Natural Resources Conservation Service
U.S. DEPARTMENT OF AGRICULTURE

Storage and Release of Water in Coastal Plain Wetlandscapes

Conservation Effects Assessment Project (CEAP) Conservation Insight

Wetlands provide a suite of ecosystem services, including fish and wildlife habitat, microclimate regulation, nutrient and sediment capture and storage, water storage to reduce flooding, and carbon storage with resulting benefits for climate change mitigation. The scope of these services may be significantly affected by variations in connectivity across wetlandscapes. The U.S. Department of Agriculture's Conservation Effects Assessment Project (CEAP), in partnership with the University of Florida, assessed the hydrology of wetlands across four coastal plain landscapes in Florida to further understand hydrological exchanges among wetlands and the effects of surface connectivity and spatial variation in surface connectivity patterns. Findings can be used to inform management decisions for a diversity of wetlandscapes and support conservation prioritization to effectively maintain ecosystem services provided by wetlands.

Key Takeaways

- Wetlands in coastal plain landscapes are often only intermittently connected by surface water flow.
- While numerous studies have demonstrated the importance of depressional wetlands in the landscape, the frequency, duration, and relative importance of surface and subsurface connections between these wetlands remains poorly understood, limiting quantification of their landscape functions.
- To understand the dynamic hydrology of these systems, water levels were simultaneously monitored in multiple wetlands and the timing, duration, and extent of surface connectivity among wetlands inferred from inflection points in recession rates as a function of stage.
- Findings from four contrasting coastal plain wetlandscapes in Florida show that hydrological exchanges among wetlands increase five-fold when connected via surface pathways.
- This landscape-scale study highlights the heterogeneity of aggregated fill and spill patterns that is unlikely to be identified from individual wetland-scale analyses.
- Maintenance of this heterogeneity in wetland fill and spill patterns is important for conservation of landscape functions including the provision of wildlife habitat, biogeochemical processing, nutrient retention, and contributions to downstream flows.

Background

Wetlandscapes are catchments containing networks of multiple wetlands. Interactions of depressional wetlands in these landscapes influence numerous ecosystem services by storing and releasing water, enhancing carbon and nutrient cycling, and providing critical wildlife habitat, among other functions. Depressional wetlands serve to store and release water slowly to groundwater and downstream surface waters (Lee et al. 2023), affecting regional hydrology and contributing to base flow in many streams (Yeo et al. 2019a,b; McLaughlin et al., 2014). In contrast to the persistent subsurface connectivity, depressional wetlands are surrounded by uplands and therefore only intermittently connected via surface pathways. The lack of persistent surface connections was part of the rationale that removed a large percentage of wetlands from inclusion in what are defined as Waters of the United States (SCOTUS 2023).

Temporary surface connections may play a critical role in wetland function and hydrology at landscape scales. Although surface connectivity in depressional wetlands is either assumed negligible or shown to have short duration (Tiner, 2003), these connections influence water balance and control retention and export of solutes (Ameli & Creed, 2017; Jawitz & Mitchell, 2011; Smith et al., 2018), nutrients,

A researcher with the University of Florida takes notes on a laptop while conducting a study in a forested wetland.
Photos by University of Florida

contaminants, and dispersal of organisms like seeds and fish (Gurnell et al., 2008; Semlitsch & Bodie, 2003). For example, variability in the level of surface connection has been shown to influence chloride accumulation (Thorslund et al., 2018), and to strongly regulate landscape nutrient retention (Cheng & Basu, 2017; Cheng et al., 2022). However, since surface connections between depressional wetlands and adjacent water bodies are not persistent, these “isolated” wetlands are often assumed to be unimportant to the hydrological and biogeochemical functions of downstream waterbodies and associated economic resources (e.g., Chesapeake Bay fisheries).

In contrast, groundwater connections among wetlands and between “isolated” wetlands and downstream waters can be significant, depending on the permeability of regional soils. While numerous studies have demonstrated the importance of depressional wetlands in the landscape, the frequency, duration, and relative importance of surface and subsurface connections between depressional wetlands remains poorly understood, limiting quantification of their landscape functions.

