The Peculiar Hydrology of West-Central Florida's Sandhill Wetlands, Ponds, and Lakes – Part 1: Physical & Chemical Evidence of Connectivity to a Regional Water-Supply Aquifer

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Abstract

The sandhill wetlands, ponds, and lakes of west-central Florida, USA, are an understudied, poorly understood variant of geographically isolated features. Their karst origin and xeric setting impart a characteristic ecohydrology, which is a function of their connectivity to a regional water-supply aquifer. This study describes their general hydrologic character and provides physical and chemical evidence of this connectivity. These findings advance fundamental understanding of sandhill wetland/water ecohydrology and endeavor to ensure their proper management and protection amidst increasing groundwater demands, ever-expanding development, and a changing climate.

Water level elevations and/or geochemistry were compared for 12 wetlands, five ponds, two lakes, and 12 monitor wells (10 constructed in limestone, two in surficial sand) in west-central Florida. Hydrograph and regression analyses indicate widely ranging water levels for most features and wells that are similar in elevation and very highly correlated with each other ($0.84 \leq R^2 \leq 0.99$). Water geochemistry varies from rainwater to water in contact with limestone as a function of feature depth relative to the depth of the rainwater-limestone water mixing zone. Results suggest sandhill wetland/water features are surface water expressions of the underlying regional aquifer hydrology, distinguishing them from isolated features elsewhere and establishing them as a groundwater endmember along the hydrologic continuum.

Background & Introduction

Geographically isolated wetlands (GIWs) and waters (i.e., ponds as lakes) are defined as aquatic islands in a terrestrial landscape (Edwards and Sharitz, 2000), those surrounded by upland (Tiner, 2003), and other definitions depending upon scale and perspective (e.g., ecological or hydrologic isolation, etc.) (Liebowitz and Nadeau, 2003). While not navigable or of commerce value (and thus not federally protected), they contribute valuable functions on the landscape including: flood storage, water table regulation, nutrient/sediment retention, and wildlife and aquatic habitat (Novitzki et al., 1996). Recent studies suggest they do this in aggregate as a complex or portfolio with other nearby wetlands and waters, collectively offering landscape support and benefitting downstream waters along a spatial and temporal continuum (Uden et al, 2014; Cohen et al, 2016; Nowicki, 2019). Tiner (2003) described GIWS as being among “America’s most valuable and threatened natural resources,” having suffered numerous losses and degradation from habitat destruction, altered hydrology, and water pollution, of which they continue to be at risk.

Understanding the hydrology of GIWs/waters is fundamental to their protection. For most, *local* factors—meteorological, geologic or both—control their hydrology. This is true for Carolina Bays along the Atlantic Coastal Plain (Lide et al., 1995); moraine, ice-scour, and kettle ponds in Alaska (Rains, 2011); playa wetlands across the Southern High Plains (Tsai et al., 2007); prairie potholes in the Upper Midwest (Hayashi et al., 2016); vernal pools in the Northeast and California (Brooks, 2004; Rains et al., 2006; Rains et al., 2008; O’Driscoll & Parizek, 2008;); and others. It also is true of many sandhill wetlands and waters in Nebraska (Ginsberg, 1985) and Florida (Jones Edmunds, 2006; CH2M Hill, 2005). But for a unique variant of GIWs/waters in west-central Florida, hydrologic control is *regional*, via connectivity to the Upper Floridan aquifer (hereafter U Fldn), which is part of the expansive Floridan aquifer system and one of the most productive aquifers in the world (Miller, 1990).

The hydrology of sandhill wetlands and waters of west-central Florida is not well studied. Short of work by Henderson (1986), which documents the close relationship between Hunter's Lake (one of this study's sites) and the regional groundwater system, little is documented of the hydrology of scores of other sandhill wetlands and waters dotting the landscape. This makes them particularly vulnerable to increasing groundwater demands, expanding residential and commercial development, and a changing climate.

This study is one of a pair of studies intended to improve understanding of the ecohydrology of Florida's sandhill wetlands and waters. In this study, water levels and water geochemistry from 12 wetlands, five ponds, and two lakes in west-central Florida are examined for connectivity to the U Fldn. The general hydrologic nature of sandhill wetlands and waters is described, with characteristic and uncharacteristic qualities noted to aid in their distinction from other types within their geographic range. In a companion study, geophysical exploration and lithologic data were used to develop conceptual models depicting: 1) the mechanisms of their hydraulic connection to the U Fldn; and 2) fundamental sandhill wetland and water ecohydrology (Nowicki et al., in review). The hydraulic connection of sandhill wetlands and waters to a regional aquifer distinguishes them from other GIWs/waters and establishes them as an endmember along the hydrologic continuum. This has important implications for natural resource management and for wetland and groundwater regulation.

Study Area

The study area includes portions of two west-central Florida counties, Hernando and Pasco, and two physiographic provinces, the Gulf Coastal Lowlands and Brooksville Ridge (White, 1970) (Fig. 1). Land surface elevations generally range from 1–30 m above sea level (NAVD 1988 datum) across the Gulf Coastal Lowlands (4–19 m at the wetlands/waters and monitor wells), with small relict dune features as high as 37 m. Land surface elevations generally range from 12–80 m (NAVD 1988 datum) across the Brooksville Ridge (14–35 m at the wetlands/waters and monitor wells).

Figure 1 Project study area with physiographic provinces (FDEP, 2018), sandhill habitat (FFWCC & FNAI, 2016), monitoring locations and regional (U Fldn) hydraulic gradient (FDEP, 2018)

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) to 2120 mm (SWFWMD Chassahowitzka gage WY 2003; SWFWMD Richloam Tower gage WY 2003) have been recorded at local gages, generally in association with drought and La Nina events or with tropical storm and El Nino events, respectively. Strong local rainfall variation exists whereby annual differences of 300 mm or more have been reported for gages within 1 km of each other (Hernando County Utilities Department [HCUD], unpublished data). 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).

Hydrogeologic Setting

The hydrogeology of the study area varies by physiographic province. In the Gulf Coastal Lowlands, the U Fldn occurs as a sequence of near-surface, highly transmissive karstic limestone that occasionally outcrops. It is overlain by a relatively thin overburden of unconsolidated sand with minor amounts of silt and clay and is considered regionally unconfined (Arthur et al., 2008; Basso, 2004). The absence of low-permeability sediments allows groundwater to move freely between the sand and limestone. The high permeability of the overburden allows little surface runoff, and recharge is relatively high.

In the Brooksville Ridge, low permeability clay sediments discontinuously lie between the limestone and mostly sand overburden. These clay sediments are remnants of the Hawthorn Group and are thickest along the central part of the province where land elevation is highest (Arthur et al., 2008). Although not expansive enough to confine the U Fldn, the clay sediments can produce locally perched water table conditions above it (Basso, 2004). The clay sediments thin away from the center (westward and eastward), becoming discontinuous or altogether absent.

The regional (U Fldn) hydraulic gradient (for the study area as a whole) is relatively gradual at approximately 0.3 m/km (May 2015 and varying over time, FDEP, 2018) (Fig. 1). The direction of the gradient is generally northwest.

Methods

Study Sites

Surface water elevations and geochemistry were evaluated from 12 wetlands, five ponds, and two lakes. (Ponds here are distinguished from wetlands in their permanent inundation and from lakes in their lack of wave action, Nowicki et al, in review.) Groundwater elevations and/or geochemistry were evaluated from shallow wells located in the interior of 10 of the wetlands and from 12 deeper monitor wells located in uplands, of which 10 were constructed within limestone and two were constructed within the overlying surficial sands. Five of the 12 wells were evaluated for their water level elevations, five for their water geochemistry and two for their water levels and geochemistry (Fig. 1). General site information and the type of analyses performed at each monitoring location are presented in Table 1.

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 #20005789.009, 2015) and are not evenly distributed among physiographic provinces (Fig. 1). The five non-regulatory wells, all constructed in limestone, were included in this evaluation to compare their water levels with those of the wetlands, ponds, and lakes. Unlike the other monitor wells, these wells are not adjacent to groundwater production wells and have lengthier, more consistent water level elevation records.

Monitor Well Construction

Groundwater data were measured and/or sampled from wells constructed in four settings: 1) surficial sands in wetland interiors; 2) surficial sands in uplands; 3) limestone in uplands adjacent to wetlands; and 3) limestone in uplands not adjacent to wetlands. Wells in wetland surficial sands were constructed of 5.1 cm inside diameter PVC, screened over the lower interval, and 1.0–3.0 m in total depth. Wells in upland surficial sands were constructed of 2.5–5.1 cm inside diameter PVC, screened over the lower interval, and 1.5–24 m in total depth. Wells in limestone (adjacent or not adjacent to wetlands) were constructed of 2.4–3.2 cm inside diameter stainless steel or PVC, with solid casing set to 20–78 m below the ground surface and just below the top of the limestone, and with open boreholes over the remaining limestone to total depths of 36–162 m.

Water Level and Rainfall Data Collection

Water level data obtained for most of the 19 wetlands, ponds, and lakes include two period-of-records (PORs) beginning in either 2002 (Gulf Coastal Lowlands sites) or 2008 (Brooksville Ridge sites) and both ending in 2018 (HCUD unpublished data) (Table 2). Data generally include twice monthly staff gage readings when surface water was present, or shallow monitor well readings when surface water was absent. Where both staff gage 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).

The PORs for groundwater level data for the five U Fldn water level monitor wells begin between 1967 and 2008 and end in 2018 (HCUD, unpublished data; Southwest Florida Water Management District [SWFWMD], 2018; USGS, 2018)). Data consist 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.

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 (Fig. 1) (Arguez et al., 2010).

Water Geochemistry Data Collection

Water geochemistry data were collected once each at the end of the 2015 dry and wet seasons (May/June and October, respectively). Parameters sampled include: field pH, specific conductance, and temperature; major ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, and SO_4^{2-}); and stable isotopes (^2H and ^{18}O). 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) (Fig. 2).

Figure 2 Water geochemistry sampling depths along vertical gradient at surface and groundwater monitoring locations

At the wetlands, ponds, and lakes, one or two surface-water samples were collected each season 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 collected at approximately 0.5 m below the top of the water column using the grab method. At the ponds and lakes (and one wetland) where water depth was greater than 2 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 4.5 m or 0.5 m above the bottom elevation, whichever was less. 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 wells, one to three groundwater samples were collected based on the total depth of the well (Fig. 2). At wells in surficial sands (screened only along the bottom intervals), one sample was collected approximately 0.3 m above the bottom of the well. At wells in limestone (open boreholes throughout all but the uppermost limestone), up to three samples were collected at 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. Samples were collected using a peristaltic pump or bailer. Pumped samples were collected directly into 500 mL HDPE containers; bailed samples were transferred to 500 mL hdp containers upon retrieval.

