldn 20+ m below (survey and measurement errors have been ruled out). Factors that may contribute to a steep gradient include: the presence of a first order magnitude spring (i.e., discharge > 2.8 m^3/sec) located 3.5 km down-gradient; possible caverns (known to occur in the area) beneath Weeki Wachee Prairie or along the groundwater flow path from it; and shifts in wetland bottom permeability from extensive historical dredge and fill associated with residential development and canal construction. It is plausible these factors, acting individually or in concert, enhance down-gradient flow from the on-site U Fldn monitor well, resulting in its lower than expected water level elevation. The offset between surface water levels and those of the on-site U Fldn monitor well at Hunter's Lake are not similarly high (0.15 m), likely because the well is located at the upgradient shore of the lake where the hydraulic gradient is more gradual.

An unexpected relationship between surface water levels and those of the U Fldn also occurred at Banshee Pond. Here surface water levels exhibited a dichotomous relationship with those of the U Fldn measured at the WR6-b monitor well (7 km away). During low water periods the elevation offset was high (1.8 m), and wetland water levels poorly tracked and were not well correlated with those of the U Fldn (R^2=0.24). During high water periods the offset decreased notably (33% to 1.2 m), and wetland water levels closely tracked and were highly correlated (R^2=0.92) to those of the U Fldn. The 7 km distance between wetland and well likely contributes to the higher overall offset at the wetland during both periods. The reduced offset and shift in behavioral responses and correlation between periods, however, suggests an elevation-dependent state change. The wetland interior shows signs of historical excavation (possibly as a watering pond for grazing cattle or as a sand borrow pit), including: a clear hydrologic shift in the aerial imagery (from typically dry conditions to typically wet), the formation of an interior scarp, a sizable limestone boulder at the wetland bottom and the atypical presence of clayey limestone residuum within centimeters of the sandy surface near the historical wetland edge. The excavation would have not only increased the wetland hydroperiod from intermittent to semi-permanent, but also brought its bottom much closer to the underlying residuum. The clayey texture of the residuum may act to perch surface water, causing it to disconnect with the U Fldn water level as the U Fldn drained. This disconnection is apparent in the wetland hydrograph in the early part of the POR, a period of sustained low rainfall (Figure 3-5e). Following periods of higher rainfall, a rising U Fldn water table would converge with the perched surface water at a threshold elevation, restoring synchronization and thus correlation as shown in the latter part of the POR. This wetland would still be considered a sandhill wetland, but with a modified hydrology.

This study demonstrates hydrologic control of sandhill wetland and water features by an expansive, regional water supply aquifer. Local factors are suggested to influence the features' responses to rainfall (or lack thereof) in consistent and predictable patterns which help explain their residual variation. These factors include those inherent to the features' open depressions (e.g., size, shape, depth and specific yield) and those subject to their situation (e.g., substrate, antecedent conditions, landscape setting, adjacent land use/land cover and rainfall intensity/duration). Least understood, but believed to have an important effect on sandhill wetland and water behavioral responses are the complex surface water-groundwater exchanges that occur, both as bottom leakage and along the features' banks. These effects appear to be greatest at: 1) the larger lake and wetland systems (e.g., Tooke Lake and Willow Sink, respectively) whose greater surface areas may contribute greater losses to evaporation and whose longer shorelines may contribute more opportunities for surface water-groundwater exchange; and 2) at the seasonally inundated wetlands (e.g., Ref 4), which are subject to substrate effects and response differences between surface water and shallow groundwater phases. The relative simplicity of the ponds (i.e., smaller size and single surface water phase) likely explains the greater overall correlation of their water levels with those of the U Fldn. The near-perfect correlation exhibited by water levels at Croom Road Marsh and those of the U Fldn would then seem unexpected given the wetland's intermittent hydroperiod. It may be, though, that because the wetland is only infrequently inundated and is small, it is rarely subject to the substrate effects and complex surface water-groundwater exchanges operating at other features. Its proximity to the U Fldn monitor well (1 km) may further improve its correlation because of their greater hydrogeologic similarity. The lower correlation at other small, intermittently inundated features (e.g., Norman Marsh and Croom Rital Marsh) may be related to lesser hydrogeologic similarity between the wetlands and wells which are much further apart [7 km and 10 km, respectively].

CONCLUSIONS

Florida's sandhill wetlands and waters are an understudied, poorly understood variant of geographically isolated wetlands and waters (GIWs). Findings from this study place those in west-central Florida at the far side of the GIW hydrologic continuum where hydrologic control is regional, by an expansive water-supply aquifer. This distinguishes them from other GIWs and waters whose hydrology is controlled primarily by precipitation or by groundwater from a surficial aquifer. It also highlights the importance of evaluating them within the context of geology.

The scarcity of detailed ecohydrologic studies of sandhill wetlands and waters exposes them to potential losses at a time when federal protections for GIWs are under repeal and a changing climate promises uncertain challenges. Florida's GIWS are protected at the state-level, but the unusual ecohydrology of sandhill wetlands and waters limits the application of current regulatory assessment methods. The characteristic attributes of sandhill wetland and water hydrology, as defined in this study, are intended to promote their understanding and may be helpful in the development of well-suited regulatory methods to ensure their long-term protection.

ACKNOWLEDGEMENTS

Gratitude to Zachary Atlas and the University of South Florida (USF) Center for Geochemical Analysis Laboratory for ion analyses. Additional gratitude to Jessica Wilson and the USF Stable Isotope Lab for isotope analyses. Funding for laboratory analyses were provided in part by the Fred L. & Helen M. Tharp Endowed Scholarship Fund. Special thanks to USF students and professors who assisted during the field and/or laboratory sampling: Tim Fallon, Hilary Flower, Jason LaRoche, Laura Lotero, Dana Noble and Mark Rains. Extra kind thanks to Jason LaRoche for valued hydrogeologic discussions and review of this chapter.

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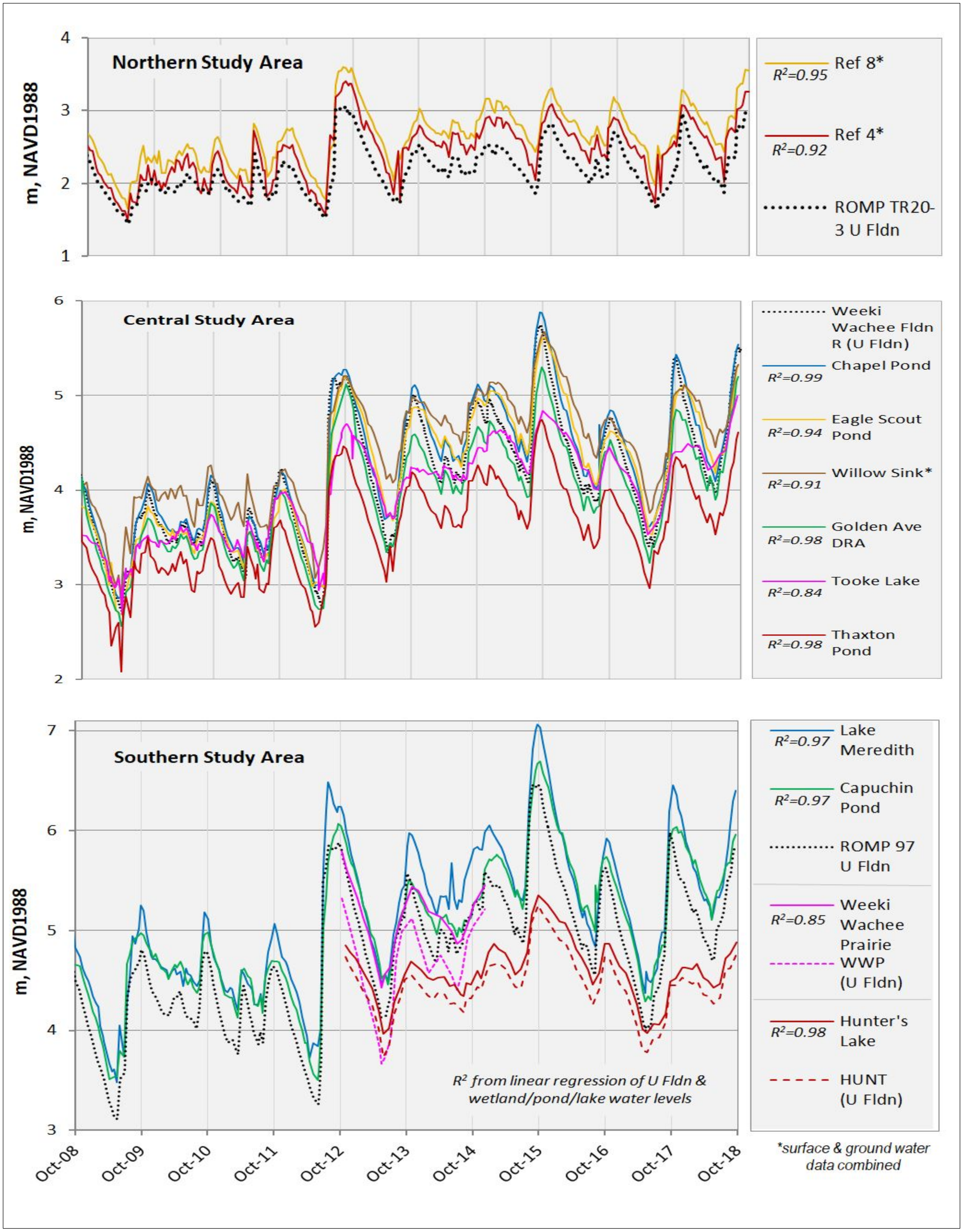
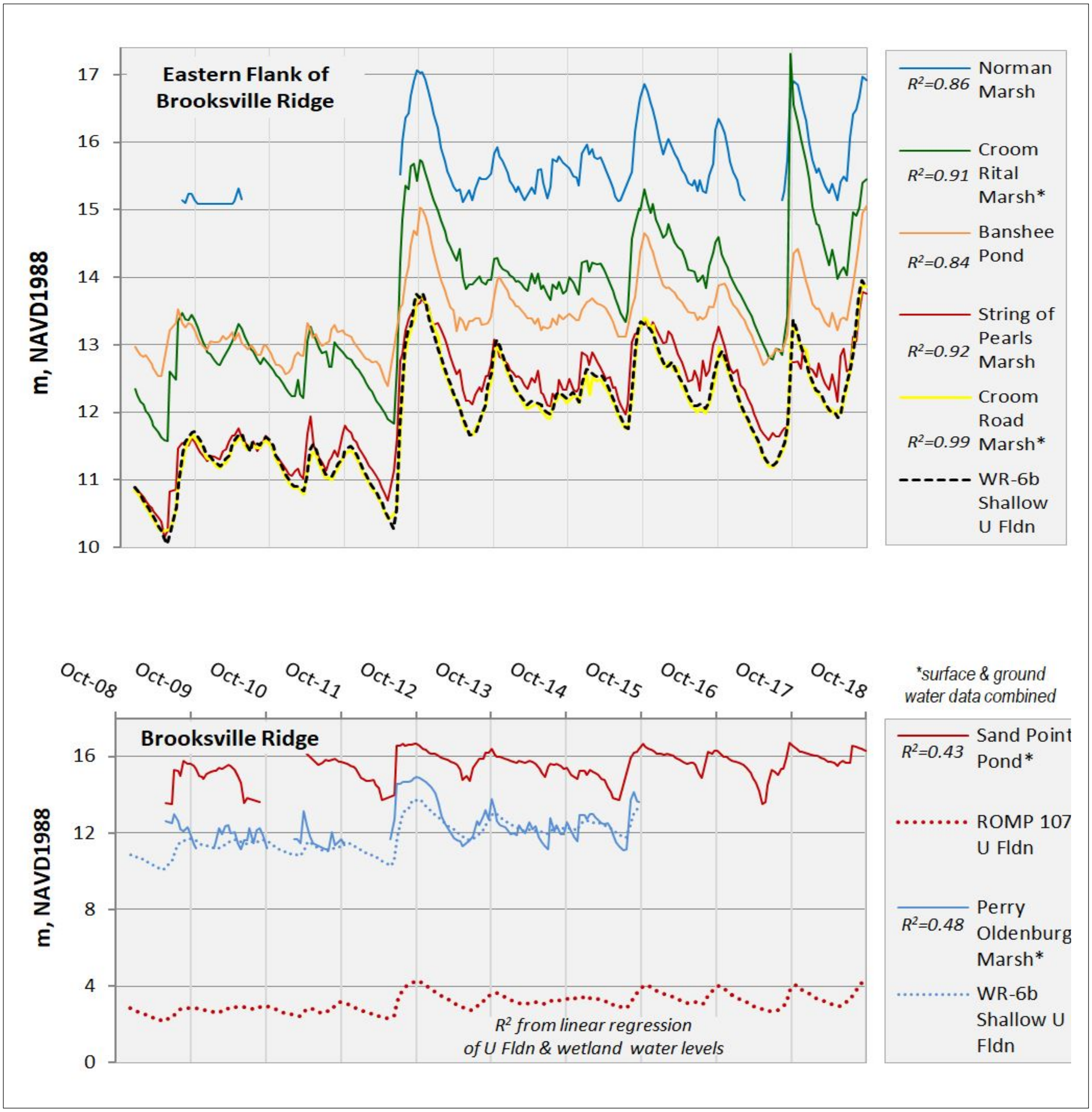
APPENDIX 3-A1 – Surface/ Ground Water Levels of Gulf Coastal Lowland Wetlands & Waters



APPENDIX 3-A2 – Surface/Ground Water Levels of Brooksville Ridge Wetlands & Waters



Chapter 4: Hydrogeologic controls on geographically isolated wetlands & waters - Mechanisms of connectivity to a regional water-supply aquifer & fundamental ecohydrology

ABSTRACT

Ground penetrating radar and electrical resistivity were used to collect stratigraphic data within and near six sandhill wetlands and a wetland-pond complex in west-central Florida to examine their connectivity to a regional water supply aquifer. These data were compared with borehole logs, lithologic data and water level data from wetlands and monitor wells to develop site-specific hydrogeologic configurations, from which two conceptual models were developed. The first model conceptualizes the mechanisms of wetland connectivity to the regional aquifer as: 1) direct connection by wetland embedment in the aquifer, with regional hydrologic control; 2) indirect hydraulic connection due to breaches in the underlying semi-confining unit, groundwater exchange through the breaches and regional hydrologic control; and 3) indirect hydraulic connection due to semi-confining unit breaches, but no groundwater exchange (due to a thick overburden) and surficial, not regional, control of wetland hydrology. The second model conceptualizes fundamental sandhill wetland (and lake, pond and sink) ecohydrology as a function of the geomorphology of the depression occupied, relative to the typical range of the regional water table. Findings from both models contribute to the limited understanding of sandhill wetland ecohydrology and may be used to improve how they are classified, assessed, managed and preserved as valuable natural resources.