A study, supported by the U.S. Department of Agriculture’s Conservation Effects Assessment Project (CEAP), was designed to further explore these connections and their impacts on wetland functions and services. This study included multiple years of stage variation in 67 depressional wetlands across four contrasting coastal plain wetlandscapes in Florida, USA. The objectives were to:

- examine spatiotemporal patterns of hydrologic connectivity via both surface and subsurface pathways across different wetlandscapes; and
- characterize the climatic, topographic, geological, and vegetative controls on heterogeneity in wetland hydrologic functions.

Study Design

There are approximately 11 million acres of wetlands in Florida (NOAA Office for Coastal Management), more than any other state outside of Alaska. Wetlandscapes occur across diverse geological settings due to a humid climate and numerous depression-forming mechanisms in the relatively flat terrain. Most of Florida’s freshwater wetlands are forested, occurring in wet flatwoods comprised of forested depression and bottomland wetlands within a pine upland mosaic, as well as in small depressions and ponds. The hydrologic characteristics of flatwoods vary due to human water management — including use of ditches, groundwater extraction, and vegetation management — and depth to shallow confining units (e.g., Nilsson et al., 2013).

Differences in the functions and types of wetlands expected across these various wetlandscapes are thought to arise from the relative importance of surface versus subsurface connectivity. This study therefore focused on a total of 67 wetlands in four sites that span a gradient of hydrological behavior: Big Cypress National Preserve (BICY), Osceola National Forest (OSC), Austin Cary Forest (ACF), and Ordway Swisher Biological Station (OSBS; Figure 1). The selected sites represent a range of topographical types (Figure 2) as well as a gradient of hydrologic conditions from principally groundwater connected (e.g., OSBS) to principally surface water connected (e.g., BICY). Water level variation was measured in each multiple times per day to produce a time series ranging from 1.5 to 3+ years duration.

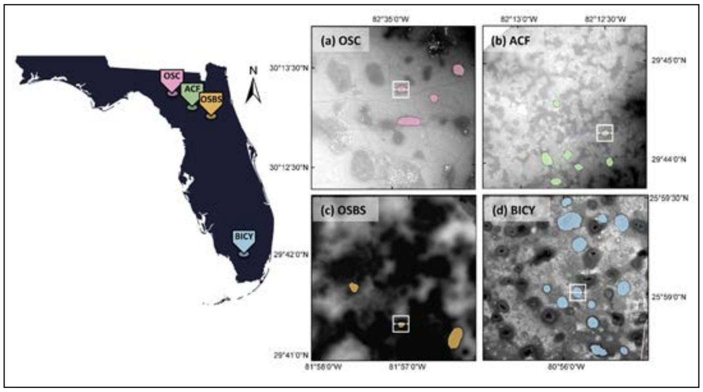

Figure 1. Study sites across four wetlandscapes in southeastern coastal plain: Osceola National Forest (OSC), Austin Cary Forest (ACF), Ordway Swisher Biological Station (OSBS), and Big Cypress National Preserve (BICY). LIDAR digital elevation models (DEMs; National Center for Airborne Laser Mapping) depict subsets of study wetlands in the four landscape blocks (1.5 × 1.5 km each).

Diversity of Wetlandscapes

The relatively flat Florida terrain results in abundant wetland area (45,000 km^2; NOAA Office for Coastal Management) but these wetlandscapes occur across diverse geological settings. The most common are wet flatwoods comprised of forested depression and bottomland wetlands within a pine upland mosaic (Rains et al., 2016). While flatwoods vary with regard to depth to shallow confining units (e.g., Nilsson et al., 2013), this variation is dwarfed by differences between sandhill landscapes with deep depressional features (Nowicki et al., 2022) and shallow karst landscapes with numerous regularly patterned depressions (Quintero & Cohen, 2019).

Differences in the functions and types of wetlands expected across these wetlandscapes are thought to arise principally from water flow patterns, specifically the relative dominance of surface versus subsurface connectivity. As such, wetlandscape study sites were selected that span a gradient of hydrological behavior.