Field parameters—pH, temperature, and specific conductance—for both surface-water and groundwater samples were measured using a YSI 556 MPS or the equivalent (YSI Inc., Yellow Springs, Ohio, USA). Samples were then sealed and transferred to the mobile staging area. Samples to be analyzed for dissolved ions were filtered with a 0.45 micron filter and then transferred to separate 30–50 mL hdp containers and maintained at ± 4°C until analysis. Samples analyzed for cations were treated with nitric acid within 1 week of collection. Samples to be analyzed for stable isotopes were transferred to 30–50 mL hdp containers, completely filled and capped with both laboratory film and airtight caps to ensure isolation from the atmosphere. All sampling equipment was thoroughly rinsed with deionized water between samples.

Cation (Na^{+}, K^{+}, Mg^{2+}, Ca^{2+}) and anion (Cl^{-}, SO_4^{2-}) composition were determined at the University of South Florida's (USF) Center for Geochemical Analysis or at Advanced Environmental Laboratories, Inc. using a Perkin Elmer Optima 2000 DV ICP-OES or the equivalent. Alkalinity as bicarbonate (HCO_3^{-}) was then calculated as the missing ion using the modeling function in AquaChem (Waterloo Hydrogeologic, Inc., 2020). Stable isotope composition (^{2}H, ^{18}O) relative to the Vienna Standard Mean Ocean Water (VSMOW) was determined at USF's Stable Isotope Laboratory using a Picarro Cavity Ringdown Spectrometer, model L2130-i.

Water Level and Geochemistry Data Analyses

Water levels from wetland, pond, and lake features are compared to water levels from nearby monitor wells via hydrograph and linear regression analyses (Addinsoft, 2019). Water geochemistry is compared using scatterplots, piper diagrams, meteoric water lines (MWLs), Agglomerative Hierarchical Clustering (AHC) and multiple pairwise comparison tests. Scatterplots present field pH relative to specific conductance and to Ca^{2+} (Addinsoft, 2019). Piper diagrams depict water types based on major ion composition (e.g., calcium bicarbonate) (Waterloo, 2020). Global and local MWL plots relate isotopic data relative to a global rainfall standard according to the equation $\delta^2H = 8\,\delta^{18}O + 10$ (Craig, 1961). ^2H and ^{18}O values that plot along this line reflect global precipitation that has not evaporated (e.g., groundwater), while values that plot below the line generally reflect water enriched in heavy isotopes left behind after lighter isotopes evaporate (e.g., surface water). AHC explores the dissimilarity between samples by iteratively pairing them into clusters based on their least dissimilarity; it pairs clusters until the desired (or automatically generated) number is reached (Reddy, 2018). For this study: sample dissimilarity was based on collective specific conductance, Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, $SO^{2-}{}_4$, ^2H, and ^{18}O and measured as the Euclidian distance between objects; Ward's method was selected as the agglomeration method (Ward, 1963); and the final number of clusters was generated automatically. Kruskall-Wallace and Steel-Dwass-Critchlow-Fligner multiple pairwise comparison tests identify significant differences between sample groups for individual parameters (Addinsoft, 2019).

Results

Water Level Analyses

Hydrograph and regression analyses reveal two key characteristics of sandhill wetland/water hydrology: (1) their water levels range widely, both seasonally (0.5–2 m) and over their POR (2–5 m) (Tables 4a-b), increasing north to south and west to east along the regional hydraulic gradient (Fig. 1); and (2) water levels are synchronous and highly correlated to those of the U Fldn monitor wells (Brooksville Ridge features excluded) (Figs. 3a-b). At all but the Brooksville Ridge features, correlation 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. Coefficients at the Brooksville Ridge features are low (R^2 = 0.43 and 0.48), suggesting some other factor(s) explains most of their water level variation. The highest correlations are generally associated with features: distributed across both physiographic provinces; proximal to the monitor wells (generally within 3 km); smaller in area (generally 5 hectares or less); and represented by all three 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 = 0.84–0.98) (Table 3).

Closer inspection of feature-well water level synchronicity shows deviations occur as two basic types—an elevation offset and behavioral responses. An elevation offset is the median deviation between the feature and well water levels (Fig. 4a). It varies little over a feature's POR and may range from negligible (e.g., Croom Road Marsh) to more than 3 m (e.g., Norman Marsh), depending mostly on relative feature-well positions along the regional hydraulic gradient (Fig. 1). Elevation offsets are generally small for features and wells in close proximity and during periods of high or low recharge (i.e., when the gradient flattens between sites). In contrast, behavioral responses are numerous and vary in their magnitude, rate, and timing in response to rainfall or lack thereof (Fig. 4b). 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. In general, behavioral responses at the features (relative to the U Fldn monitor wells) show a lower *magnitude*, but similar *rate* of incline and a similar *onset*, but slower *rate* of decline (except during hydrologic highs, when onset lags, but rate is similar). The less the deviation in feature-well behavioral responses, the greater the synchronicity and correlation.

Deviations are examined more closely for three exemplar features (i.e., those expressing characteristically high correlation and low deviation) and three exceptional features (i.e., those with low correlation and high or unusual deviation) in Figs. 5a-c and 5d-f, respectively. Water levels at two of the exemplars exhibit near-perfect correlation (R^2 = 0.99), despite their stark hydrogeomorphic (and physiographic) differences. Croom Road Marsh is a very shallow, intermittently inundated wetland located along the eastern flank of the Brooksville Ridge, while Chapel Pond is a deep, permanently inundated pond located in the Gulf Coastal Lowlands (Fig. 1, Table 1). Water levels at Croom Road Marsh are nearly coincident with those of the U Fldn well, owing to a negligible elevation offset and minimal differences in behavioral response (Fig. 5a). Water levels at Chapel Pond deviate some from those of the U Fldn well, both in elevation offset (which is small, 0.1 m, compared to most other sites) and in behavioral responses (which also are small and similar to those described previously) (Figs. 4b, 5b). Water levels at the third exemplar, Ref 4—a moderately deep, seasonally inundated wetland in the Gulf Coastal Lowlands—are highly correlated with the nearby U Fldn well (R^2 = 0.92), but with a greater elevation offset and greater response deviations (Fig. 1, Table 1, Fig. 5b). The deviations are particularly noteworthy when wetland water levels shift between surface and shallow groundwater phases.

The hydrology of the three exceptional features show uncharacteristic deviations from the nearby U Fldn monitor wells (Figs. 5d-f). At Weeki Wachee Prairie—a large deep multi-pool wetland in the Gulf Coastal Lowlands (Fig. 1, Table 1)—water levels are highly correlated to the U Fldn well (R^2 = 0.88) and show behavioral responses consistent with those of the exemplar wetlands (Figs. 5d, 5a-c), but have an unexpectedly high elevation offset (up to 0.5 m or more) given the U Fldn well is in close proximity (at the wetland shoreline). Water levels at Banshee Pond—a deep, semi-permanently inundated wetland along the eastern flank of the Brooksville Ridge (Fig. 1, Table 1)—are dichotomous relative to water levels of the U Fldn well—exhibiting a high elevation offset (2 m) and low correlation (R^2 = 0.24) during low water periods and a lower elevation offset (1.2 m) and high correlation (R^2 = 0.92) during high water periods (Fig. 5e). Water levels at Sand Point Pond—a shallow, seasonally inundated wetland located along the central ridge of the Brooksville Ridge province (Fig. 1, Table 1)—expressed a very high elevation offset (12.5 m) and many behavioral response deviations that are inconsistent with those of the exemplar features, resulting in poor correlation with U Fldn water levels (R^2 = 0.43) (Figs. 5f, 5a-c).

Water Geochemistry Analyses

Findings from the geochemical analyses show water samples vary by *feature type* (wetland, pond, lake, or monitor well), by *water type* (surface water or groundwater from surficial sands or limestone), and/or by *season* (wet or dry).) (Tables 4a-b). Generally, surface water features are highest in temperature and heavy isotope enrichment (^{2}H and ^{18}O), while groundwater sampled from limestone is highest in pH, specific conductance, and all the major ions (Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, $SO^{2-}{}_4$, HCO_3^-) (Tables 4a-b). Surface water and groundwater sampled from shallower features (e.g., wetlands) tend to exhibit a rainwater geochemistry (i.e., low in pH, ions, and specific conductance), while surface water from deeper features (e.g., ponds and lakes) tend to exhibit a more mineralized chemistry (i.e., high pH, Ca^{2+} and/or specific conductance) similar to groundwater sampled from limestone (Figs. 6a-b).

Seasonal differences also are apparent, with most dry season samples (surface and groundwater) expressing a calcium-sodium-bicarbonate or sodium-calcium-bicarbonate water chemistry and most wet season samples expressing a calcium-bicarbonate chemistry (i.e., reduced sodium ion between seasons). Surface water and groundwater sampled from surficial sand generally become more acidic, less mineralized, less conductive, and less enriched in heavy isotopes (i.e., apparent dilution by recharge of unevaporated rainwater). In contrast, groundwater sampled from limestone becomes less acidic and more mineralized (Ca^{2+}) between seasons (i.e., apparent dilution by more mineralized water) (Tables 4a-b, Figs. 7–8).

Results from the isotope analyses are presented in Tables 4a-b and Fig. 8. Values for ^{2}H and ^{18}O are reported as the relative difference of heavy and light isotope ratios ($\delta\,^0/_{00}$). For the *dry* season, a clear demarcation is apparent between surface water samples, all of which are enriched in heavy isotopes ($\delta\,^2$H = + 2.6 to + 34.6 and $\delta\,^{18}$O = + 0.4 to + 7.9), and limestone water samples, all of which are depleted ($\delta\,^2$H = − 19.2 to − 11.9 and $\delta\,^{18}$O = − 4.0 to − 2.9) (Table 4a, Fig. 8). Surficial sand water samples were variable ($\delta\,^2$H = − 16.4 to + 13.4, $\delta\,^{18}$O = − 3.6 to + 2.5), showing isotope enrichment when collected from wetlands inundated at the time of sampling (R4, R8, WS) and isotope depletion when collected from wetlands that were not inundated (CrRi, CrRo, POM, SOP) and from uplands (M5, SH). For the *wet* season, results were more variable (Table 4b, Fig. 8). All groundwater samples—both surficial sand and limestone—were depleted in heavy isotopes ($\delta\,^2$H = − 18.6 to − 12.1, $\delta\,^{18}$O = − 3.9 to − 2.8) except for one limestone anomaly (WWP), which was enriched ($\delta\,^2$H = + 5.1, $\delta\,^{18}$O = + 0.93). Surface water samples varied ($\delta\,^2$H = − 19.7 to + 9.1, $\delta\,^{18}$O = − 4.0 to + 2.0)—those depleted in heavy isotopes were collected from (Brooksville

Ridge) features, which were inundated for only a short period prior to sampling, while those enriched were collected from (Gulf Coastal Lowlands) features, which were inundated much longer.