KEYWORDS

Sandhill wetland, Groundwater wetland, Groundwater pond, Groundwater lake, Hydraulic connection

INTRODUCTION

Embedded in the sandhill upland communities of Florida are a unique type of geographically isolated wetland (GIW) and water (i.e., those surrounded by upland (Tiner, 2002) known locally as "sandhill" wetlands and waters. "Waters" as referenced here include ponds, lakes and sinks, often with contiguous wetlands occurring as a fringe or adjacent pool(s). Their characteristic xeric setting and widely varying hydrology—which for wetlands may fluctuate between inundation and desiccation over seasons, years or even decades—distinguish these features from their isolated counterparts elsewhere (Nowicki et al., in prep.; Jones Edmunds, 2006; CH2MHill, 2003). Those in west-central Florida are especially distinct because they are largely surface-water expressions of a regional water-supply aquifer (Nowicki et al., in prep.; Henderson, 1986)—the Upper Floridan aquifer (U Fldn), part of the massive Floridan aquifer system, which underlies all of Florida and parts of four other states (Marella and Berndt, 2005). Hydrologic control of GIWs by a regional aquifer is not well documented and has implications for natural resource management and wetland and groundwater regulation.

This investigation is part of a suite of studies intended to improve understanding of the ecohydrology of sandhill wetlands and waters, particularly those in west-central Florida. In a prior study, water levels, dissolved constituents and stable isotopes are used to show that these features are hydraulically connected to the U Fldn (Nowicki et al., in prep.). In this study, borehole logging and geophysical exploration are used to develop models conceptualizing: 1) the mechanisms of their hydraulic connection and; 2) their fundamental ecohydrology. Also explored are the anomalous distribution of hydrophytic vegetation to examine seepage as a potential secondary hydrologic control. Results from both studies contribute to the limited body of knowledge of sandhill wetland and water ecohydrology and can be used to improve how these unique features are classified, assessed, managed and preserved as valuable natural resources.

BACKGROUND

Sandhill wetlands and waters are found in sandhill—xeric plant communities situated in marine sands on both steep and gently rolling hills and ridges in the northern Florida peninsula and panhandle (FNAI, 2010). Sandhill wetlands and waters would not exist in these locations without widespread karst activity—the dissolution of limestone and subsequent subsidence of sandy overburden. This activity has created the numerous depressions of variable shape, depth and size occupied by the sandhill wetlands and waters seen today (Tihansky and Knochenmus, 2001; Kindinger et al., 1999). Sandhill and the wetlands and waters embedded in it are considered "Imperiled" in the state and "Very Rare" globally because of their rarity or vulnerability to extinction (Noss et al., 1995; Kautz, 1998; Stein et al., 2000; FNAI, 2010).

Depressional wetlands formed in karst have been described elsewhere, including: cypress domes and freshwater marshes in mesic communities of west-central Florida (Lee et al., 2009); limesinks in the Dougherty Plain ecoregion within the Coastal Plain Physiographic Province of Georgia (Deemy, 2017; Kirkman et al., 2012; Hendricks & Goodwin, 1952); sinkhole ponds, sagponds in the Valley & Ridge physiographic province between Georgia and Pennsylvania (Cartwright and Wolfe, 2016); and karst pans and compound sinks in the Highland Rim section of the Interior Low Plateaus Physiographic Province of Indiana, Kentucky and Tennessee (Wolfe, 1996). With some exceptions (certain compound sinks in Tennessee and potential Dougherty Plain wetlands), the hydrology of these depressional wetlands appears to be controlled locally by rain, runoff and/or groundwater discharge from a surficial aquifer. Similar local hydrologic controls have been described for sandhill wetlands and waters beyond west-central Florida and for other better-studied GIWs, including: Carolina Bays of the mid-Atlantic (Lide et al., 1995); moraine, ice-scour, and kettle ponds of Alaska (Rains, 2011); playa wetlands of the Southern High Plains (e.g., Texas) (Tsai et al., 2007); prairie potholes of North Dakota (Sloan, 1972, Richardson et al., 1992); and vernal pools of California (Rains et al., 2008; Rains et al., 2006) and the northeast U.S. (Brooks, 2004).

The extreme hydrologic conditions characteristic of Florida sandhill wetlands and waters are reflected in their ecology—largely treeless prairies of obligate wetland to facultative grasses, sedges and forbs with mostly sandy soils (Hernando County Utilities Department [HCUD], unpublished data). Vegetation zonation is common and often expressed as characteristic rings, with species of greatest wetland affinity (i.e., frequency of occurrence in wetlands) predominant in deeper areas and those of decreasing wetland affinities dominant landward. Anomalous vegetation patterns have been noted, however, at several study sites. These patterns include hydrophytic vegetation growing well above the elevation of the wetland edge or as a patch or fringe along it. These patterns are generally found along the steeper of wetland slopes, suggesting a potential lithologic cause, as is examined in this study.

STUDY AREA

The study area is located in west-central Florida, USA, in the Gulf Coastal Lowlands and Brooksville Ridge physiographic provinces (White, 1970). Six wetlands and one wetland-pond complex were evaluated in this study (Figure 4-1).

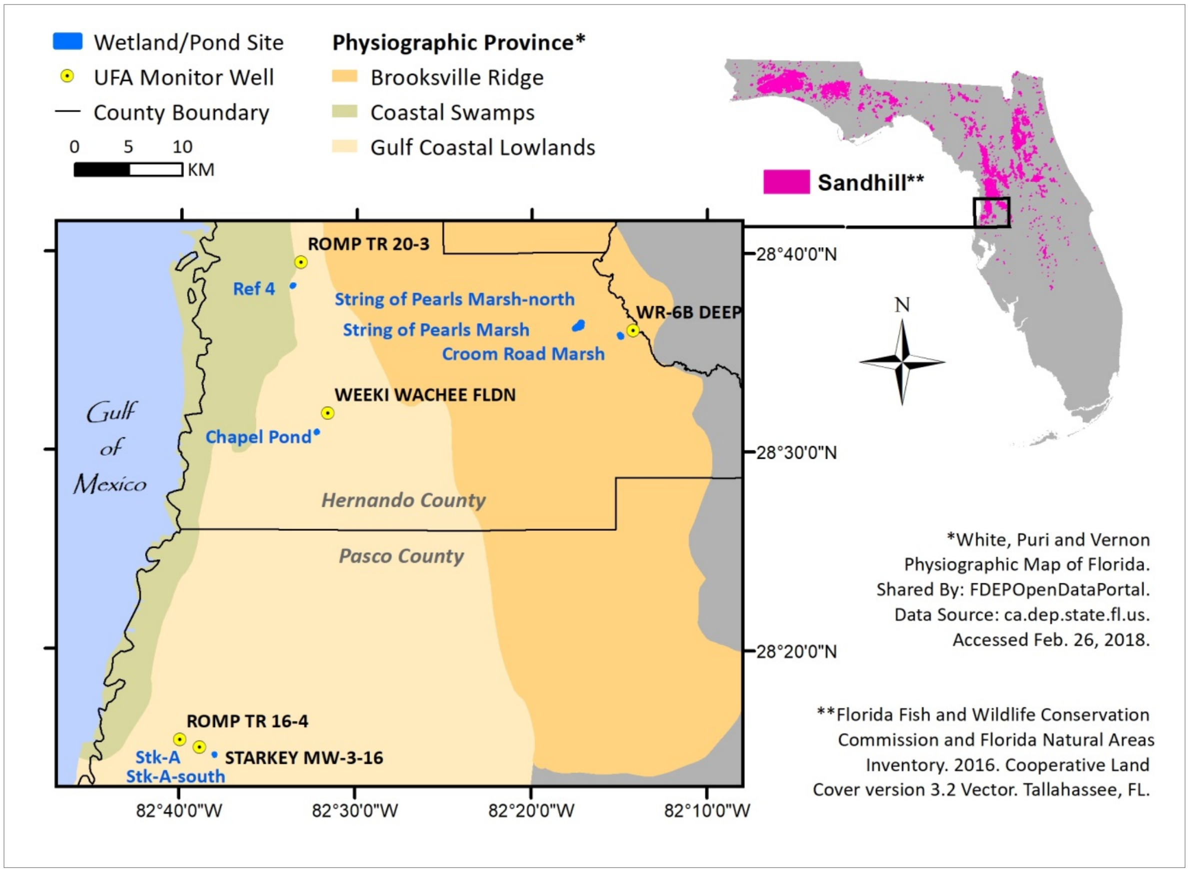


Figure 4-1. Monitoring point location and physiographic provinces in study area, with Florida sandhill communities.

Climate

The west-central Florida climate is humid subtropical. The 30-year (1980-2010) normal, annual rainfall is 1341 mm, 57% of which falls from convective storms during a 4-month wet season (June-September), with the remainder contributed by frontal storms during a longer 8-month dry season (October-May) (Brooksville Hernando Co Airport, Florida, USW00012818, 1981-2010) (Arguez et al., 2010). Annual rainfall extremes as high as 2120 mm have been recorded at local gages, often in association with El Nino or tropical storm events (Water Year [WY] 2003 at Chassahowitzka and Richloam Tower gages, Southwest Florida Water Management District [SWFWMD]); and annual rainfall extremes as low as 860 mm have been recorded at local gages, often in association with drought or La Nina events (WY 1980 at

Richloam Tower gage, SWFWMD). Average annual evapotranspiration is approximately 1000 mm (Bidlake et al., 1996), with annual average lake evaporation occasionally exceeding the long-term annual average rainfall (Sacks et al., 1994; Lee et al., 1997; Swancar et al., 2000).

Hydrogeologic Setting

The geology of the study area varies north to south along a gradient of deepening carbonates and a sandy overburden (Arthur et al., 2008). In the northern part, Tertiary carbonate rocks of the Ocala and Suwannee Limestones occur near the surface and are occasionally exposed (Figure 4-2). Above them lies a thin veneer of unconsolidated, siliciclastic sand with minor amounts of silt and clay. Miocene clay of undifferentiated Hawthorn Group once existed above the limestone, but was mostly removed by erosion. The clay emerges in the southern part of the study area and thickens southward. Intense karst development from repeated sea-level fluctuations occurred throughout the study area, with the most intense activity in the north where the clay is thin or absent (Tihansky, 1999). This activity produced a pitted (hummocky) limestone surface, sometimes with caverns, into which the overburden differentially settled. Persistent dissolution of limestone containing sand and clay can produce a clayey residue (limestone residuum) above the limestone surface that may impede recharge under certain (unspecified) conditions (Miller, 1986). The lithologic records suggest that the residuum is present across the study area and may be thickest in the eastern part (personal comm. Ted Gates, 2018).

System	Series	Litho-Stratigraphic Unit	General Lithology	Major Lithologic Type	Hydrostratigraphic Unit	
Quaternary	Pleistocene-Holocene	undifferentiated sand and clay	Predominantly fine-grained siliciclastic sands; gray-white-orange-brown; some gradational clayey sands with depth	Sand	Upper Floridan aquifer (regionally unconfined)	Floridan aquifer system
Tertiary	Miocene-Pliocene	Hawthorn Group (undifferentiated)	Olive gray to reddish brown clayey sands to silty clays and pure clays	Clay	semi-confining unit	
	Oligocene	Suwannee Limestone	Limestone; white to gray; can be sandy, fossiliferous	Carbonate		
	Eocene	Ocala Limestone	Limestone; white to pale orange; chalky, foraminiferal; dolomitic near bottom			
		Avon Park Formation	Limestone and crystalline dolostone; tan to brown; fossiliferous; intergranular evaporites occur in lower portion			
				Carbonate with Evaporites	middle confining unit II	

Figure 4-2. General stratigraphic framework of the study area. (modified from Miller (1980, 1986).

The hydrogeology of the study area also varies north to south (Figure 4-3). In the northern part where Hawthorn clay that makes up the regional confining unit is absent, the U Fldn is considered regionally unconfined (Basso, 2004). This allows near free exchange of water between the surficial sands and limestone. In the southern part of the study area where the clay is present but is thin and often breached, the U Fldn is considered semi-confined. South of the study area, where the clay thickens, the U Fldn is considered regionally confined. In all cases, the U Fldn is the uppermost aquifer of the Floridan aquifer system and the principal source of fresh groundwater in the state.