- **Big Cypress National Preserve (BICY)** is a large (6,500 km^2), flat (mean slope = 0.02 m km^{-1}), karst landscape in southwest Florida comprised of a pine upland mosaic with thousands of interspersed cypress domes (Watts et al., 2014). Depressions formed by weathering of carbonate bedrock (Chamberlin et al., 2019; McPherson, 1974), yield small (mean area of 0.013 km^2), evenly spaced (Quintero & Cohen, 2019) depressional wetlands that cover 26% of the landscape (Watts et al., 2014; Figure 1d). Small regional head gradients (Duever et al., 1986) and a thick confining unit below the wetlands result in negligible vertical drainage (McLaughlin et al., 2019) despite being karst depressions. Thus, these depressional wetlands are often connected via surface flow depending on the season (Klammler et al., 2020).

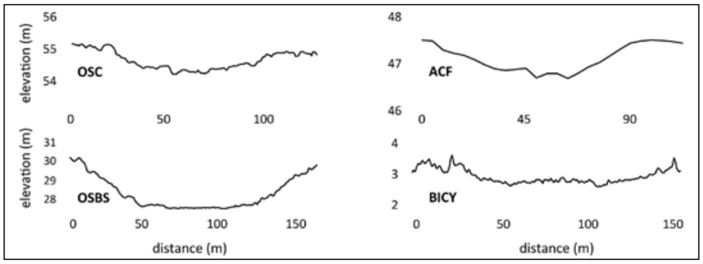

Figure 2. Depressional topography is evident in cross-sections extracted from LIDAR digital elevation models (DEMs; National Center for Airborne Laser Mapping) of four landscapes, which were obtained during anomalously dry periods to minimize interference from ponded water. A representative cross-section from each wetlandscape is shown indicating the topographic variations among wetlandscapes. Note different scales of elevation.

- **Osceola National Forest (OSC)** is a low-relief, poorly drained flatwoods located in Columbia and Baker Counties in north Florida (Miller et al., 1978). Most study wetlands are comprised of cypress and hardwood forests within the Osceola National Forest. There is a thick confining unit composed of marine limestones, evaporites, and clays under the entire area that prevent vertical drainage and create shallow water table conditions. Forested wetlands of varying sizes and hydrological connectivity are found throughout the 635 km^2 area, which is managed as low intensity pine plantations and increasingly for conservation objectives via prescribed fire, vegetation management, and hydrological restoration.
- **Austin Cary Forest (ACF)** is also a pine flatwood (8 km^2) located in Alachua County in north Florida with numerous embedded cypress depressions that variably fill with water and drain via natural and engineered features. The forest is managed for silvicultural demonstration purposes, with land management goals ranging from longleaf pine habitat restoration to intensive pulp production on short rotations. The site is relatively flat and poorly drained (Abrahamson & Hartnett, 1990; Riekerk & Korhnak, 2000) for the same reasons as OSC, which leads to shallow subsurface flow with seasonal surface water connectivity.
- **Ordway Swisher Biological Station (OSBS)** is a 38 km^2 sandhill landscape in Putnam County, Florida, comprised of embedded depressional wetlands, lakes, and ponds that span a wide gradient of upland vegetation densities. Landscape topography is relatively dramatic compared to other wetlandscapes in this study (Figure 2). Due to relatively high relief and the depth and permeability of the sands that form the aquifer, the depressional wetlands are dominated by groundwater flow and rarely connect via surface flowpaths even during the wet season. Perennial streams are nearly totally absent on the site despite abundant rainfall, showing that lateral export as groundwater is rapid enough to largely prevent surface flow.