AHC analysis shows dry and wet season water samples were clustered into three and four classes, respectively (Fig. 9). Classification for both seasons is similar, with Class 1 representing only surface and 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 sample types and depths (i.e., endmember mixing class). Profile plots show specific conductance and Ca^{2+} as the most influential parameters in their agglomeration, followed by ^{2}H and sulfate $SO^{2-}{}_{4}$. Results from Kruskall-Wallace and Steel-Dwass-Critchlow-Fligner (multiple pairwise comparison) tests are consistent with the AHC and scatterplot analyses, indicating surface water from ponds and lakes (as a group) are not significantly different than groundwater from limestone (Table 5) (Addinsoft, 2019).

Discussion

From raised bogs (Large et al., 2007) and vernal pools (Schlising and Saunders, 1982; Rains et al., 2006) to fens (Wilcox et al., 1986) and Carolina bays (Lide et al., 1995), studies of GIWs have long characterized hydrologic control along a continuum of local forces, from precipitation to groundwater of a surficial aquifer. Few studies, however, document hydrologic control by groundwater of a regional aquifer. This study provides physical and chemical evidence that GIWs and waters in the sandhill of west-central Florida are hydraulically connected to the U Fldn—a large, regional water supply aquifer. This connection distinguishes the sandhill wetlands and waters of west-central Florida from most other GIWs and waters and places them at the far end of the hydrologic continuum (Fig. 10). These findings are important both to the field of wetland ecohydrology and to the proper identification, management and protection of these unique and vulnerable natural resources.

Figure 10 Sandhill wetlands as regional groundwater endmembers along a geographically isolated wetland hydrologic continuum

Characteristic Hydrology & Evidence of U-Fldn Connectivity

This study examines water levels and water geochemistry of sandhill wetlands and waters in west-central Florida. It documents their characteristic (and certain uncharacteristic) hydrologic attributes and compares them to those of the U Fldn as evidence (where applicable) of a hydraulic connection with the regional aquifer. The key *physical* attributes of sandhill wetland and water hydrology, as defined here, are widely ranging water levels (2–5 meters or more) that are synchronous with those of the U Fldn (Figs. 3a-b), deviating in consistent and predictable patterns (Figs. 4a-b), which result in very high correlations (84 $\leq R^2 \leq$ 99%) (Table 3). Within these attributes, sandhill wetlands and waters may vary markedly in their hydrologic expression—from small, shallow elliptical wetlands that remain dry for years (e.g., Croom Road

Marsh, Figs. 1 and 5a) to deep circular ponds and large amorphous lakes that maintain permanent inundation (e.g., Capuchin Pond and Hunter's Lake, Figs. 1 and 5b, respectively). Each of these features, though markedly different in expression, are exemplars of the sandhill type.

Findings here expand on a study by Henderson (1986), which shows similar behavior and correlations ($80 \leq R^2 \leq 87\%$) between a lake in this study (Hunter's Lake) and nearby U Fldn monitor wells and between that lake and a wetland in this study (Weeki Wachee Prairie). Similarly widely ranging water levels and "sympathetic fluctuations" between potential sandhill waters elsewhere in the state were reported by others (Deevey, 1988), but these features are not hydraulically connected to the U Fldn, nor does it control their hydrology (Sacks et al., 1998; and Swancar et al, 2003).

Geochemical attributes are more variable than the *physical* attributes. Most features express a predominantly calcium-bicarbonate water type (or sodium-calcium/calcium-sodium bicarbonate) similar to the limestone water samples (Fig. 7, Tables 4a-b), but vary in their specific conductance, Ca^{2+} and/or pH. In many shallow features (e.g., wetlands), specific conductance, Ca^{2+} and/or pH are low and reflective of rainwater chemistry. In many deep features (e.g., lakes and ponds), these attributes are elevated, reflective of mineralized water in contact with limestone (Figs. 6a-b). In the remaining features (wetlands, ponds, and lakes included), the attributes are intermediate, suggesting a mix of the rainwater and limestone water types.

Some of the features with intermediate or elevated Ca^{2+} are proximal to sources of leachate (e.g., septic fields and fertilized lawns or agricultural areas irrigated with groundwater). It is plausible their higher values are artificially inflated by the leachate. Two sites provide evidence of a naturally high source of Ca^{2+}. At one wetland (String of Pearls Marsh, SOP) located in the middle of a state forest outside the influence of cultural leachate, Ca^{2+} in the shallow groundwater is elevated (22 mg/L) in the wet season and intermediate (3.9 mg/L) in the dry season (Fig. 6b). With no artificial source of Ca^{2+}, one may conclude its higher Ca^{2+} is due to mixing with water residing in limestone. At Hunter's Lake (HL), which is located in a residential area with irrigated lawns and septic fields, Ca^{2+} values in the surface water are elevated (13–17 mg/L, dry and wet seasons) (Fig. 6b). Historical data show these values were comparably elevated in the 1980s (14–26 mg/L) following near build-out of the area, but were lower (6–7 mg/L) in the mid-1960s before the onset of development (Henderson, 1986). The intermediate values of the pre-development period may suggest the lake water is naturally high in Ca^{2+} but is made higher by the leachate. Historical data are not available for the other features with intermediate or elevated Ca^{2+}, but it is possible they too have naturally higher Ca^{2+} due to their connection to water residing in limestone, and that water also may be enhanced by cultural leachate from adjacent residential areas.

The low specific conductance, Ca^{2+}, and/or pH at the other wetlands and ponds (BP, CaPo, CrRi, CrRo, ESP, R4, R8) do not negate their connectivity to the U Fldn. These features simply do not intersect that part of the U Fldn that contains water residing in (or formerly in contact with) limestone. Water in the U Fldn is chemically stratified into an upper rainwater lens residing in the surficial sands, a lower body of

Ca^{2+}-rich water residing in the limestone, and a transitional, or mixing, zone in between (Fig. 11). The position of the mixing zone, which is controlled by the expansion and shrinking of the rainwater lens, and the depth of the features determine what type of water chemistry the features will have. Water in features that are not deep enough to intercept the mixing zone will maintain the chemistry of the rainwater lens. Water in features that are deep enough to intercept the mixing zone (or the limestone water itself) will reflect a mixed rainwater-limestone (or limestone water) chemistry.

Figure 11 Conceptual model of generalized sandhill wetland & water geochemistry

Uncharacteristic Hydrology & Unexpected Findings

Four features in this study are considered exceptional for their uncharacteristic or unexpected water level behavior. At Sand Point Pond, the elevation offset (relative to the ROMP 107 U Fldn monitor well) is markedly high (12.5 m) and the correlation markedly low (R^2 = 0.43) (Figs. 3b and 5f). At Perry Oldenburg Marsh, the elevation offset (relative to the WR-6b Shallow U Fldn monitor well) is much less (0.12 m), but this value is artificially low considering the 3 m drop in head that occurs along the regional hydraulic gradient between the well and wetland (see contour elevations, Fig. 1). More importantly, the offset is highly variable over the POR, and the correlation is very low (R^2 = 0.48) (Fig. 3b). Water levels at both wetlands appear to be perched, with no connectivity to the U Fldn. The presence of remnant clay along the Brooksville Ridge (where both wetlands are located), creates the opportunity for perching. For their lack of connectivity to or hydrologic control by the U Fldn, neither wetland would be considered of the sandhill type.

At Banshee Pond, wetland water levels were unexpectedly dichotomous relative to those of the U Fldn—synchronous during periods of high water, but not low water (Fig. 5e). Physical evidence of historical excavation is present on site and is believed to have deepened the wetland bottom into the limestone residuum, which is typically found at depth. This would have not only increased the hydroperiod of the wetland (from intermittent to semi-permanent), but also altered the way surface water drains from it. The now near-surface residuum, which has a clayey texture, is believed to perch surface water at a certain threshold elevation (at or around 13.5 m), disconnecting it from the U Fldn water table as it drains. As the water table rises above the threshold, it converges with the perched surface water and they reconnect. This is evident in the hydrograph where both the elevation offset and correlation coefficient shift markedly between the low and high water periods. This wetland would still be considered a sandhill wetland, but with a modified hydrology due to excavation. Sandhill wetlands/waters of Florida have historically been excavated to capture stormwater and to increase hydroperiods for aesthetic or agricultural purposes, increasing the possibility of scenarios like this at other locations of similar geology.

At Weeki Wachee Prairie, the elevation offset relative to the U Fldn monitor well (WWP) was unexpectedly high (0.5 m) (Fig. 5d). The offset is fairly consistent across the POR, and the water levels are highly correlated (R^2 = 0.88), as is typical for sandhill wetlands; but considering the wetland and well share the same position along the regional hydraulic gradient, a lower offset was anticipated. Such is the case at Hunter's Lake whose U Fldn monitor well (HUNT) also sits at the shoreline, and where the elevation offset is comparatively small (0.2 m). The study by Henderson (1986), which describes the close relationship between Hunter's Lake and the U Fldn, may help explain this. Henderson describes both features as flow-through systems, where groundwater enters from one side and leaves from another. At Hunter's Lake, the U Fldn well is located on the up-gradient shoreline where U Fldn water table contours are gradual and translate to a smaller offset; on the down-gradient shoreline, the contours are steeper and translate to a larger offset. At Weeki Wachee Prairie, the U Fldn well is (presumably) located on the down-gradient shoreline, where contours may be similarly steep. Detailed contours are not available to confirm this, but similar to Hunter's Lake, Weeki Wachee Prairie is a large feature situated at the base of a parabolic dune train (Upchurch et al, 2018) and may be subject to similar local gradients. Only at Hunter's Lake and Weeki Wachee Prairie are the U Fldn wells located at the shorelines. Monitor wells evaluated for all other features are located 1–10 km away because adjacent wells do not exist. Water levels at these more distant wells may better reflect the regional groundwater flow system because they are not subject to the local complexities and vertical gradients that are created by the surface water features themselves.

Of added intrigue, although neither characteristic nor uncharacteristic of sandhill wetlands, is a rarely noted phenomenon called the Lisse Effect, which appears to occur at the three smaller wetlands where organic material accrues above the sandy bottom (e.g., Ref 4, Ref 8, String of Pearls Marsh) (Nowicki et al, unpublished field data). The Lisse Effect occurs in response to intense rainfall, which inundates the wetland so rapidly it traps air beneath the soil wetting front. The trapped air builds up pressure, which artificially raises the head in the shallow monitor well. 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 (Heliotis et al., 1987; Weeks, 2002). On a hydrograph, this would produce a zig-zag response in shallow groundwater levels as is shown in Fig. 12. This phenomenon is not well documented and may help explain some of the residual variation between water levels at these wetlands and the U Fldn.