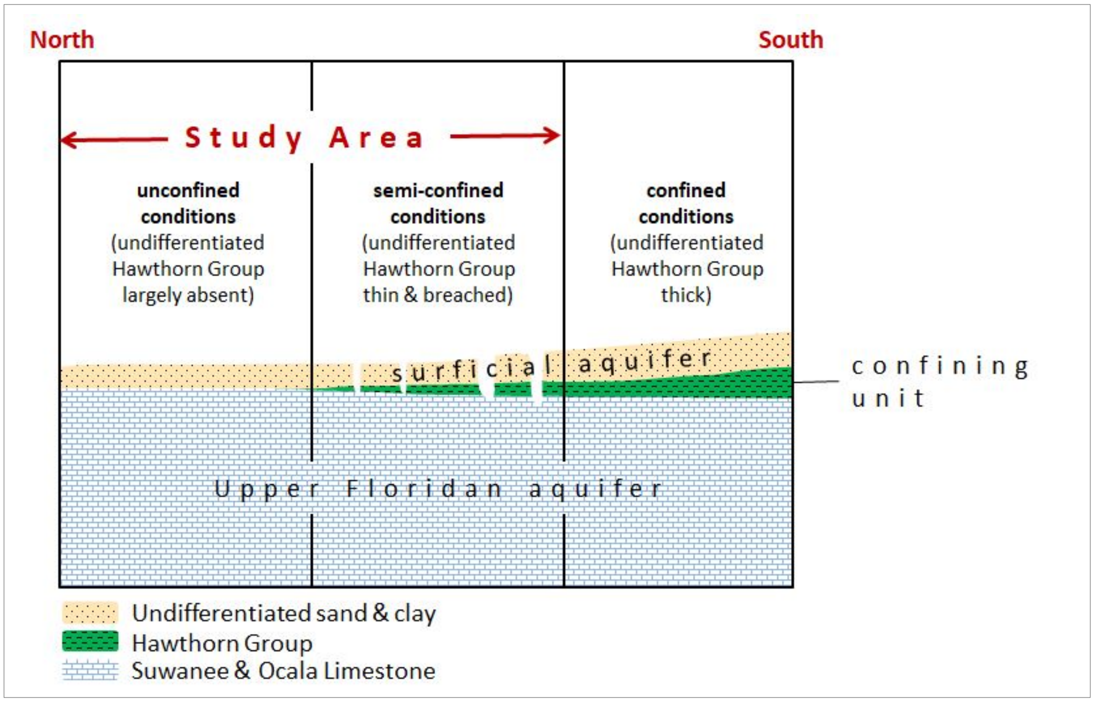


Figure 4-3. General hydrogeology of the study area.

METHODS

Geophysical methods, including ground penetrating radar (GPR) and electrical resistivity (ER), were used to infer lithologic strata from land surface to limestone, which were then used to develop site-specific hydrogeologic configurations and broader conceptual models. GPR and ER were selected for their complementary offerings to the identification of subsurface lithology. GPR is better able to resolve near-surface features such as intra-sand horizons, clay layer(s) or the water table and was used to image slope stratigraphy and potential seepage faces associated with the anomalous distribution of hydrophytic vegetation. ER has a greater penetration depth than GPR (at the frequencies used in this study) and was used to identify limestone surfaces and karst features. Used together and combined with local reference information (e.g., borehole logs, well reports and water level data), pertinent lithologic information for the areas underlying and adjacent to the study sites were obtained.

Site Description

Five of the sandhill wetland/water study sites were selected from a regulatory wetland monitoring program associated with local groundwater production administered by the SWFWMD; two other sites were added for their close proximity (Figure 4-4). The study sites, which are round or irregular in shape and contain one or more pools, range from 0.6 to 11 hectares in size and from 1.0 to 6.5 meters (m) in maximum depth. Land surface elevations (wetland bottoms and adjacent uplands included) range from 0 to 13 m NAVD88 (Gulf Coastal Plain) and from 12 to 30 m NAVD88 (eastern flank of Brooksville Ridge) (Figures 4-1 and4-4).

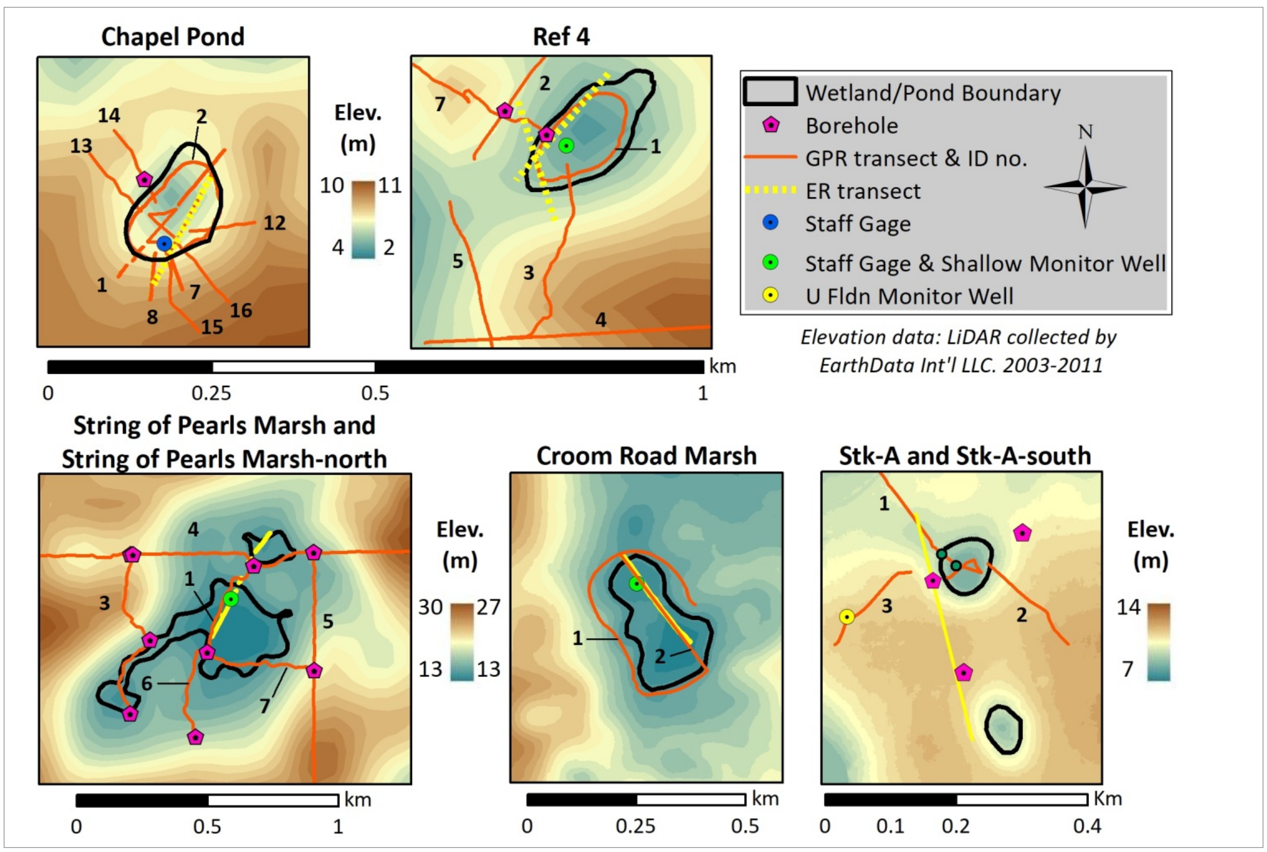


Figure 4-4. Sandhill wetland & water monitoring locations.

GPR Data Collection

Two to 17 GPR transects were surveyed at each of the seven study sites during September-December 2013 and/or May-August 2015 (Figure 4-4). GPR transects collected during 2013 were generally designed to traverse the wetland peripheries and across one or two axes and extend well into the adjacent uplands to identify broader subsurface lithology and potential hydrologic connectivity between sites. Where open water was present along a transect, the antennas were floated across the water surface. GPR transects collected during 2015 were additionally designed to traverse areas of anomalous vegetation patterns to identify changes in lithology.

GPR data were collected with MALÅ 250 MHz or 500 MHz frequency antennae (Guideline Geo, Sundbyberg; Sweden) and GroundVision v.1 acquisition software (Mala Geoscience USA, Charleston South Carolina USA) or the equivalent. GPR data were post-processed using Sandmeier Reflex-Win v.7.5 software (Sandmeier Geophysical Research, Karlsruhe, Germany). Post-processing was performed to increase the signal-to-noise ratio for improved data interpretation. The post-processed GPR data were then spatially referenced using GPS and/or LiDAR-derived topographic data (SWFWMD, 2011). Additional details about the GPR data collection or post-processing methods can be found in Downs (2017).

ER Data Collection

One or two ER transects were surveyed at each of the study sites during May-August 2015 (Figure 4-4). ER transects were located as close to the wetlands' long and short axes as possible (to compare with data collected along the GPR transects), without inundating the electrodes. Where inundation occurred along these axes, the ER transects were shifted upslope to the nearest non-inundated locations.

ER data were collected with an AGI SuperSting R8 resistivity meter (AGI USA, Austin Texas, USA) with a 56 electrode spread, spaced at 3 or 4.5 m using a dipole-inverse Schlumberger array. This array was chosen for its balance between high horizontal sensitivity to vertical structures and moderate sensitivity to horizontal structures (Loke, 2010). ER data were post-processed with Geotomo RES2DINV v.3.59 software (GEOTOMO SOFTWARE SDN BHD, Penang, Malaysia) to correct for topographic variations, remove noise and to invert apparent resistivity values to a resistivity model that could be used for geologic interpretation. The post-processed ER data were then spatially referenced using GPS and/or LiDAR-derived topographic data (SWFWMD, 2011). Additional details about the ER data collection or post-processing methods are presented in Downs (2017).

GPR & ER Data Interpretation

Interpretations of the post-processed GPR and ER data were made via qualitative examination and by cross-comparison with data obtained from borehole logs, field observations, monitor well logs, well site reports, and water level data from the monitored wetlands/waters and nearby U Fldn monitor wells.

Borehole Logs

A Geoprobe tool (Geoprobe Systems, Crystal River FL, USA) was used to collect continuous lithologic samples from land surface to depth of refusal along GPR transects (Figure 4). Between one and four borehole logs were collected at all but one study site (Croom Road Marsh) where a Geoprobe was not available.

Monitor Well Logs, Well Site Reports

Lithostratigraphic and/or hydrostratigraphic data from U Fldn monitor well logs and well site reports were used to estimate the depth to clay and limestone and the degree of secondary or cavernous porosity of an area. Data from four wells across the study area were obtained: ROMP TR16-4 (Gates, 2003), ROMP TR20-3 (Lee, 1998), ROMP WR-6b (Mallams, 2007) and the WEEKI WACHEE FLDN REPL WEEKI WACHEE ("WEEKI WACHEE FLDN") (Kuka, 2013).

Water Level Data

Water level data of variable PORs are available for the five monitored wetland/water study sites (HCUD, unpublished data) and from the four U Fldn monitor wells (SWFWMD, 2018; USGS, 2018). Water levels consist of twice monthly manual recordings at the study sites and monthly recordings or daily averages calculated from continuous recorders at the monitor wells.

RESULTS

Stratigraphic interpretations of the GPR and ER imagery correlate well with one another and with borehole and other lithologic data. GPR reveal finer differences in the shallow stratigraphy, and ER reveal deeper and broader differences. Summaries of the general findings from both techniques follow.

General Findings from the GPR Evaluation

Sand, silt, clay and limestone are discernable in the GPR imagery and exhibit similar, repeating sequences among sites (see exemplar images, Figures 4-5a-c). Borehole data along transects confirmed these strata (Figure 4-5a1) and were extrapolated to nearby transects where borehole data were not available (e.g., Figure 4-5a2). Limestone was inferred when dense plasticy clay (limestone residuum) was recorded in the tips of the drilling rods at refusal. The depths correspond with hummocky (limestone) surfaces in the ER imagery and limestone depths in the local well reports. The hummocky surface is common to all of the study sites as a consequence of karst activity (Figures 4-5a1-2, 4-5b). In some cases, dramatic drops in the limestone surface correspond to overhead surface depressions, while in other cases, depressions are not apparent suggesting other overlying forces (e.g., Aeolian) reworked the surface topography (Figure 4-5a2). Within the wetlands, densely compacted GPR reflectors near the shoreline match field observations of organic material (e.g., mucky mineral or muck) at and near the land surface (Figure 4-5b).

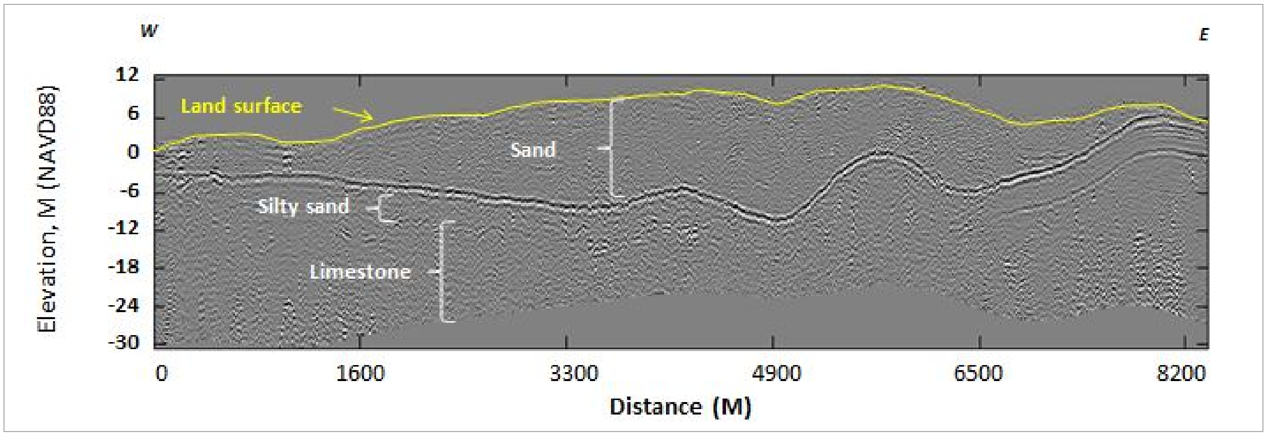


Figure 4-5a1. GPR exemplar with interpretation: upland transect #2 (parallel to wetland long axis) at Ref 4. See Figure 4-4 for location.