Wetland Connections

In order to quantify differences in water losses via groundwater and surface water flowpaths, net wetland water balance was determined on both a change-in-stage and change-in-volume basis. The water loss rate for each non-rainy day was estimated by using a modified version of the connectivity and flow from stage (CFS) method (McLaughlin et al., 2019). Sub-daily wetland stage observations were collected every 15 minutes via a total pressure transducer in PVC wells to capture daily signals and determine daily recession rate (Figure 3a). Wetland water depths were calculated from the difference of total and barometric pressure and adjusted for temperature-dependent water density as described in McLaughlin & Cohen (2011). As a significant refinement to the CFS method, the daily recession rate was directly estimated based on water level changes occurring at night (23:00–8:00) when evapotranspiration (ET) is negligible (Figure 3a) rather than relying on 24-hour changes in stage (McLaughlin & Cohen, 2011). Using this method, the daily water balance was constructed after removing estimated potential ET (White, 1932). Data for days when water levels rose at night were removed in order to exclude rain days or periods when water gains from recent rainfall were ongoing.

Spill depth of a wetland determines the partitioning of water loss between groundwater and surface water pathways. While LIDAR-derived estimates of spill depths are often possible, these estimates can be challenging in densely vegetated wetlandscapes. Use of the modified CFS method allowed for efficient identification of spill depths in three of the four wetlandscapes. Since the CFS method requires that wetland water levels exceed the spill level over the observation period, this method was not applicable in the sandhill wetlandscape of OSBS where wetlands were only groundwater-connected with no pattern of apparent surface connectivity. Given the relatively large topographic variation and sparse vegetation of those 12 wetlands, spill depth was estimated based on the LIDAR DEM following methods presented in McLaughlin et al. (2019).

In previous studies, water level recession rates in wetlands were observed to be relatively small and constant until the stage exceeds the spill depth which allows surface flowpaths to quickly move

Table 1. Geographic Coordinates, Wetland Water Levels, Spill Depths, Data Measurement Periods, Long-Term and Study Period Annual Rainfall and Annual Evapotranspiration, and Number of Study Wetlands for Each Wetlandscape.

Wetlandscape	BICY	OSC	ACF	OSBS
Geographic coordinates	25.99 N, 80.93 W	30.28 N, 82.48 W	29.75 N, 82.21 W	29.71 N, 81.99 W
Mean wetland stage (± SD) (cm)	28.6 (± 12.1)	19.9 (± 15.4)	44.6 (± 23.2)	177.5 (± 80.2)
Mean spill depths (± SD) (cm)	34.5 (± 13.5)	31.9 (± 10.0)	50.4 (± 23.6)	264.1 (± 95.0)
Study period	Dec 2018–Oct 2020	Jun 2019–Jun 2022	Oct 2018–Oct 2020	Jan 2018–Nov 2020
Long-term annual P (mm)	1253.0	1314.3	1289.5	1254.3
Long-term annual ET (mm)	1184.1	1012.5	1014.4	1031.6
Study period annual P (mm)	1341.0	1267.5	1186.7	1441.7
Study period ET (mm)	1182.5	1017.7	980.8	995.7
Number of wetlands	16	22	15	14

excess water to downstream water bodies (Figure 3b and 3c). The transition from mainly surface flow to entirely groundwater flow was therefore estimated by using breakpoints in the water level response. These estimates were validated where vegetation artifacts in the LIDAR base-surface DEM are negligible. Nearly every wetland showed an abrupt change in the fitted curve at deep stage, which likely represents the onset of rapid surface connectivity. Thus, magnitude and temporal patterns of excess water are the two factors that drive wetland hydrological states to be dry, inundated, or surface connected (Figure 3c).