Figure 12 Apparent Lisse effect in shallow groundwater levels at wetland Ref 4. The zig-zag pattern, represented by a spike and dip in the shallow groundwater levels may represent the rarely noted Lisse Effect. This occurs when intense rainfall seals the surface and builds up pressure in the monitor well. The pressure creates an artificial rise in head in the well, which equilibrates shortly after to reflect actual recharge (Heliotis et al., 1987; Weeks, 2002)

Differences in residual variation among features also may be related to factors inherent to them (e.g., size, shape, and depth) and their situation (e.g., antecedent conditions, landscape setting, adjacent land use/land cover, and rainfall intensity/duration). The effects of these factors may be greatest at: 1) the larger lakes and wetlands (e.g., Tooke Lake, Willow Sink) whose greater surface areas may contribute greater losses to evaporation and whose longer shorelines may contribute more opportunities for surface water-groundwater exchange (Wetzel, 2001; Lee et al., 1997); and 2) the seasonally inundated wetlands (e.g., Ref 4, Ref 8, String of Pearls Marsh), where water more frequently shifts between surface water and shallow groundwater phases and where accumulation of organic material may slow or speed losses to leakage or evapotranspiration, respectively. The relative simplicity of the ponds (i.e., smaller size, simpler shape, and single surface water phase) may explain why their residual variation is least among feature types. Similarly, the smaller size, simpler shape, and largely groundwater phase at Croom Road Marsh may explain its near perfect water level correlation with that of the WR-6b Shallow U Fldn monitor well. For this wetland, its close proximity to the monitor well (< 1 km) is likely a proxy for hydrogeologic similarity, which is believed to be among the most important factors contributing to the strong correlation between their water levels.

Conclusions

The peculiarity of the sandhill wetland/water features of west-central Florida lies in their connectivity to the regional water table. It is the reason for their widely ranging hydrologic cycles (4–10 years or longer) and sometimes depauperate ecological expression—natural characteristics that have spurred speculation and misunderstanding, with consequences to impact assessments and boundary determinations. Research presented here is intended to account for their unusual ecohydrologic behavior and confirm their connection to the regional aquifer.

This study is among the first to characterize sandhill wetland/water hydrology, which may assist in their identification and distinction from other seemingly similar types. Key findings show that sandhill wetland/water levels range widely (up to 5 m) and are similar in elevation and very highly correlated to the regional water table. Findings also show that connectivity to the regional aquifer does not guarantee a mineralized chemistry as might be expected. While the chemistry of deeper features (including many lakes and ponds) is mineralized, the chemistry of most shallow features (wetlands) reflects that of rainwater. This is not because shallow features are not connected to the regional aquifer, but because they sit within its upper sandy part, which contains the rainwater lens—above the depth where rainwater mixes with water residing in limestone.

The unique connectivity of sandhill wetlands and waters to the regional aquifer distinguishes them from other GIWs and waters and places them at the far end of the hydrologic source continuum. The scarcity of sandhill wetland/water hydrologic (and ecological) studies exposes them to potential impacts and losses at a time when residential development is rampant, groundwater production increases in response, and a changing climate promise uncertain challenges. While Florida's GIWs/waters are protected at the state-level, the peculiar ecohydrology of sandhill wetlands and waters limits the application of widely used regulatory assessment methods. Findings here are intended as a first-step to advance general knowledge of their unique character—regionally, to support the development of assessment methods more specific to their nature and globally, to benefit others studying hydrologic controls of GIWs/waters in other xeric communities or karst terrain.

Declarations

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Conflicts of interest/Competing interests

Not applicable.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable

Authors' contributions

MR and RN contributed to the study conception and design. Material preparation and field data collection were performed by RN, MR, and JL. MP provided geochemical review and analytical support. The first draft of the manuscript was written by RN, with support from JL and MR. All authors read and approved the final manuscript.

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Tables

Due to technical limitations, table 1 to 5 is only available as a download in the Supplemental Files section.

Figures

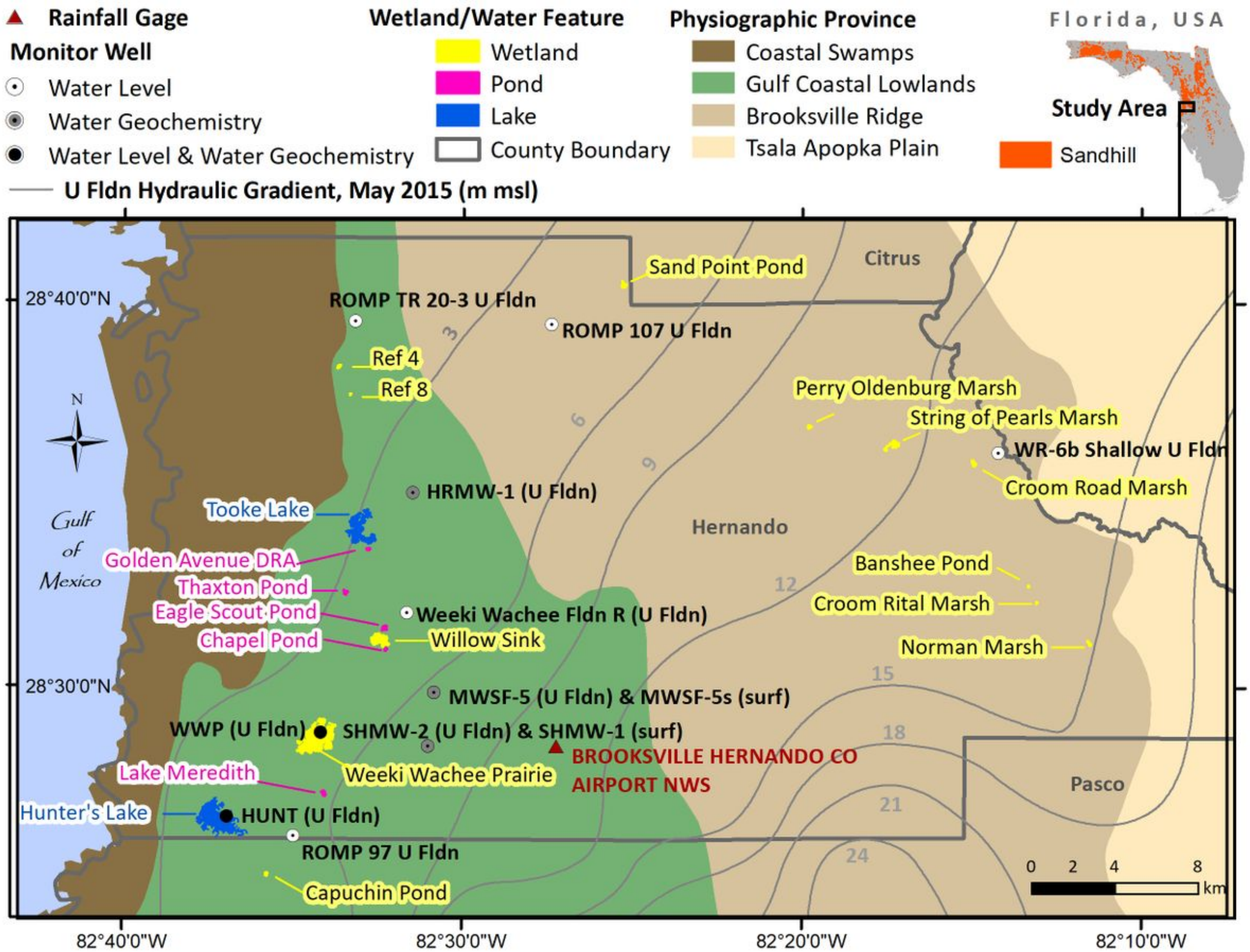


Figure 1

Project study area with physiographic provinces (FDEP, 2018), sandhill habitat (FFWCC & FNAI, 2016), monitoring locations and regional (U Fldn) hydraulic gradient (FDEP, 2018) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

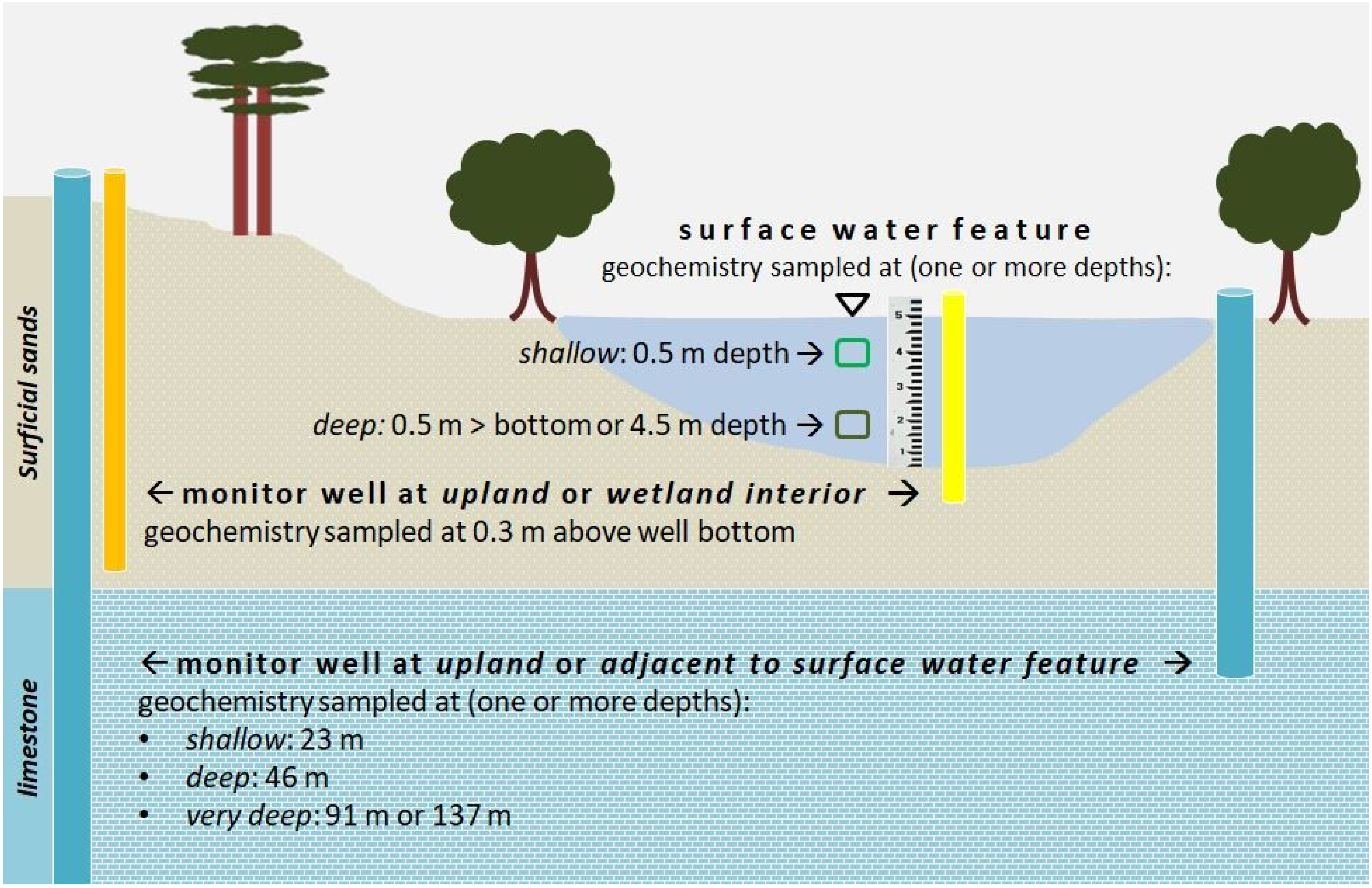


Figure 2

Water geochemistry sampling depths along vertical gradient at surface and groundwater monitoring locations