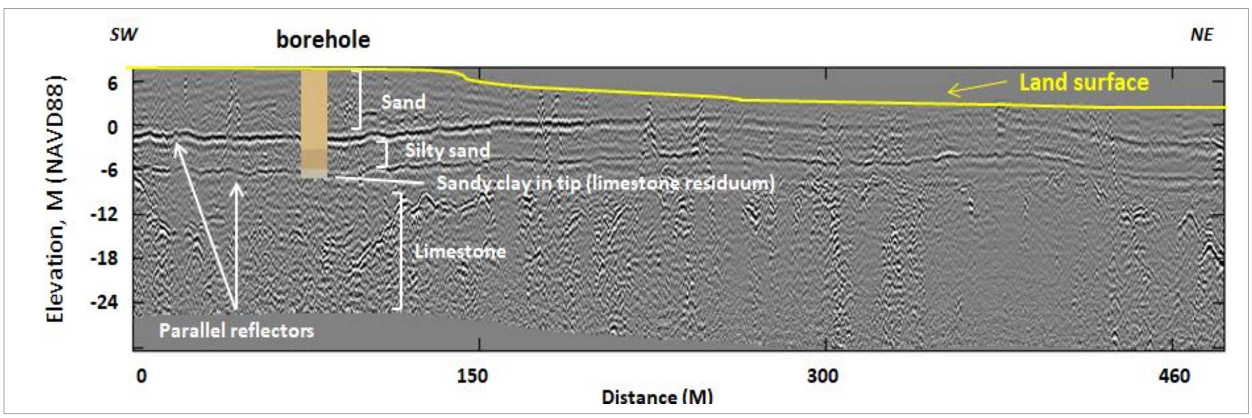


Figure 4-5a2. GPR exemplar with interpretation: upland transect #4 (east-west) south of Ref 4. See Figure 4-4 for location.

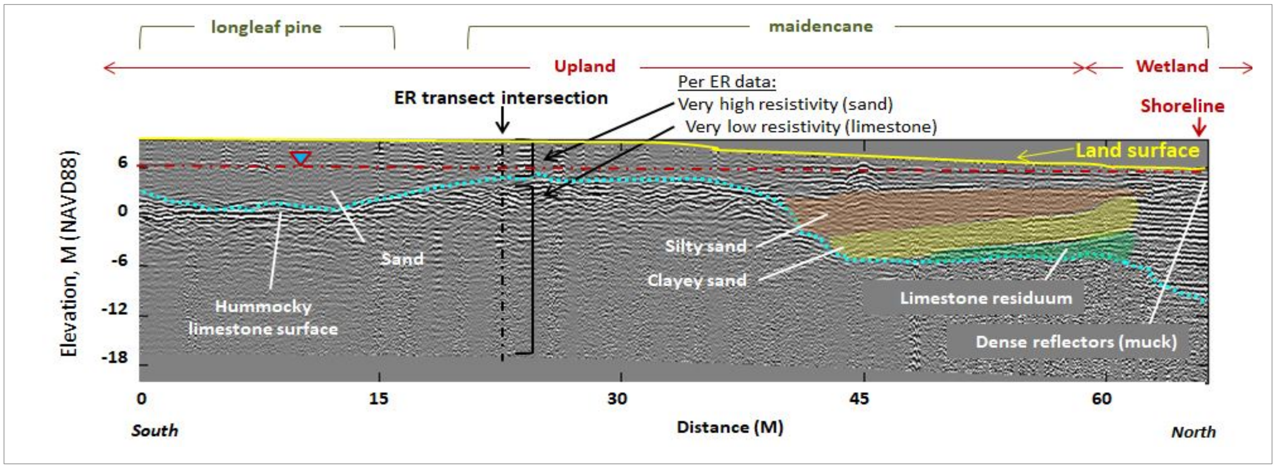


Figure 4-5b. GPR exemplar with interpretation: upland/wetland transect #8 (from southern uplands, north to shoreline) at Chapel Pond. See Figure 4-4 for location. Note the beds of silty sand (orange shading) and clayey sand (yellow shading) beneath the shoreward area of obligate wetland (maidencane grass) plant growth. Note also the adjacent limestone pinnacle beneath the landward area of this plant. The presence of these beds and the limestone pinnacle may enhance capillary effects in the area where this plant grows, allowing it to grow well beyond the range of a typical wetland plant.

In the southern part of the study area, a clay layer 2 – 4 m thick was found in boreholes near the study site. The olive/brown color, plasticy texture, thickness and depth correspond with that of the undifferentiated Hawthorn Group described for the nearby well (Gates, 2003). The clay layer appears breached beneath the wetland where it was identified (Figure 4-5c).

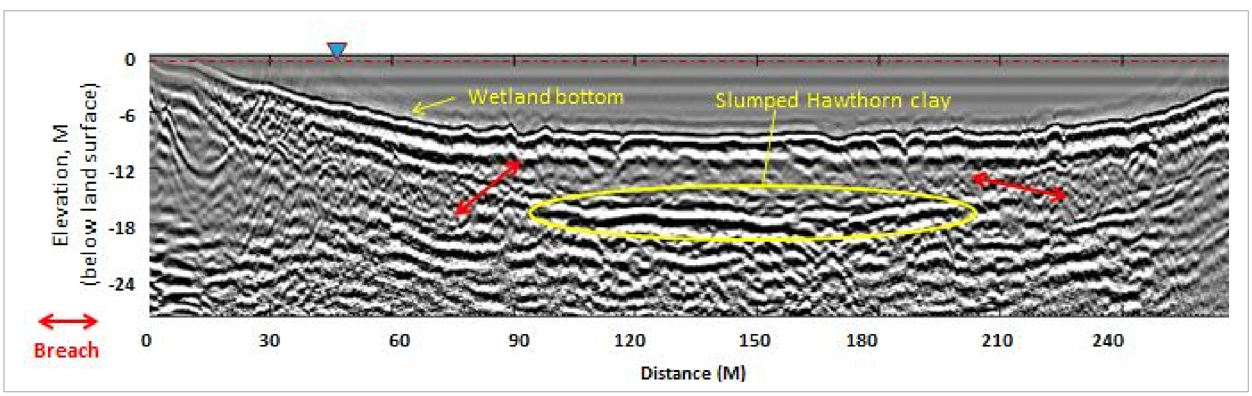


Figure 4-5c. GPR exemplar with interpretation: wetland transect #1 showing breaches in semi-confining unit beneath wetland depression at Stk-A. See Figure 4-4 for location. Note a breach in the clay semi-confining unit would allow water from the underlying regional aquifer to connect with water from the surficial aquifer and wetland.

In areas of anomalous vegetation distribution—hydrophytic species growing well above or along the wetland edge—surface moisture (as might be expected from seepage hydration) was absent during the field survey. However, beds of fine-grained materials (e.g., silty and clayey sand) and near-surface limestone (between the 20 and 45 m marks along the transect) are apparent in the imagery (Figure 4-5b).

General Findings from the ER Evaluation

Interpretation of the ER imagery support findings from the GPR data and add greatly to the understanding of the deeper lithology (20 to 50+ m, site-dependent) beneath and adjacent to the study sites. ER data are particularly useful at distinguishing sand (high resistivity to an electric current) and limestone (lower resistivity to an electrical current). Silt and clay are interpolated from areas of intermediate resistivity and are best discerned with data from boreholes and GPR imagery. Sand in the ER imagery is represented by purples and reds at depths typically extending downward from land surface, while limestone appears in shades of blue as thick, broad areas extending to great depths (Figures 4-6a, 4-7a, 4-8a and 4-9a). Limestone signatures correspond well with depths of limestone documented in the local well reports and depths noted for dense, plasticy clay at refusal in the borehole logs.

Within the low resistivity limestone, sizable pockets of higher resistivity material are evident. In one case the material appears highly resistive, but its composition is unknown (Figure 4-6a). More commonly, the material reflects low to moderate resistivity and may represent sand mixing with limestone along preferential pathways (e.g., Figures 4-6a, 4-7a, 4-8a and 4-9a) or higher and lower resistivity materials that coalesced during a collapse event (Figures 4-6a and 4-10a).

Site-Specific Hydrogeologic Configurations

Hydrogeologic configurations were constructed for each of the study sites by combining stratigraphic data interpreted from the geophysical analyses with hydrologic and limited ecological data (e.g., wetland indicator species, anomalous vegetation patterns, organic soils). Pertinent findings from each site follow.

Chapel Pond

Chapel Pond is a 1.5-hectare, 6.5-m maximum depth wetland-pond complex (Figure 4-4). Beneath its steep southern slope, thick sands are separated from limestone by a thin veneer of residuum. Beneath its gentler northern slope, organic material occurs at the surface above silty and clayey sand over limestone (possibly with residuum above the limestone) (Figure 4-6a). Dramatic pitting of the limestone surface is apparent, even 2 km away, where a 12 m drop in limestone was noted over a 9 m distance (Kruse, personal comm., 2015). Deeper within the limestone, two anomalous features of notable size occur (Figure 4-6a): (1) a highly resistive body of unknown material and (2) a moderate resistivity column beneath the pool that may represent a throat containing collapsed limestone and overburden. The site is located in an area well known by cave divers for its massive underground caverns (Caveatlas.com, 2018). A broad swath of maidencane (*Panicum hemitomon*), a hydrophytic grass, was found growing along the wetland's steep southern slope, well into the uplands. GPR data indicate beds of fine-grained materials (e.g., silty sand over clayey sand) and near-surface limestone (pinnacle) beneath this swath, beyond which upland longleaf pine trees (*Pinus palustris*) dominate an area underlain by a deep, sand-filled pit (Figures 4-5b and 4-6b).

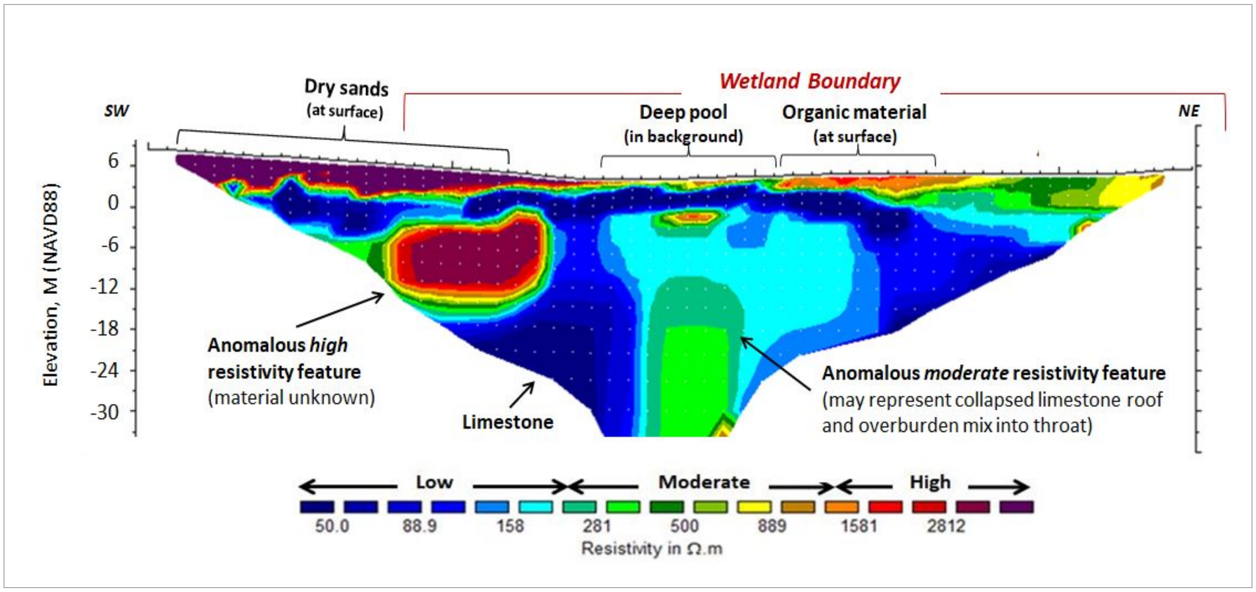


Figure 4-6a. Electrical resistivity (ER) image with interpretation - Chapel Pond, parallel to long axis (landward of deep open water pool). See Figure 4-4 for location. Note the broad area of very low resistivity (royal blue coloring), which reflects limestone beneath highly resistive sand of variable thickness (purple coloring) and the lack of a clay confining unit between them. Note also the large columnar feature likely representing a throat that opened up and was filled in by a mix of sand and collapsed limestone resulting in its low to moderate resistivity (aqua and green coloring). Note also the round body of high resistivity (purple coloring) left of the throat whose composition is unknown.