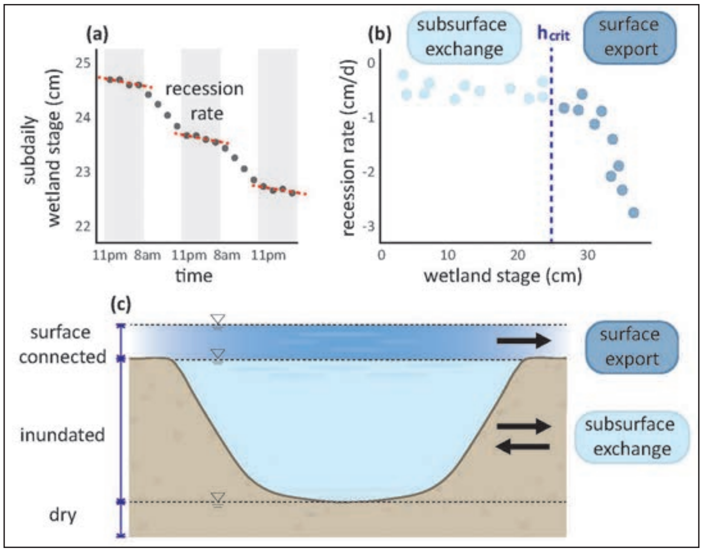

Figure 3. Method for estimating wetland spill threshold based on modified CFS method where (a) sub-daily wetland stage is used to estimate mean recession rate during nighttime. (b) Relationship between recession rate and wetland stage, where a break point in the trend indicates a spill threshold (hcrit) (c) where surface connection is activated in addition to subsurface exchange.

The timing and duration of water levels above the surface connectivity threshold defines wetland depth. Wetland depth allowed us to distinguish subsurface- and surface-dominated flow regimes (Table 1; Figure 4) and to quantify the relative water loss rates between surface connected and surface disconnected states (Figure 5). Percent of time inundated (PTI) and surface connected (PTC) were calculated as the durations of period when wetland water level stays above wetland bottom and when water level exceeds the spill threshold, respectively.

Landscape-level Hydrology

Study findings underscore that surface connections among wetlands serve to bypass the prevailing groundwater loss process, suggesting that it is the combination of surface and subsurface flowpaths that is relevant for understanding wetland roles in landscape functions. Estimates of PTI and PTC indicate that wetlands serve as water storage venues, connected only via slow subsurface flowpaths 50% to 90% of the time. The observed wetland spill depth is exceeded only 10% to 40% of the time, with substantial variation within and between wetlandscapes. Recession rates below spill depth were surprisingly consistent, with values ranging from −0.44 cm d^{-1} to −1.0 cm d^{-1}. In contrast, recession rates for stages above spill depth are roughly twice as high, with values ranging from −1.2 cm d^{-1} to −2.1 cm d^{-1} (two wetlands only in OSBS; Figure 5). Water export via groundwater exchange in BICY and OSBS wetlands was comparable to the combined surface and groundwater export rates observed with surface connectivity in ACF and OSC, perhaps due to the high permeability of the regional surface sediments and low aridity values for these two locations (Table 1).

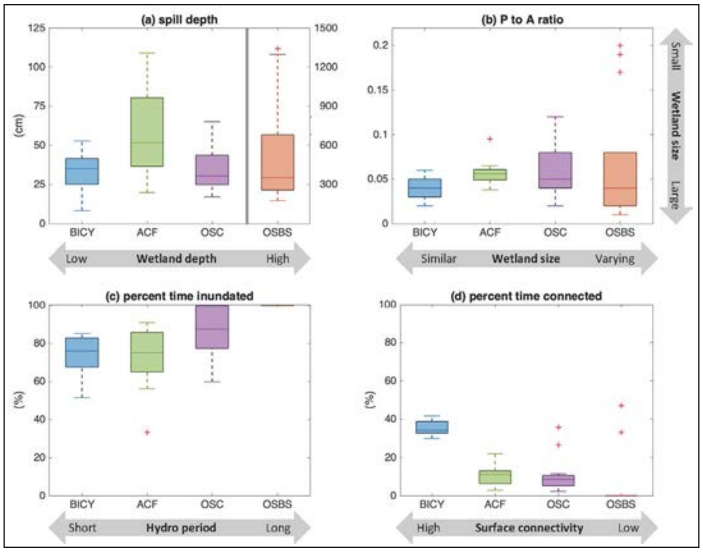

Figure 4. Heterogeneity within and across four different wetlandscapes showing distributions of (a) spill thresholds with respect to wetland bottom elevations (0 cm depth), (b) perimeter to area ratio, (c) percent time inundated, and (d) percent time surface connected via surface flowpaths.