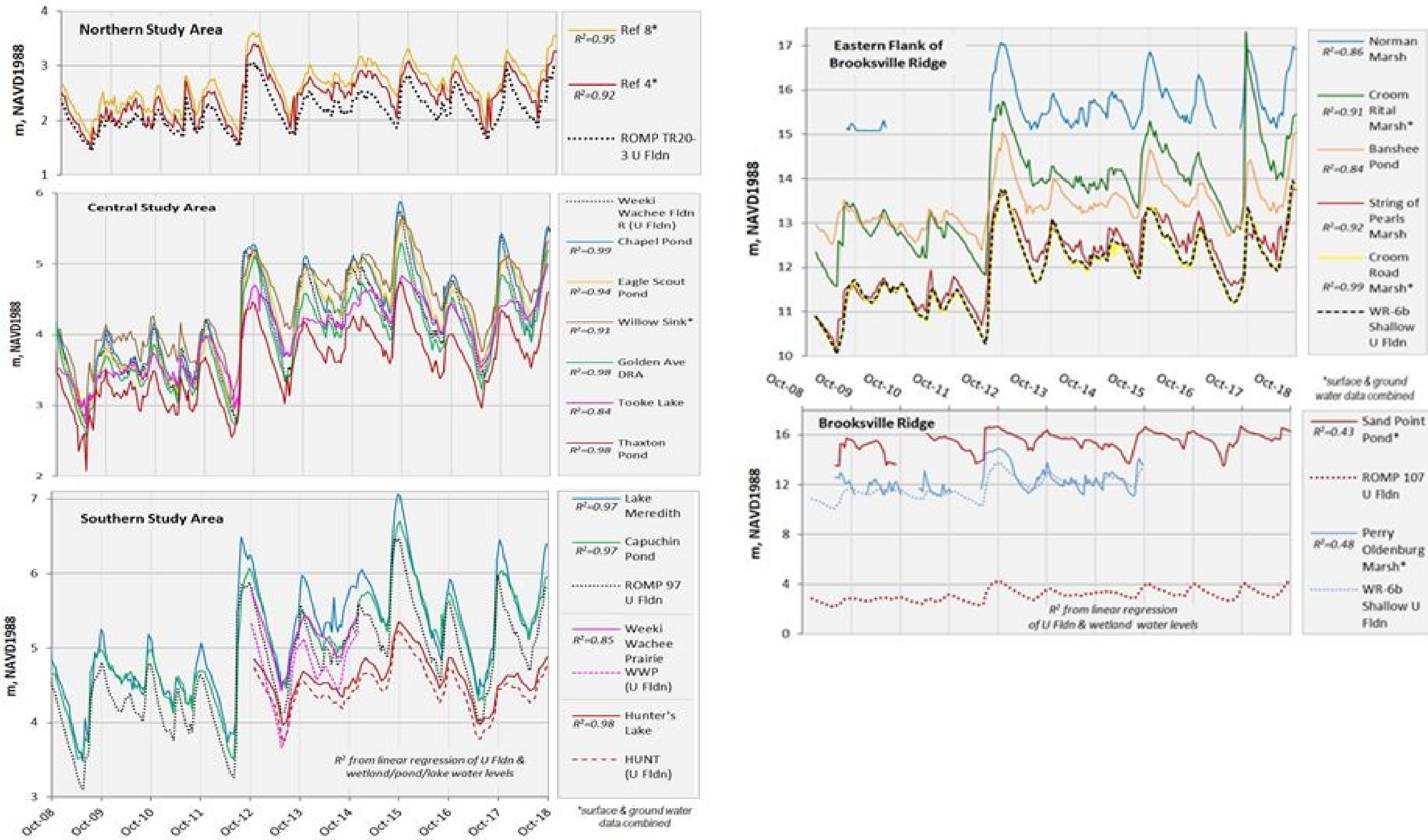
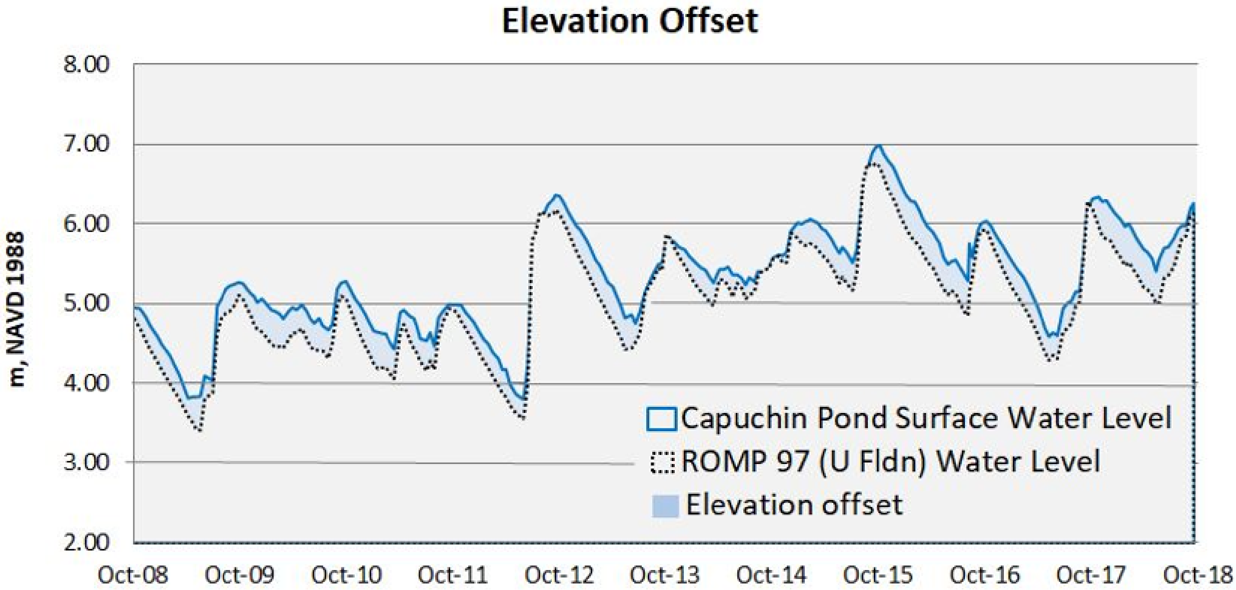


Figure 3

a Hydrographs of wetland/water features and U Fldn monitor wells of the Gulf Coastal Lowlands physiographic province (northern, central and southern parts of the study area). For clarity, only the most recent 10 of the 6- to 52-year PORs are shown b Hydrographs of wetland/water features and U Fldn monitor wells of the Brooksville Ridge physiographic province (eastern flank and atop the Ridge feature itself). For clarity, only the most recent 10 of the 6- to 52-year PORs are shown



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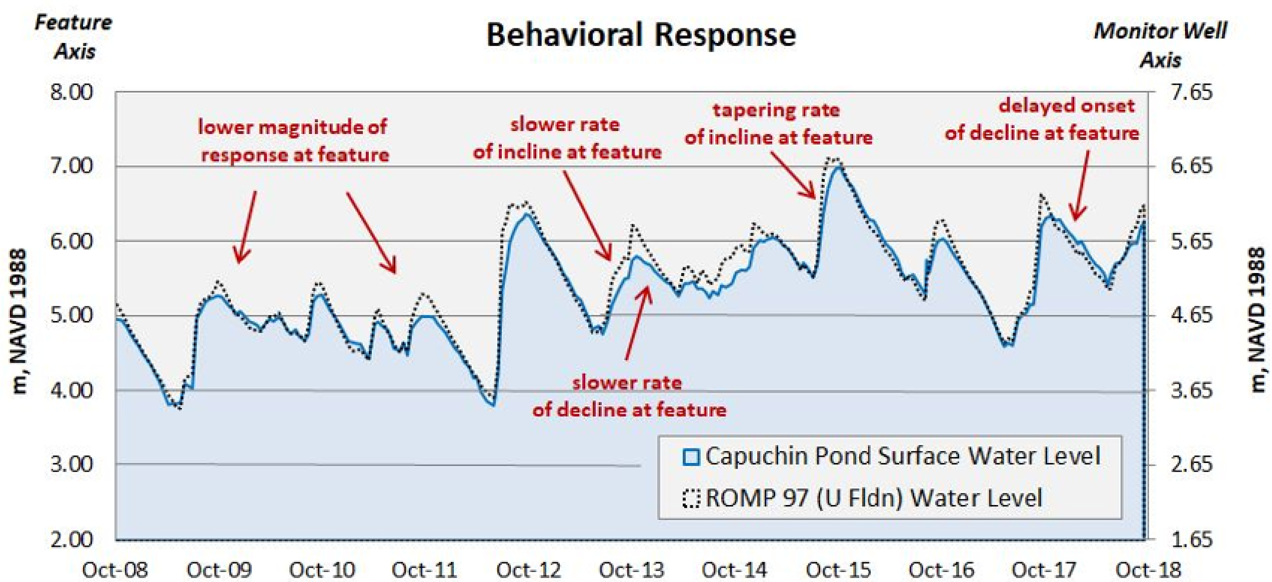