Overall, these findings suggest a wetland-pond complex resulting from a cavern collapse in an area where the U Fldn is unconfined. The collapse was deep enough to intersect the portion of the U Fldn that is typically saturated and created a permanent pool of water (Figure 4-6b). Shallower (subsidence) areas of the wetland intersect the water table above its typical range, and as a result, are only seasonally or intermittently inundated or saturated. Soils along the steeper southern slope are strongly mineral and do not accrue organic material, while those along the gentler northern slope do. Hydrophytic vegetation growing along and beyond the site's steep, southern slope were found in association with subsurface beds of fine-grained materials and near-surface limestone, suggesting a potential ancillary (lithologic) control on the wetland and adjacent upland hydrology.

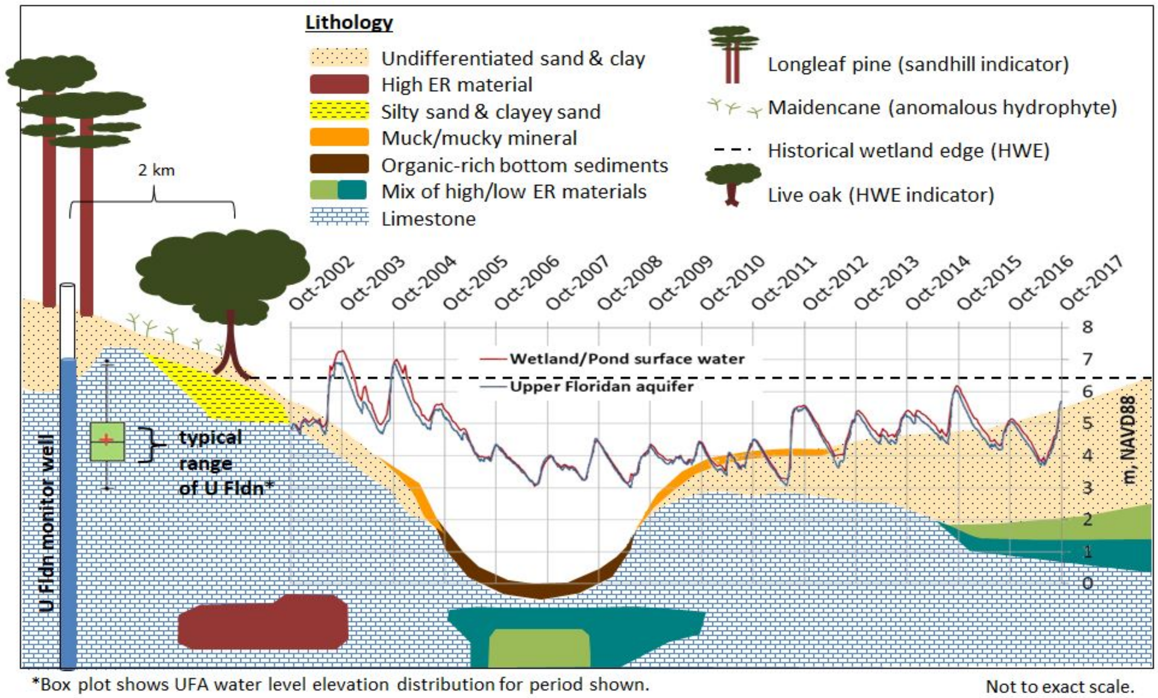


Figure 4-6b. Site-specific hydrogeologic configuration: sandhill wetland-pond system in unconfined aquifer setting (e.g., Chapel Pond). Presentation interpreted from GPR and ER data in combination with borehole logs and surface observations. Note the range of water levels relative to the wetland-pond's bottom and edge elevations. Given the widely ranging water levels observed over this 15-year period, shallower portions of the wetland have the potential to inundate only intermittently, resulting in a lack of organic material accumulation in these areas (shown) and lack of hydrophytic vegetation (not shown).

Ref 4

Ref 4 is a 2.0-hectare, 1.7-m maximum depth wetland surrounded in part by relatively steep terrane (Figure 4-4). Similar to other sites, the limestone surface is deeply pitted (Figures 4-5a2 and 4-7a), corresponding to a high degree of secondary porosity (and potential cavernous zones) noted for the area (Lee, 1998). Within the wetland, moist sand and silty sand fill the pits, upon which sits a thin layer of organic soil in the deeper wetland interior. Beneath the sand, spodic material (which may be leached into the subsurface from decomposing vegetation) was documented above limestone residuum (Figure 4-7a). Beneath the limestone surface, areas of higher resistivity may represent differentially weathered limestone or a solution feature containing overburden and collapsed limestone.

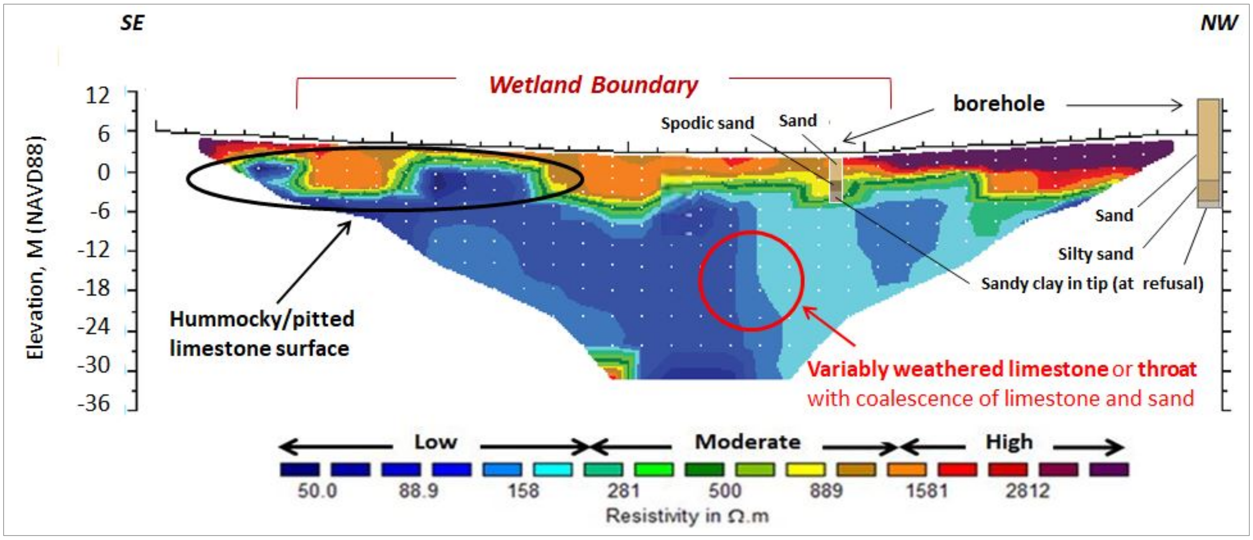


Figure 4-7a. Electrical resistivity (ER) image with interpretation – Ref 4, along wetland short axis. See Figure 4-4 for location. Note the hummocky limestone surface (deep blue) in contact with sand, silty sand or organic material (red, orange or yellow, respectively) at the borehole. Note also the variability resistivity in limestone resistivity (shown in blue and light blue), which may indicate either variably weathering or a coalescence of sand and limestone along preferential pathways.

Overall, these findings indicate a wetland formed of subsidence due to the gradual dissolution of the limestone surface or a cavern collapse (or both). The site occurs in an area where the U Fldn is unconfined, allowing for a direct wetland-aquifer hydraulic connection. Due to the site's relatively shallow nature and higher bottom elevation, it intersects the U Fldn water table in the upper part of its typical range of saturation (Figure 4-7b); thus, a permanently inundated pool is not present, and the site inundates approximately seasonally. Organic materials accumulate in deeper portions of the wetland during wetter periods, but frequent oxidation during dry periods result in relatively modest amounts. The anomalous distribution of hydrophytic vegetation (e.g., maidencane grass growing well above the wetland edge) seen at other sites was not observed at this site.

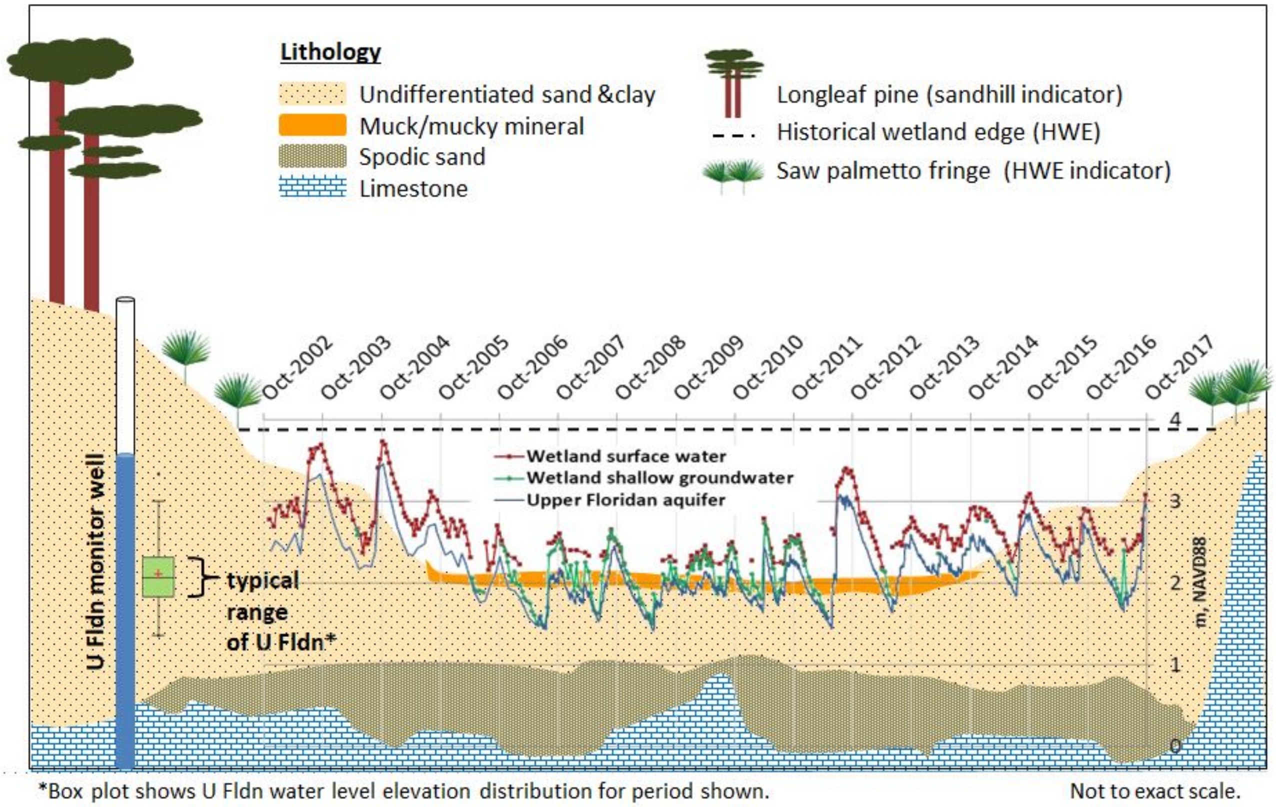


Figure 4-7b. Site-specific hydrogeologic configuration: seasonally hydrated sandhill wetland in unconfined aquifer setting (e.g., Ref 4). Presentation interpreted from GPR and ER data in combination with borehole logs and surface observations. Note the range of water levels relative to the wetland's bottom and edge elevations. Given the widely ranging water levels observed over this 15-year period, shallower portions of the wetland have the potential to inundate only intermittently, while deeper portions inundate more seasonally. The absence of muck/mucky mineral in the shallower areas and its presence in the deeper areas are evidence of the consequences of a widely ranging hydrologic cycle.

String of Pearls Marsh and String of Pearls Marsh-north

String of Pearls Marsh is a 11-hectare, 1.4-m maximum depth multi-pool wetland in a basin surrounded by relatively steep terrane (Figure 4-4). Within the basin 110 m to the north is the smaller (1.4 hectares), shallower (1.0 m maximum depth) wetland, String of Pearls Marsh-north. Both occur in an area of massively pitted limestone where sandy-filled pits range 2 to 20 m deep (Figure 4-8a). String of Pearls Marsh-north occurs within one such pit. Beneath it resides a deep (40+ m) area of what may be weathered structureless decomposed limestone (i.e., thickened bodies of residuum) as described in the local well report (Mallams, 2007), or it may represent sand mixing with collapsed limestone. Beneath String of Pearls Marsh, the ER profile indicates more intact limestone, which highlights the variability of limestone weathering over a relatively small area (Figure 4-8a). A thin layer of organic soil was noted in the deeper interior of String of Pearls Marsh during the field event. Maidencane grew beyond the edges of String of Pearls Marsh and String of Pearls Marsh-north into the adjacent uplands. Patches of hydrophytic trees (laurel oak, *Quercus laurifolia*) also grew in these areas and as a partial wetland fringe. Similar to Chapel Pond, fine-grained beds and near-surface limestone (pinnacles) were found in areas of laurel oak (Figure 4-8a).

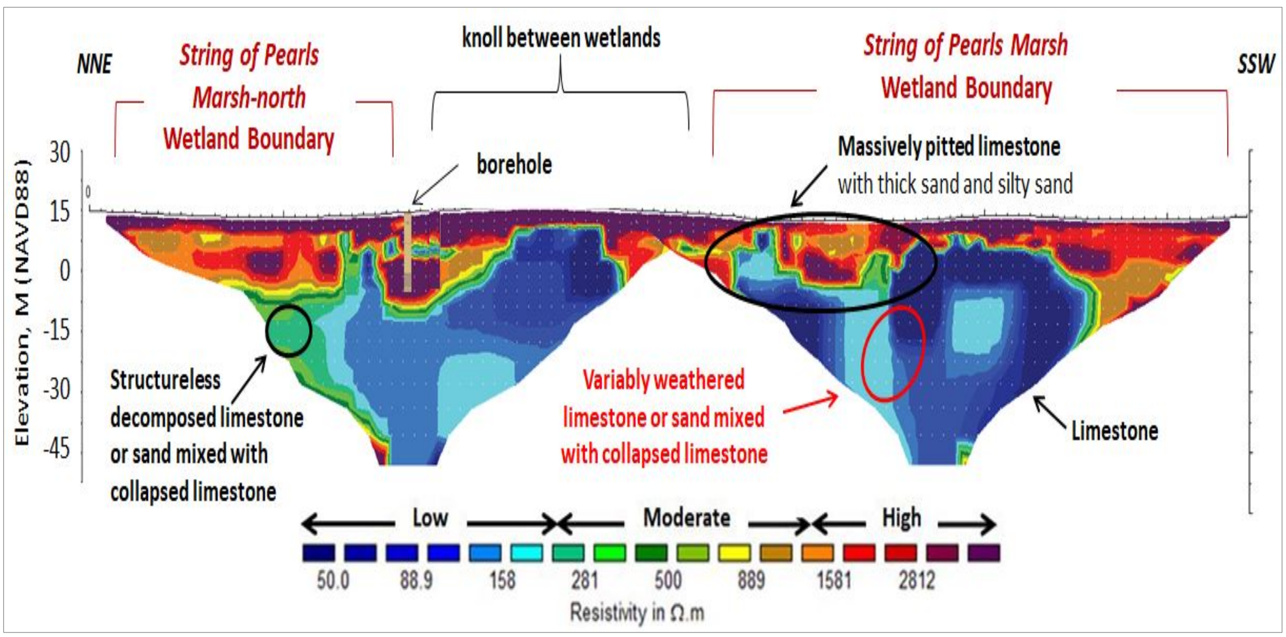


Figure 4-8a. Electrical resistivity (ER) image with interpretation – String of Pearls Marsh and String of Pearls Marsh-north. See Figure 4-4 for location. Note the broad areas of very low resistivity (royal blue coloring), which reflect intact (unweathered) limestone beneath highly resistive sand (purple coloring) or silty sand (red-orange) and the lack of a clay confining unit between them. Note also the very hummocky nature of the limestone surface. Limestone resistivity is least (royal blue coloring) at the two pinnacles, which directly underlie thin layers of sand at the surface (purple coloring). Limestone resistivity is greatest (most weathered) beneath String of Pearls marsh-north, where it is believed to reflect the structureless, decomposed limestone (green coloring) described in lithologic data for a nearby monitor well.

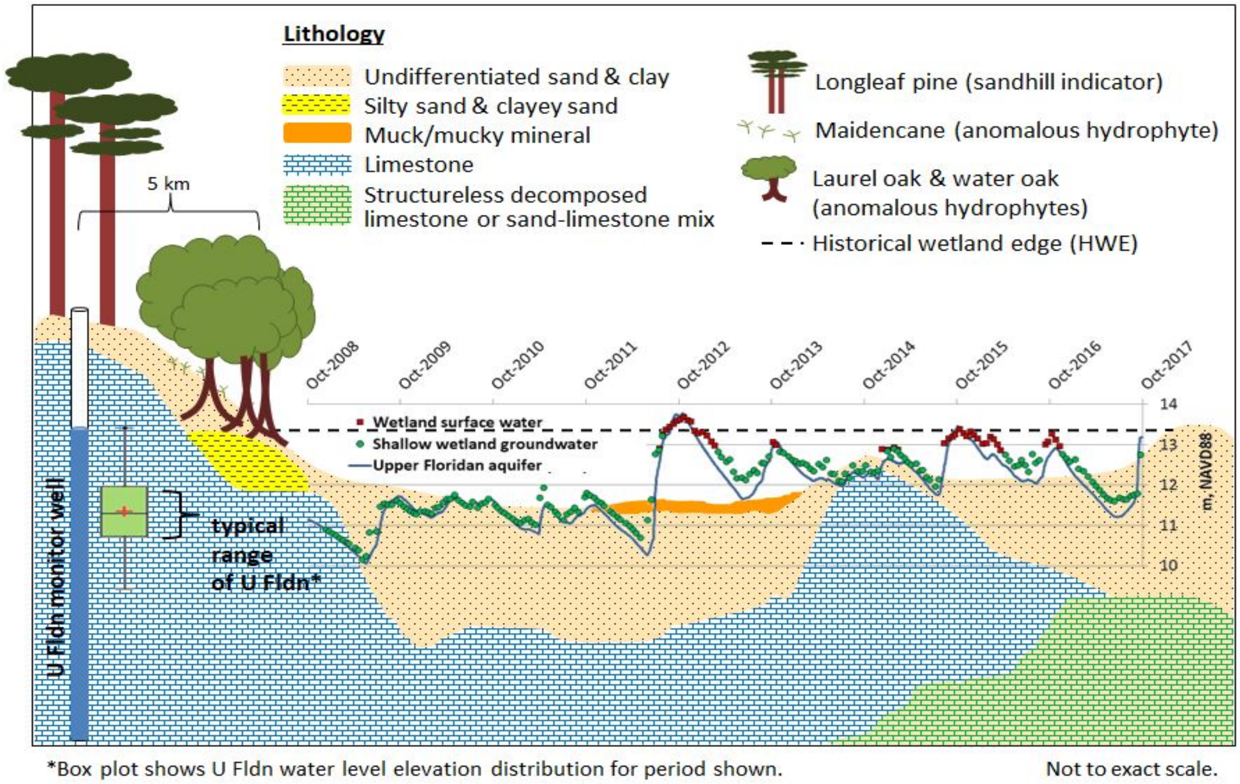


Figure 4-8b. Site-specific hydrogeologic configuration: seasonally hydrated sandhill wetland in unconfined aquifer setting (e.g., String of Pearls Marsh). Presentation interpreted from GPR and ER data in combination with borehole logs and surface observations. Note the range of water levels relative to the wetland's bottom and edge elevations. Given the widely ranging water levels observed over this 9-year period, shallower portions of this wetland have limited potential to inundate except intermittently, while deeper portions have greater potential and inundate more seasonally, allowing the development and accumulation of muck.

Croom Road Marsh

Croom Road Marsh is a 4.5-hectare, 1.5-m maximum depth, dual pool wetland (Figure 4-4). Here, a thin layer of sand sits atop a hummocky limestone surface. Beneath this surface are sizable pockets of either structureless decomposed limestone or sand mixed with collapsed limestone (or both) (Figure 4-9a). Organic material was present only in the deeper of the two pools at the time of the fieldwork. Anomalous vegetation patterns are apparent, including maidencane growing landward of the wetland edge and a partial fringe of hydrophytic trees (laurel oak, water oak [*Quercus nigra*] and dahoon [*Ilex cassine*]). Near-surface beds of fine-grained materials were noted in these areas and appear to deepen where these trees are absent.

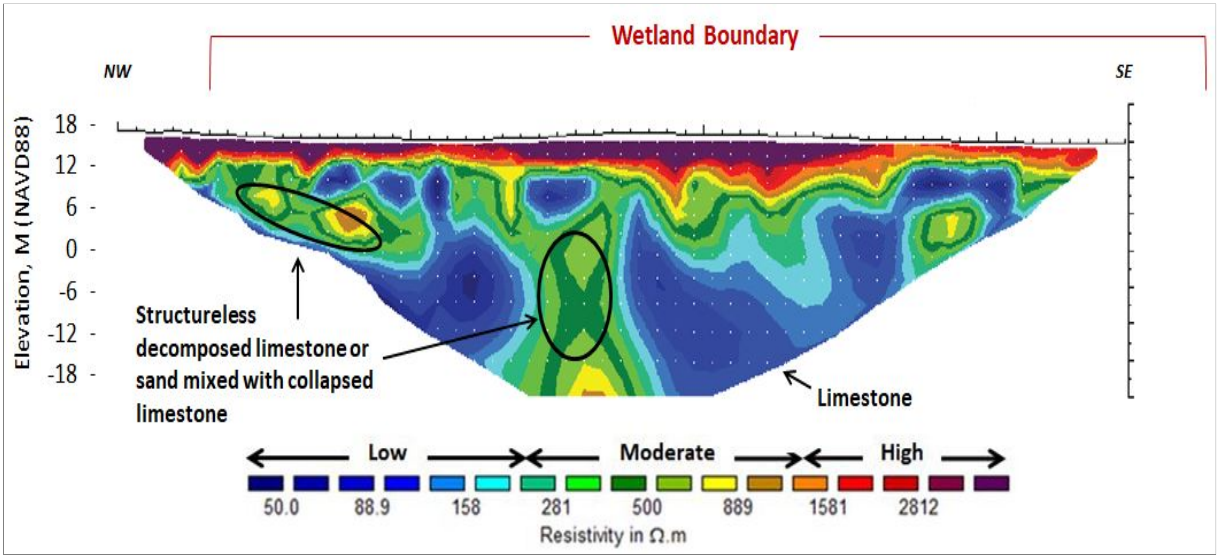


Figure 4-9a. Electrical resistivity (ER) image with interpretation – Croom Road Marsh. See Figure 4-4 for location. Note the broad areas of very low resistivity (royal blue coloring), which reflect limestone beneath highly resistive sand (purple coloring) or silty sand (red-orange) and the lack of a clay confining unit between them. Note also the noteworthy interruption of this limestone matrix by large pockets of what may be structureless and decomposed limestone residuum (green coloring) or the mixing of sand and silt with collapsed limestone.

Overall, Croom Road Marsh is a shallow wetland likely formed by subsidence in an area where clay confinement is absent and sands are in direct contact with extensively weathered limestone. Croom Road Marsh occurs as two very shallow depressions whose bottoms intersect that portion of the U Fldn that saturates only infrequently. Consequently, inundation at this wetland is intermittent (Figure 4-9b). Minor amounts of organic material may accumulate along deeper portions of the wetland interior during wetter periods, but are lost to oxidation during drier periods. Areas of anomalous vegetation patterns may indicate an ancillary lithologic control on the site's hydrology, as described for other sites.

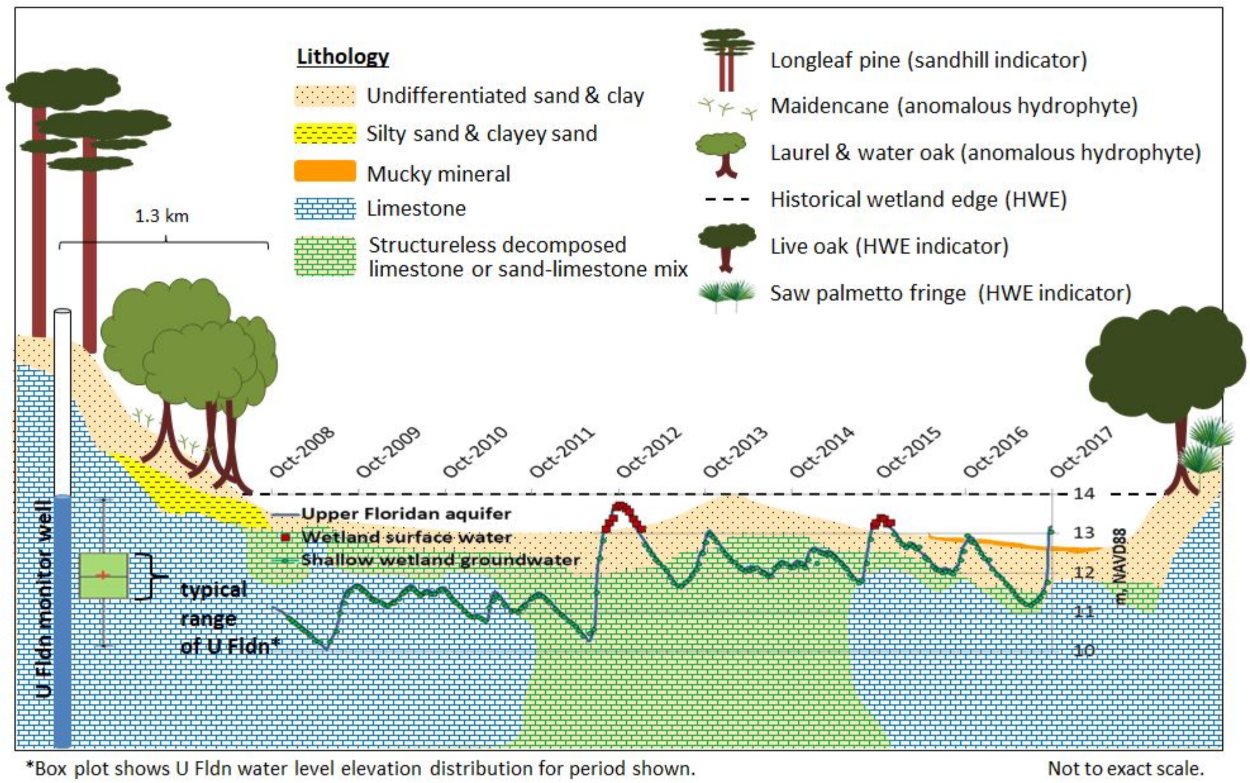


Figure 4-9b. Site-specific hydrogeologic configuration: intermittently hydrated sandhill wetland in unconfined aquifer setting (e.g., Croom Road Marsh). Presentation interpreted from GPR and ER data in combination with lithologic data from nearby well and surface observations. Note the range of water levels relative to the wetland's bottom and edge elevations. Given the widely ranging water levels observed over this 9-year period, the shallower of the wetland's two pools has the potential to inundate only intermittently, which prevents the development of muck of mucky mineral (as shown) and limits the growth of hydrophytic vegetation in favor of facultative species (not shown). The deeper of the two pools has a greater potential to inundate more frequently, allowing for some development of muck/mucky mineral and hydrophytic vegetation.