B

Figure 4

a Elevation offset example between a sandhill wetland (Capuchin Pond) and a nearby monitor well (ROMP 97 U Fldn). Note the offset is fairly consistent over time b Behavioral response deviations example between a sandhill wetland (Capuchin Pond) and a nearby monitor well (ROMP 97 U Fldn). The elevation offset has been adjusted (note different vertical axes) to highlight these deviations. Note that while numerous deviations may occur for a given site, the general patterns are consistent across the POR

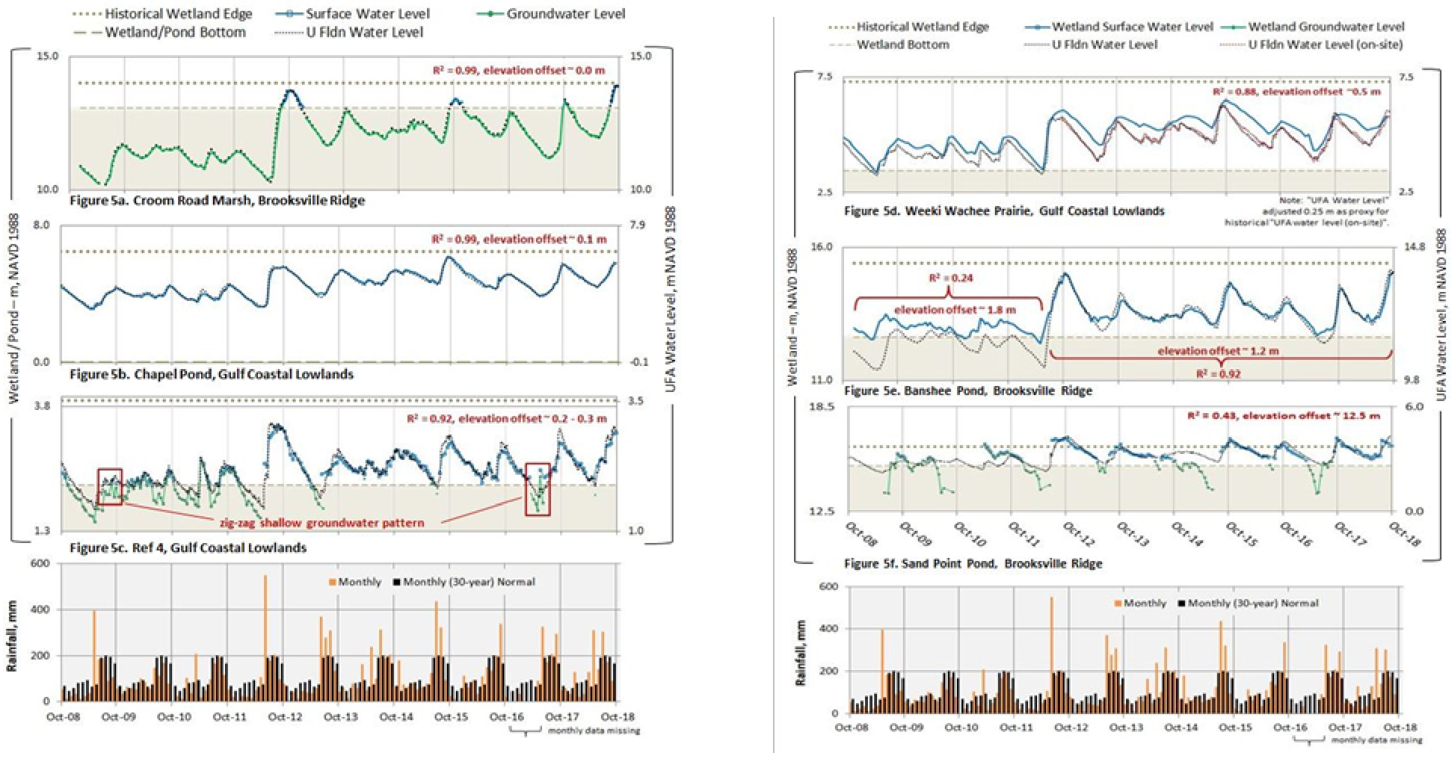


Figure 5

a-c Hydrographs of exemplar wetland & water features (i.e., those with high correlation/low deviation relative to U Fldn). Note U Fldn monitor well water levels (right axis) are adjusted relative to wetland water levels (left axis) to remove elevation offsets (where present) and highlight behavioral responses 5a Shallow, intermittently inundated sandhill wetland (Croom Road Marsh) and nearby U Fldn well (WR-6) with negligible elevation offset and minimal behavioral response deviations b Deep, permanently inundated sandhill pond (Chapel Pond) and nearby U Fldn well (WW FLDN) with small elevation offset and small behavioral response deviations typical for sandhill features c Seasonally inundated sandhill wetland (Ref 4) and nearby U Fldn monitor well (ROMP TR20-3) with somewhat higher elevation offsets (0.2–0.3 m, surface water and shallow groundwater, respectively) and typical behavioral responses. Highlighted is periodic zig-zag pattern potentially representing the Lisse Effect (Heliotis et al., 1987; Weeks, 2002) d-f Hydrographs of exceptional wetland & water features (i.e., unusual or with low correlation and high deviation relative to U Fldn). Note monitor well water levels (right axis) are adjusted relative to wetland water levels (left axis) to remove elevation offsets (where present) and highlight behavioral responses 5d Large, multi-pool sandhill wetland (Weeki Wachee Prairie) with U Fldn monitor well (WWP) at shoreline and more distant U Fldn monitor well (WW Fldn). Here, the elevation offset (0.5 m) is unexpectedly high, but behavioral responses are typical for sandhill features. (Note, water levels from the nearby (WW Fldn) well were used as a proxy for the WWP well in the early POR e Deep, semi-permanently inundated sandhill wetland (Banshee Pond) and nearby U Fldn monitor well (WR-6b). Note the dichotomous elevation offset and behavioral response deviations between low and high water level periods 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 (R2 = 0.43) and behavioral responses not typical of sandhill features

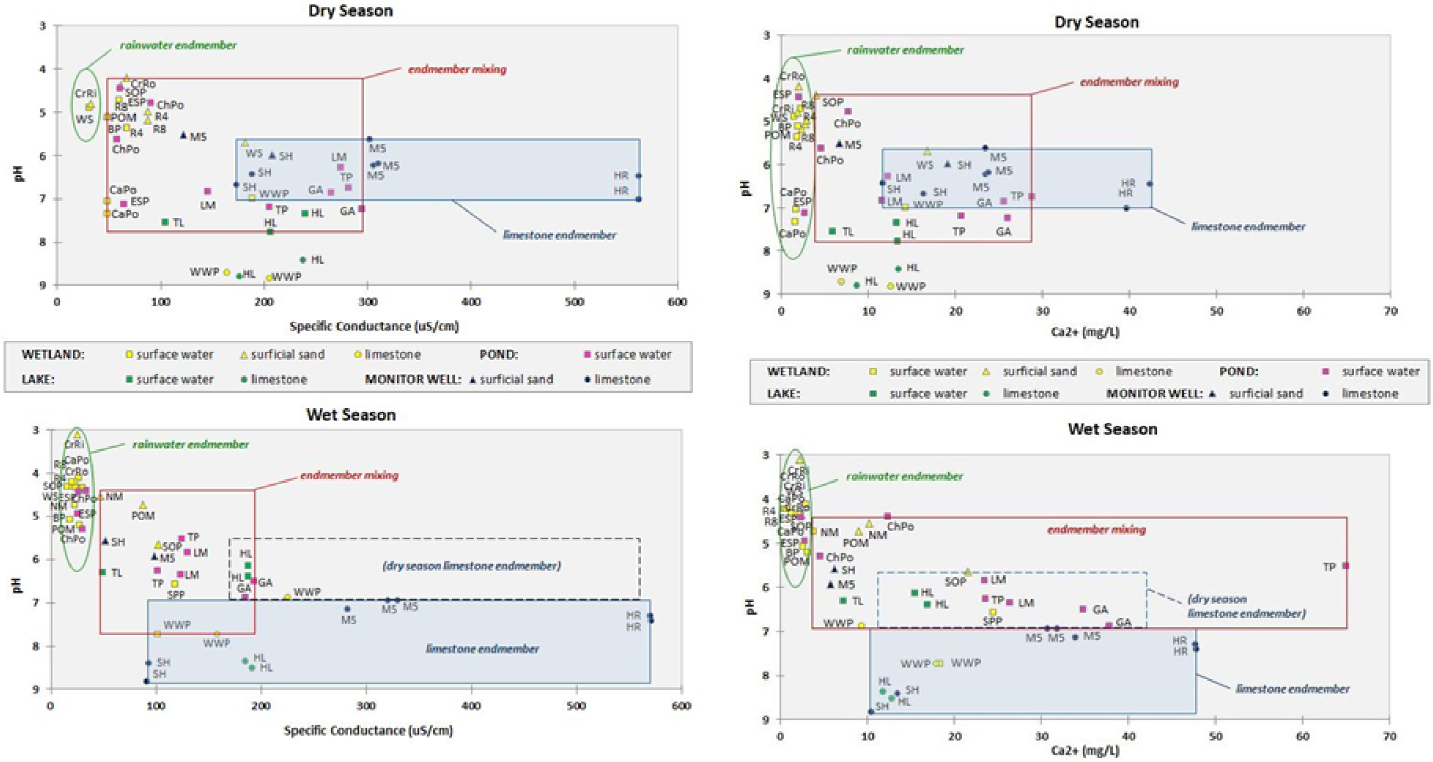


Figure 6

a 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, limestone water samples collected 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) b 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

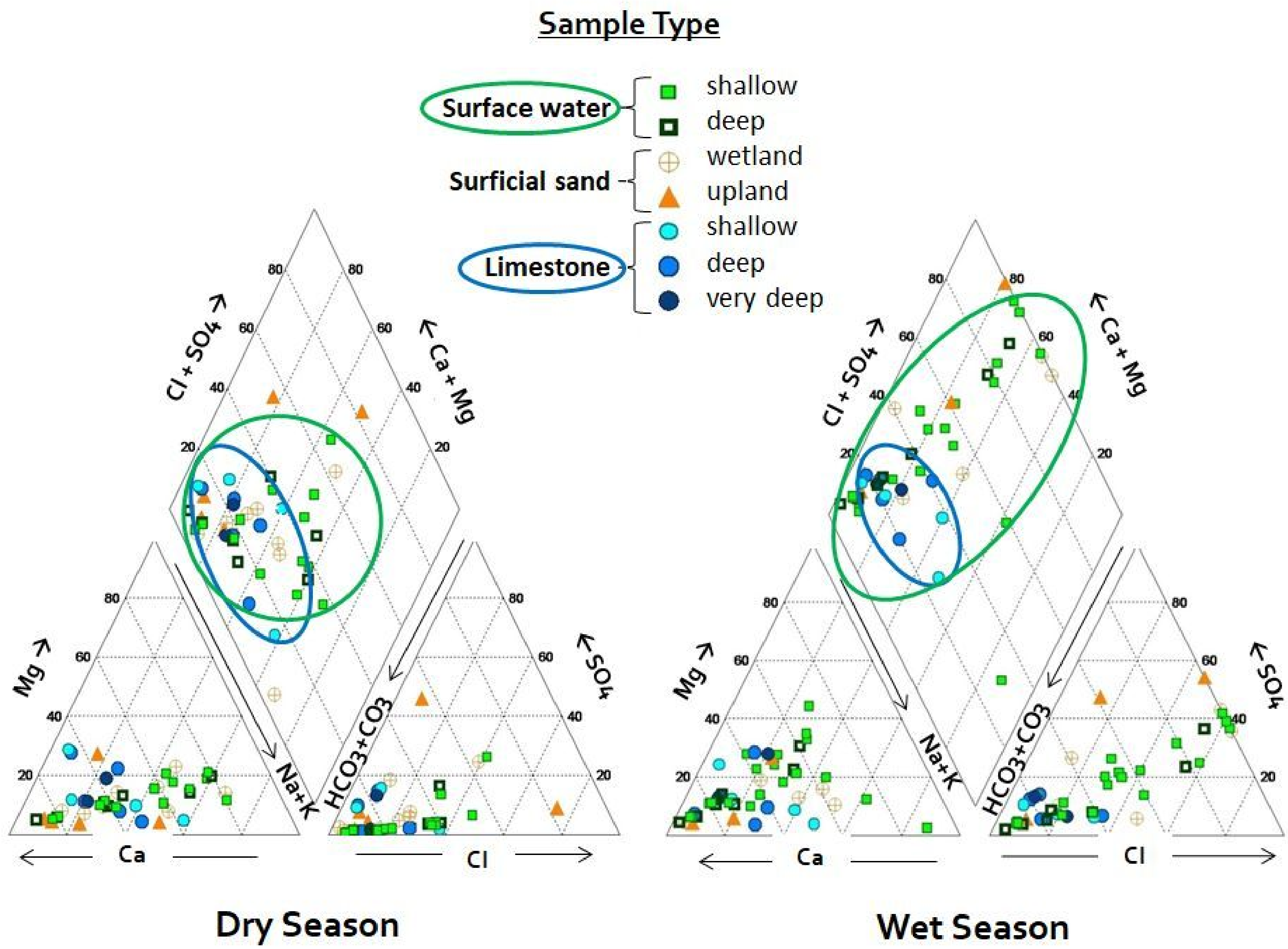


Figure 7

Piper diagrams for dry and wet season water samples along vertical gradient. Note most samples reflect a calcium-bicarbonate (with or without sodium) water type

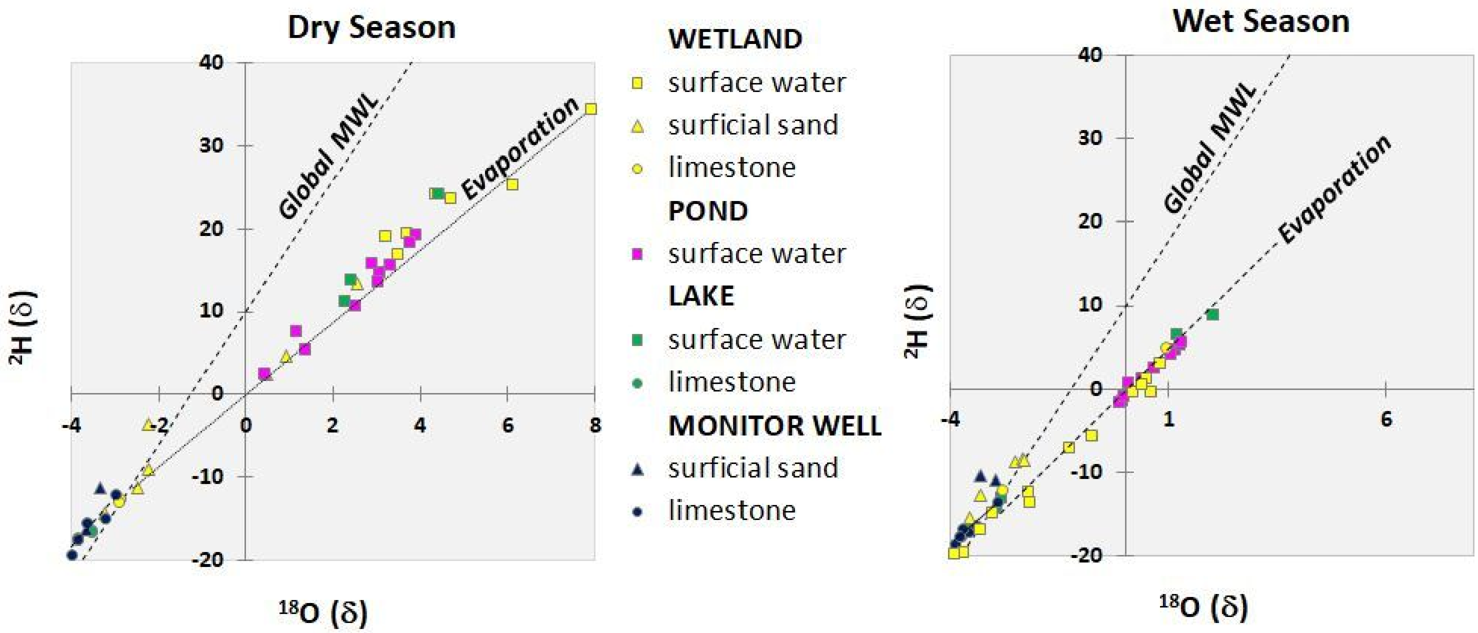
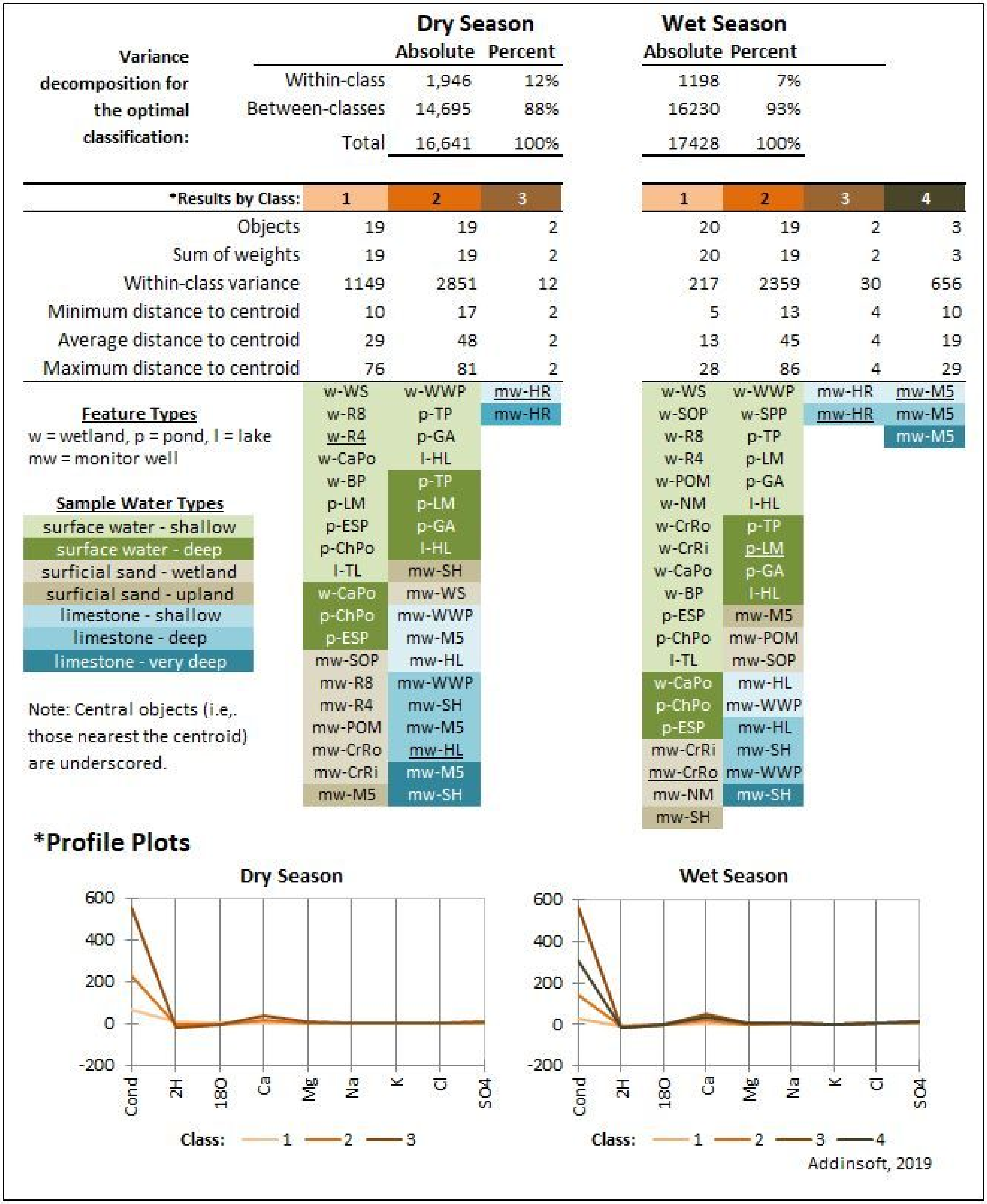


Figure 8

Local and Global Meteoric Water Lines (MWLs) for dry and wet season water samples. Overall, results indicate enrichment of heavy isotopes (2H and 18O) in most surface water samples and depletion in most groundwater samples (surficial sand and limestone), with an overall reduction of heavy isotope enrichment between seasons due to dilution by fresh, unevaporated rainwater



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

Dry 1	Dry 2	Dry 3	Wet 1	Wet 2	Wet 3	Wet 4
w-WS	w-WWP	mw-HR	w-WS	w-WWP	mw-HR	mw-M5
w-R8	p-TP	mw-HR	w-SOP	w-SPP	mw-HR	mw-M5
w-R4	p-GA		w-R8	p-TP		mw-M5
w-CaPo	l-HL		w-R4	p-LM		
w-BP	p-TP		w-POM	p-GA		
p-LM	p-LM		w-NM	l-HL		
p-ESP	p-GA		w-CrRo	p-TP		
p-ChPo	l-HL		w-CrRi	p-LM		
l-TL	mw-SH		w-CaPo	p-GA		
w-CaPo	mw-WS		w-BP	l-HL		
p-ChPo	mw-WWP		p-ESP	mw-M5		
p-ESP	mw-M5		p-ChPo	mw-POM		
mw-SOP	mw-HL		l-TL	mw-SOP		
mw-R8	mw-WWP		w-CaPo	mw-HL		
mw-R4	mw-SH		p-ChPo	mw-WWP		
mw-POM	mw-M5		p-ESP	mw-HL		
mw-CrRo	mw-HL		mw-CrRi	mw-SH		
mw-CrRi	mw-M5		mw-CrRo	mw-WWP		
mw-M5	mw-SH		mw-NM	mw-SH		
			mw-SH			