Stk-A & Stk-A south

Stk-A and Stk-A-south are small (0.9 and 0.6-hectare, respectively), shallow (approximately 1.5 m maximum depth) wetlands in an area of relatively moderate terrane. Unlike the other sites, the sandy overburden is separated from a hummocky limestone surface by a layer of undifferentiated Hawthorn confining unit, 1 – 4 m thick (Figure 4-10a). Borehole data suggest the clay is thickest near Stk-A and thinnest at a knoll between it and Stk-A south. The clay layer appears to be fragmented approximately 7 m below the wetland bottom, which may represent a slumped portion of the clay confining unit

(Figure 4-5c). Pockets of moderate resistivity materials beneath Stk-A support slumping in these areas (Figure 4-10a). Breaches from the slumping would allow hydraulic connection between the wetland and U Fldn. GPR data were not available at Stk-A-south, but similar hydrogeologic conditions are expected. Sizable low-resistivity bodies in the subsurface may represent a larger collapse feature. The sites were fully inundated during the field events, so the presence of organic soils could not be determined.

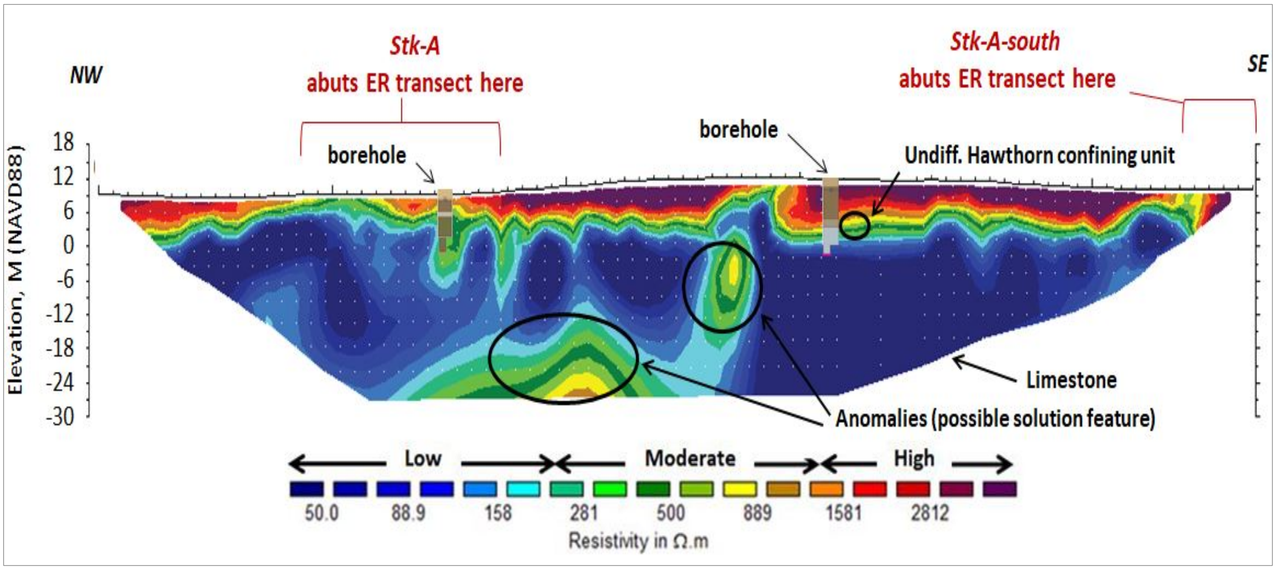


Figure 4-10a. Electrical resistivity (ER) image with interpretation – Stk-A and Stk-A-south. See Figure 4-4 for location. Note the broad areas of very low resistivity (royal blue coloring), which reflect intact (unweathered) limestone. Note also the pockets of what appear to be breaches in the clay semi-confining unit (green coloring), which interrupt the limestone and the large body at the base of the image, which may be a solution feature.

The anomalous distribution of hydrophytic vegetation described for other sites was not noted at Stk-A or Stk-A-south, although a dense ring of (upland) live oak trees (*Quercus virginiana*) enclosed both wetlands. The presence of these trees along the edge of wetlands is not unexpected, as their lower limit often serves as a local indicator of a historical (i.e., pre-development) wetland edge when saw palmetto (*Serenoa repens*, the common historical wetland edge indicator) is absent. Their densely packed distribution, however, may represent a different type of lithologic discontinuity—exposed Hawthorn clay left behind (i.e., unslumped) during the sites' formation.

Overall, Stk-A and Stk-A-south appear to be the result of shallow collapse events in a region where low permeability confining sediments are present, but are thin or discontinuous or are breached from these and numerous other collapse events. The breaches at Stk-A and Stk-A-south would allow for an indirect hydraulic connection between the wetlands and U Fldn, as is evident by the strong similarity in the Stk-A and U Fldn water level elevations and fluctuations in the hydrograph (Figure 4-10b). Hydroperiods at Stk-A vary from intermittent to seasonal, with wetland ecological conditions varying accordingly (SWFWMD, 2018).

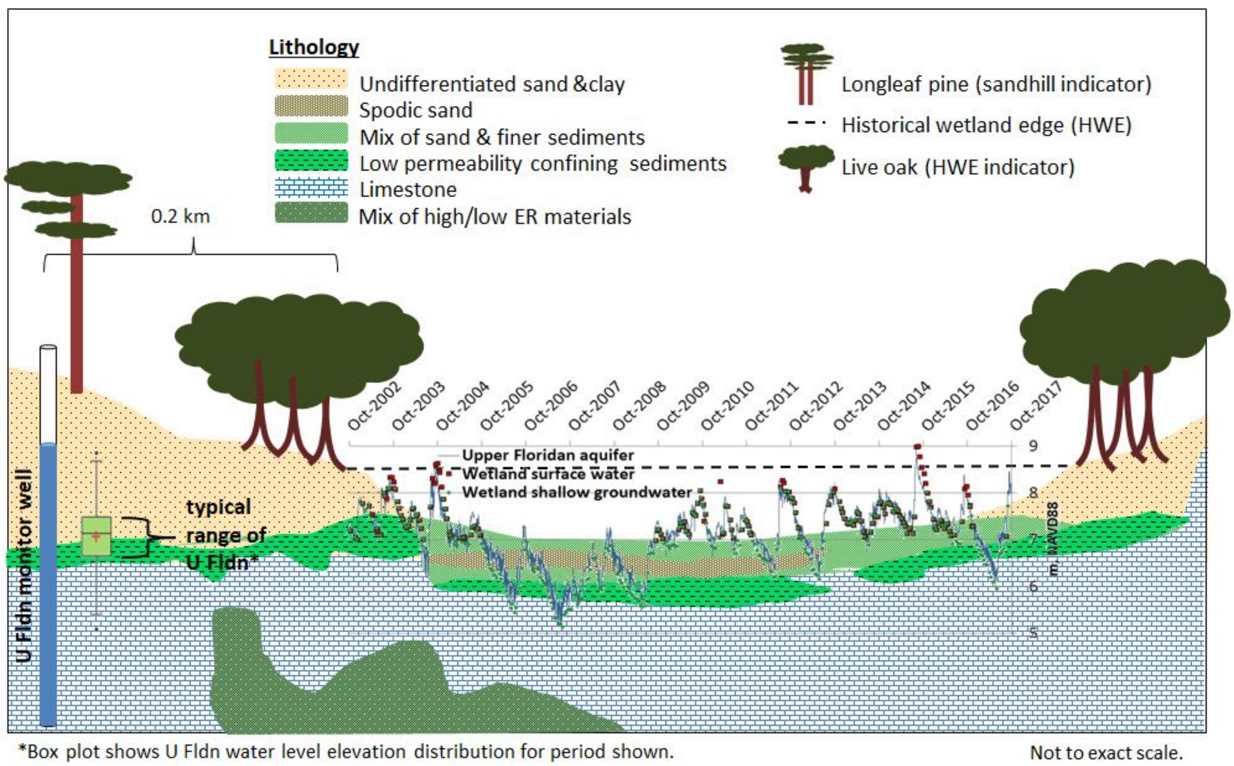


Figure 4-10b. Site-specific hydrogeologic model: sandhill wetland in semi-confined aquifer setting (e.g., Stk-A). Presentation interpreted from GPR and ER data in combination with borehole logs and surface observations. This configuration is different than the others due to the presence of a semi-confining unit, which appears breached in the GPR and ER data and is characteristic for the area. This would allow water from the regional aquifer to connect with that of the surficial aquifer and wetland. Note the range of water levels relative to the wetland's bottom and edge elevations suggests the wetland has the potential to inundate approximately seasonally (during periods of normal rainfall).

DISCUSSION

To date, little has been documented about the ecohydrology of Florida's sandhill wetlands and waters. A recent companion study showed those in west-central Florida are unique in their hydraulic connection to a large, regional water-supply aquifer (Nowicki et al., in prep.; Henderson, 1986). Models conceptualizing the mechanisms for that connection are proposed here. The models were developed from site-specific hydrogeologic configurations that characterize the structure and hydrology of five exemplar wetlands/waters in the study area relative to the underlying and adjacent lithology. Also presented is a general conceptual model of sandhill wetland/water ecohydrology. These models contribute to the very limited body of knowledge of sandhill wetland and water ecohydrology—knowledge sorely needed to improve how: they are identified, their boundaries are determined, their health and impacts are assessed and their character is understood and preserved. As surface water expressions of a regional water-supply aquifer, these findings also have implications for groundwater and wetland regulation.

Fundamental Sandhill Wetland & Water Hydrogeology

Overall, the hydrogeologic configurations reveal depressions of various shape, depth and size embedded in a karst terrane; the limestone is variably weathered and characterized by a hummocky surface beneath an undulating sandy overburden with or without a clay confining unit (Figures 4-6b, 4-7b, 4-8b, 4-9b, 4-10b). In the northern part of the study area, clay confinement is absent, and wetlands/waters are embedded in the sandy overburden, which sits directly atop the limestone. With no confining unit, the sands comprise the upper part of the U Fldn, and a *direct* hydraulic connection exists between the wetlands and U Fldn because the wetlands are embedded in it—the water table of the U Fldn essentially becomes the wetland water table. When viewed on a hydrograph, water levels of these sandhill wetlands and waters are generally coincident with those of the U Fldn (Figures 4-6b, 4-

7b, 4-8b and 4-9b), although elevation offsets may be apparent due to differences in wetland-well positions along the hydraulic gradient and/or site-specific factors (Nowicki et al. in prep.).

In the southern part of the study area, the wetlands also are embedded in the sandy overburden, but the overburden is separated from the limestone by a thin, clay semi-confining unit, as shown in the GPR and ER imagery and described in the local well report (Figures 4-10a and 4-10b). With this unit present, the sands comprise the surficial aquifer. Water from the U Fldn flows into and out of it through breaches in the semi-confining unit and may enter the wetlands as a hybrid of surficial aquifer-U Fldn water (Figure 4-5c). This reflects an *indirect* type of hydraulic connection because the wetlands are not embedded in the U Fldn, rather they are embedded in the surficial aquifer which connects to the U Fldn through the breaches. When viewed on a hydrograph, differences between water levels of the U Fldn and those of the surficial aquifer and wetland are minimal, and U Fldn control is evident (Figure 4-10b).

Generalized hydrogeologic models for these two mechanisms are depicted in Figure 4-11. This figure shows how the degree and depth of aquifer confinement determine how the wetlands/waters connect with the regional aquifer. A third model, not directly evaluated in this study, is presented for Florida sandhill wetland and water features located outside the study area. In this model, the regional aquifer (U Fldn) is semi-confined, but deep (9 to 60 m) relative to the overlying features [Sinclair and Stewart, 1985]. The features are embedded in a prominent surficial aquifer which controls their hydrology (Jones Edmunds, 2006; CH2MHill, 2003; Grubbs, 1995; Sacks et al., 1992). The water table of the regional aquifer may influence vertical outflow from the features due to hydraulic head differences, but water from the regional aquifer never directly enters the features (Swancar, 2003; Sacks et al., 1998). Despite this different mechanism, these sandhill wetlands and waters share a characteristic ecohydrology with those represented by the two other models. This occurs because in all three models, the wetlands and waters occupy depressions of karst origin in xeric communities where climate is similar and water levels vary widely in response to regional or regionally influenced groundwater fluctuations.