Figure 9

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/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 all chemistry types, suggesting rainwater-limestone water mixing. The profile plots identify specific conductance and calcium (Ca2+) as the most influential parameters in generating these groupings, followed by 2H and SO2-4

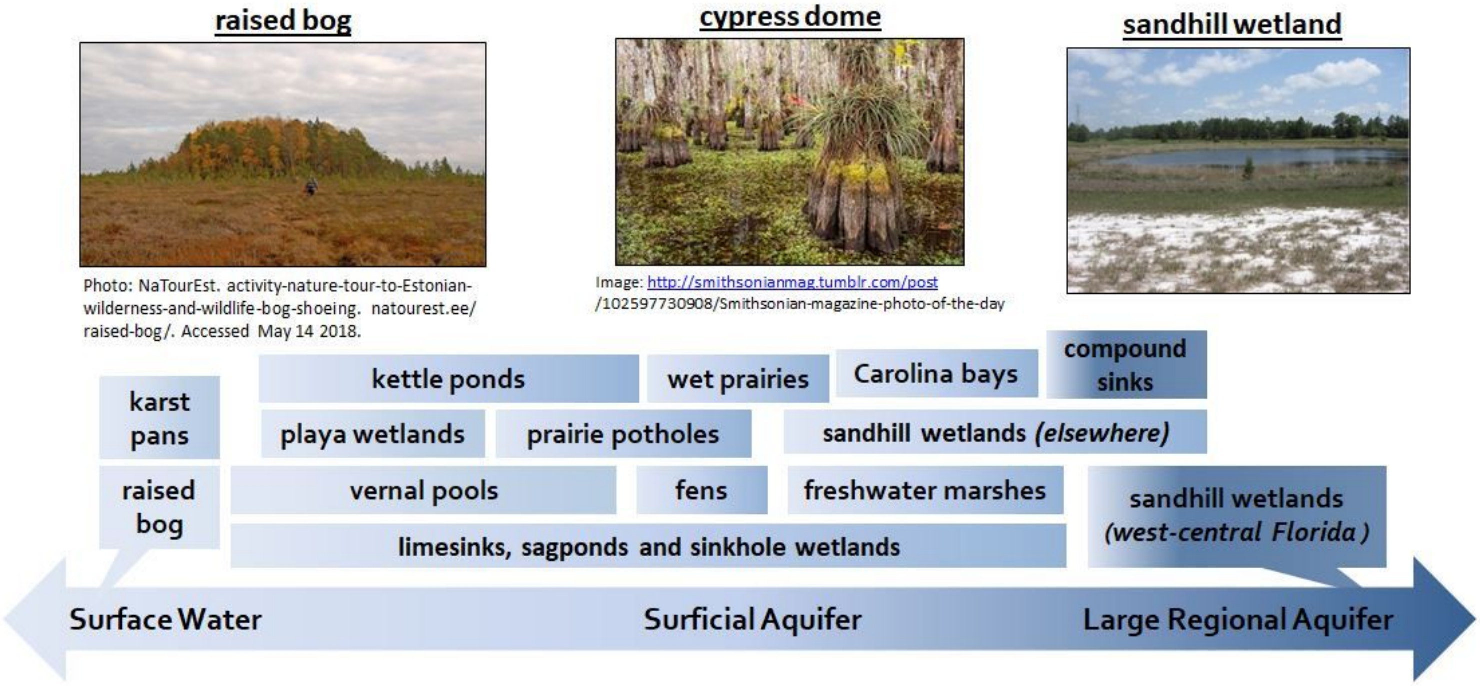


Figure 10

Sandhill wetlands as regional groundwater endmembers along a geographically isolated wetland hydrologic continuum

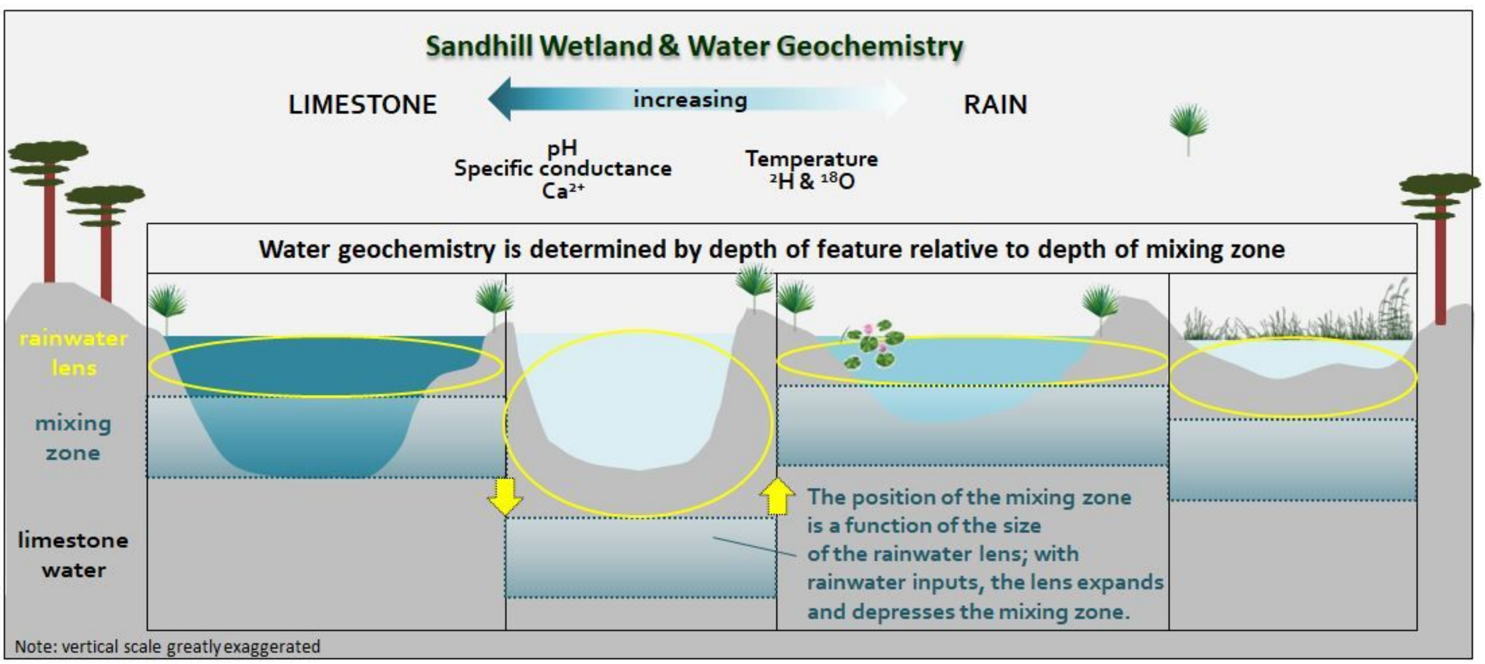


Figure 11

Conceptual model of generalized sandhill wetland & water geochemistry

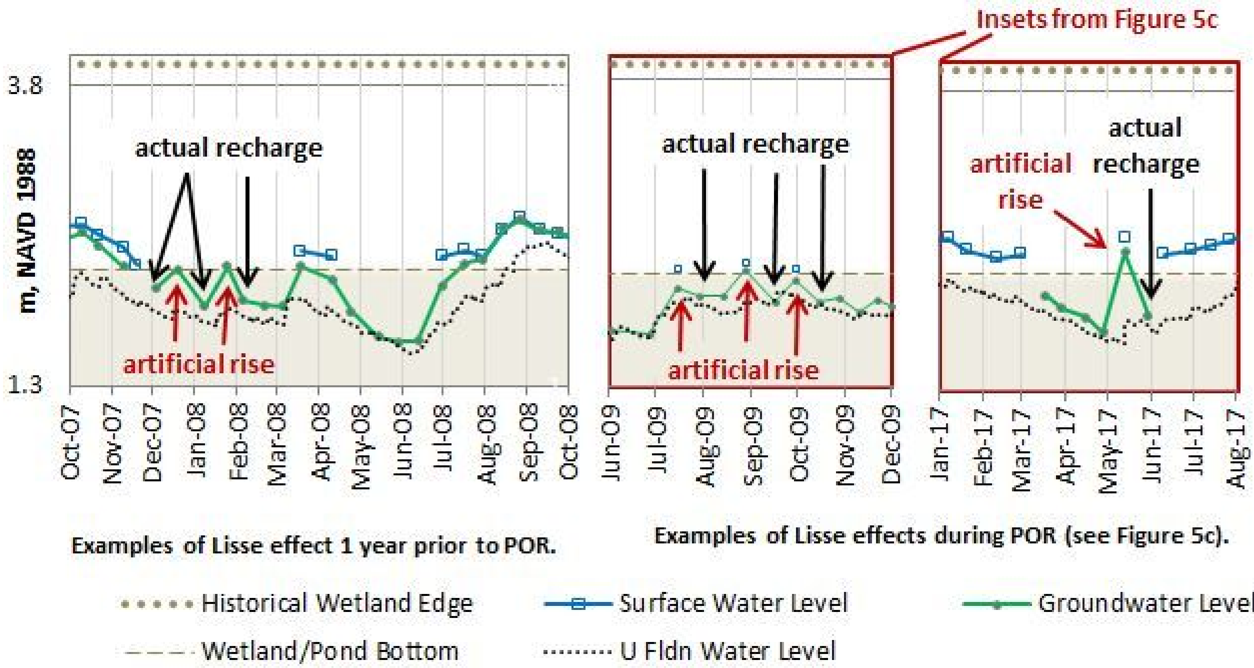


Figure 12

Apparent Lisse effect in shallow groundwater levels at wetland Ref 4. The zig-zag pattern, represented by a spike and dip in the shallow groundwater levels may represent the rarely noted Lisse Effect. This occurs when intense rainfall seals the surface and builds up pressure in the monitor well. The pressure creates an artificial rise in head in the well, which equilibrates shortly after to reflect actual recharge (Heliotis et al., 1987; Weeks, 2002)

Supplementary Files

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- 4PeculiarHydro1of2NowickiEtAlTABLES.docx