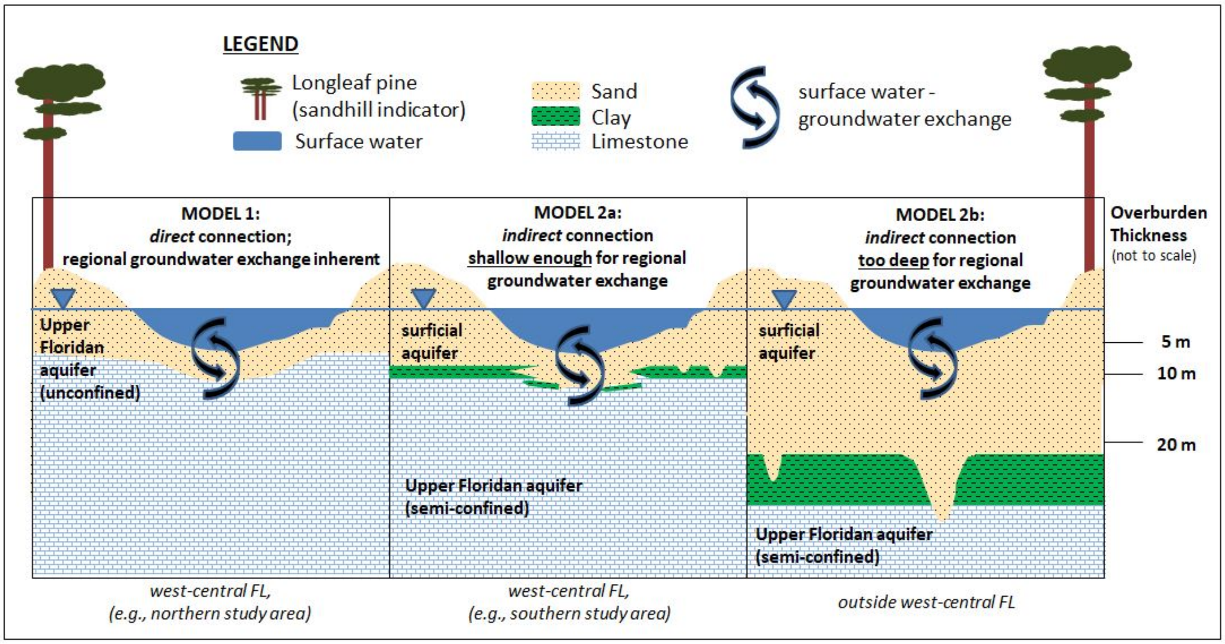


Figure 4-11. Generalized sandhill wetland & water hydrogeologic models. The degree and depth of aquifer confinement determines how the wetland and water features hydraulically connect with the regional aquifer. Where the aquifer is unconfined, the features are embedded in it and thus have a direct connection and surface water-groundwater exchange is inherent (MODEL 1). Where the regional aquifer is semi-confined, the features are embedded in a surficial aquifer and have only an indirect connection with the regional aquifer. The depth between the features and regional aquifer determine whether surface water and regional groundwater are exchanged (MODEL 2a) or not (MODEL 2b).

Their hydraulic connection to a large, water-supply aquifer (as described here) differentiates sandhill wetlands and waters from other GIWs and waters, including those similarly found in a karst terrane such as the cypress domes and freshwater marshes of west-central Florida's pine flatwoods (Lee et al., 2009); or the limesinks and sagponds of Georgia's Dougherty Plain (Deemy, 2017; Cartwright and Wolfe, 2016). For these GIWs, hydrologic control is local by rain, runoff and/or groundwater discharge from a surficial aquifer. This is the norm for most GIWs, including those not associated with karst, such as the: Carolina Bays of the mid-Atlantic (Lide et al., 1995); kettle ponds of Alaska (Rains, 2011); prairie potholes of North Dakota (Sloan, 1972, Richardson et al., 1992); and vernal pools of California (Rains et al., 2008; Rains et al., 2006) and the northeast U.S. (Brooks, 2004).

Fundamental Sandhill Wetland & Water Ecohydrology

While the water table of the regional aquifer ultimately controls the water level elevations of west-central Florida's sandhill wetlands and waters, geomorphology controls their hydrologic, and thus ecological, expression. A simple conceptual model highlighting the role of geomorphology in structuring the fundamental ecohydrology of sandhill wetlands and waters is proposed in Figure 4-12 and described below.

- For deeper depressions whose bottom elevations intersect *below* the typical range of the regional water table (e.g., pond portion of Chapel Pond, Figure 4-6b), inundation is permanent and open water conditions prevail. If the depressions are large enough to allow wave action, they manifest as

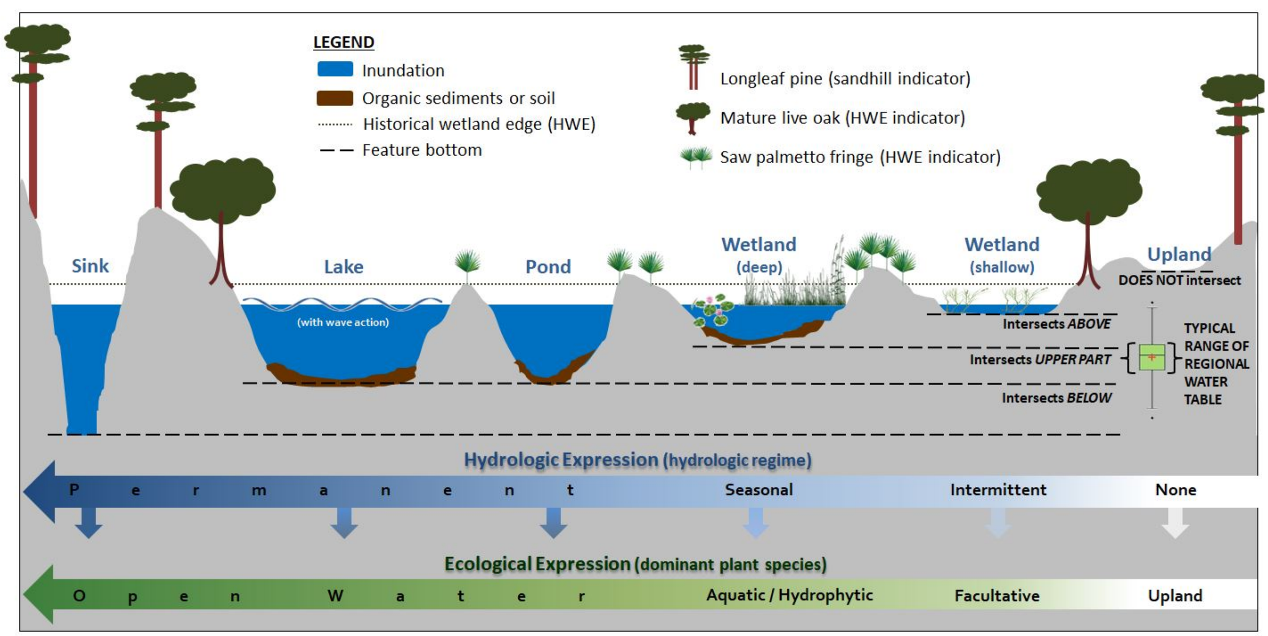


Figure 4-12. Proposed conceptual model of sandhill wetland & water ecohydrology in west-central Florida. Geomorphology is a fundamental control on sandhill wetland & water ecohydrology. Where the wetland/water bottom intersects the regional water table determines the hydrologic regime which determines the ecological expression (accumulation of organic sediments or soils and plant species composition).

lakes; otherwise they manifest as ponds. Ponds whose bottoms are not infilled with overburden manifest as sinks, characterized by an open vertical shaft.

- For less deep depressions whose bottom elevations intersect the *upper part* of the typical range of the regional water table (Figures 4-7b and 4-8b), inundation is seasonal, and the depressions manifest as deep wetlands. Organic material has the potential to accumulate, and hydrophytes or aquatic vegetation are typically dominant.
- For shallow depressions whose bottom elevations are *above* the typical range of the regional water table (but within the overall range) (Figure 4-9b), inundation is intermittent, and the depressions manifest as shallow wetlands. Organic soils have the potential to develop during high periods of the hydrologic cycles, but otherwise quickly oxidize, and facultative species are dominant.
- For multiple depression features or features whose bottom elevations vary substantially (Figure 4-6b), a mosaic of ecohydrologic conditions manifest (e.g., wetland-pond complex).
- For depressions whose bottom elevations are completely outside the range of the regional water table, neither inundation nor saturation occurs and the depression manifests as an upland (Figure 4-12).

For sandhill wetlands and waters exhibiting anomalous vegetation patterns—hydrophytic grass growing at elevations well above the range of the regional water table or hydrophytic trees growing as a patch or fringe along (or beyond) the wetland edge—lithologic discontinuities are apparent in the subsurface. GPR and ER data for four of the seven study sites where this phenomena was noted reveal beds of fine-grained sediments and near-surface limestone beneath swaths of maidencane grass and/or patches of laurel oak and water oak trees (Figures 4-5b, 4-6a, 4-6b, 4-8a and 4-9a). The lower permeability of the sediment beds and limestone in these areas may retain moisture and enhance capillary action, allowing hydrophytes to establish above them. Where the limestone and beds deepen, the hydrophytes dissipate in favor of obligate upland vegetation (e.g., longleaf pine or sand live oak [*Quercus geminata*] trees) (e.g., Figure 4-5a).

Hydration of this kind does not meet the criteria of seepage, as water does not "ooze from the earth," nor does it reflect perching, as an unsaturated zone does not occur beneath the fine-grained sediments or limestone (AGI, 1976). Rather it appears to be a function of another aspect of geomorphologic control—depression shape, or hillslope. During the sites' formative collapse or subsidence event, a portion of the limestone is lost, leaving behind an intact pinnacle and low permeability materials, which settle along it. If these lithologies are not too far below land surface to produce a capillary effect, hydrophytic vegetation may benefit from the moisture and establish above them. It also may be that the hydrophytic trees, while not able to survive the widely varying hydrology of the wetland interior, are able to survive the more stable hydration at the wetland edge (with or without lithologic help). The anomalous vegetation patterns described here are common to many other sandhill wetlands and waters (Nowicki, unpublished data). Geophysical and borehole evaluations are recommended at these locations to examine their underlying lithology and mechanism(s) of hydration further. This understanding is important for:

- recognition of a potential ancillary control on sandhill wetland and water ecohydrology;
- potential use of these hydrophytes as lithologic indicators in sandhill communities;
- proper sandhill wetland/water boundary determinations; and
- thoughtful, accurate sandhill wetland/water health and impact assessments.

Significance of Sandhill Wetland & Water Ecohydrologic Characterization

The unusual ecohydrology of sandhill wetlands and waters presents challenges to their identification, delineation, assessment and regulation. Their dependence on a groundwater table that may vary 4 m or more over its POR, translates to an ecological expression that varies widely in response, over both time and space. For many sandhill wetlands, this corresponds to a general lack of broadleaf plants in favor of sedges and rushes and periodic shifts from: 1) obligate wetland species to those found in wetlands and uplands alike (facultative); and 2) organic soils to mineral soils through frequent oxidation (HCUD, unpublished data). These qualities may cause sandhill wetlands to appear depauperate, particularly during extended dry periods or for those shallow features with naturally intermittent hydroperiods (Figures 4-9b and 4-12). For other types of isolated wetlands with a more stable hydrology, dominance by hydrophytic vegetation and organic soils are the norm and represent a healthy wetland unimpacted by anthropogenic effects such as groundwater production or ditching, whereas abundant facultative species and oxidized soils—such as occur naturally at sandhill wetlands—generally indicate impact. The anomalous vegetation patterns found at many sandhill wetlands and waters create further challenges because the appearance of health (or impact) may vary depending on which slope of the wetland is assessed. Wetland assessors tasked with determining jurisdictional boundaries for sandhill wetlands may underestimate their true extent and depth, sometimes grossly so and at the exclusion of much of the wetland transitional zone. While contemporary methods of wetland delineations and health assessments may run the risk of minimizing a sandhill wetland or falsely declaring it impacted, the inverse may occur as well.

Better tools are needed to identify sandhill wetland and water features, classify them according to their hydrologic control(s), properly define their boundaries and perform health and impact assessments appropriate for their morphology and dynamic ecohydrology. Two of the state's wetland regulatory agencies responsible for wetland and water resources—the Southwest Florida Water Management District (SWFWMD) and the St. John's River Water Management District (SJRWMD)—have taken special steps towards the assessment and protection of sandhill wetlands and waters. The SWFWMD has undertaken preliminary studies to develop a sandhill wetland assessment protocol (focusing on isolated wetlands) and funded the geophysical assessment which produced the hydrogeologic configurations presented here. The SJRWMD has conducted thorough literature reviews and undertaken studies to develop criteria and thresholds to prevent significant harm to sandhill lakes and the fringe wetlands associated with them (SJRWMD FAC 40-c, 2019; Nkedi-Kizza and Richardson, 2007; Jones Edmunds, 2006; Richardson, 2004; CH2MHill, 2003). The authors of this study hope the research presented here can be used to continue their efforts and develop tools that would benefit sandhill wetlands and waters in both Districts and beyond.

CONCLUSIONS

Florida's sandhill wetlands and waters are a unique and imperiled subset of GIWs and waters. They occur in xeric settings, express a characteristic ecology and exhibit a widely fluctuating hydrology, which may vary from inundation to lack thereof over seasons, years or decades. They occupy depressions formed from the dissolution of limestone (karst processes) in a rolling topography of marine sands where drainage is quick, rainfall is ample and aquifer confinement is absent, thin or breached. The sandhill wetlands and waters of west-central Florida (the primary focus of this study) are particularly unique because they are hydraulically connected to and exchange water with a large regional water-supply aquifer.

This study was part of a suite of studies intended to add to the limited body of knowledge of sandhill wetland and water ecohydrology. Through the use of geophysical exploration and data obtained from borehole logs, well reports and other lithologic datasets, sandhill wetland and water conceptual models were developed which identify:

1) the mechanisms by which sandhill wetlands and waters hydraulically connect to a large regional aquifer; and

2) geomorphology as the primary factor that controls their characteristic ecohydrologic expression.

These findings can be used to improve the means by which these unique and Imperiled features are classified, assessed, managed and preserved as valuable natural resources.

ACKNOWLEDGEMENTS

Funding for this study was provided in part by the Southwest Florida Water Management District (SWFWMD). GPR and borehole data were collected by the Natural Resource Conservation Service for the SWFWMD. ER and additional GPR data collection were led by Christine Downs and Sarah Kruse and supported by Sanaz Esmaeili, Sajad Jazayeri and ReNae Nowicki. Christine Downs processed the GPR and ER data and provided images and GPS data for use in this chapter. Jason LaRoche assisted in the interpretations of geophysical and other lithologic data. Caroline Masek provided editorial review.

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