Across wetlandscapes, there is a more than five-fold increase (567%) in daily volumetric water export rates above spill depth compared with periods below that, underscoring the significance of surface connected periods to water balance (Figure 5b). The temporal alignment of wetland surface connectivity with regional flow dynamics illustrates the relevance of these surface connectivity patterns for downstream waters (Figure 6), with a clear alignment of wetland connectivity patterns (e.g., the proportion of wetlands with stage at or above spill depth) and flows observed in streams. For example, during periods in which up to 80% of the ACF wetlands are surface connected, the landscape exports 35 times more water (Figure 6b). A similar pattern is evident in OSC, albeit with more evenly distributed wetland population connectivity compared to ACF, including only a third of the time with 10% of wetlands or fewer surface-connected (Figure 6c). As with ACF, as the number of surface connected wetlands in OSC increases, reaching 80% at the maximum, the downstream stream flow rapidly increases.

These results imply that sensitivity to weather variation differs among wetlandscapes which provides different levels of function. Asynchronous groundwater-connected landscapes like OSBS provide limited intra-annual but marked inter-annual variability (Figure 7a), while more synchronous surface-connected BICY provides considerable intra-annual, but limited inter-annual, variation in storage and connectivity. Notably, the groundwater recession rate was never influenced by the adjacent vegetation cover nor the wetland elevations with respect to the mean landscape topography.

Although PTC in BICY was in close agreement with previous work (Klammler et al., 2020; McLaughlin et al., 2019), PTC in OSBS and ACF was consistently lower during the study period, suggesting that on average surface connectivity in flatwoods wetlands (ACF and

OSC) occurs about 15% of the time. Prolonged inundation at OSBS (where PTC is very low) and shorter inundation at BICY (where PTC is high) illustrate that inundation duration does not clearly relate to surface connectivity duration, emphasizing the heterogeneity of wetlandscape hydrological functions. PTC varied far more between wetlandscapes, ranging from approximately 10% of the measurement period in OSC to approximately 40% in BICY (Figure 3). PTC was shortest at OSC despite restricted groundwater export, and the augmentation of water export during surface connected periods was far higher here than at ACF (the other flatwoods site). This provides further indication that the balance of climatic water surplus and subsurface export governs surface connectivity patterns.

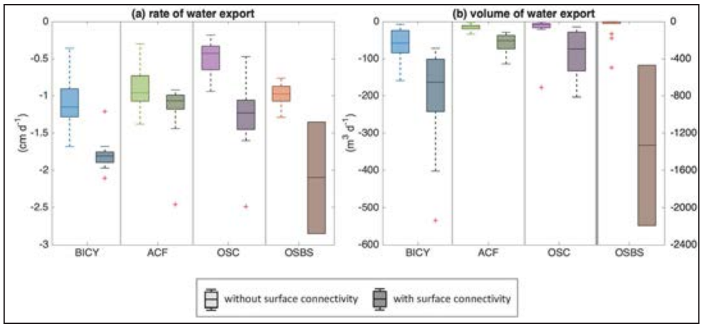

Figure 5. Rates of wetland water export based on (a) stage and (b) volume water loss for wetlands below and above the spill threshold across the four wetlandscapes.

As many studies have noted (Calhoun et al., 2017; Cohen et al., 2016; Mushet et al., 2015), these embedded depression wetlands are not hydrologically isolated, as evidenced by the maintenance of low salinity (Thorslund et al., 2018) and seasonal exceedance of storage capacity (Leibowitz et al., 2018; McDonough et al., 2015). Topographic depressions of the wetlands in this study naturally fill with excess runoff, merge with adjacent depression lobes, and spill when water levels exceed their aggregate storage capacity (Leibowitz et al., 2016). These periods of surface connectivity rapidly export water downstream, with observed rates of water export (m^3 d^{-1}) above spill depth increasing 350% to 850% compared with export when stage is below the threshold (Figure 5). This highlights the hydrological significance of these relatively brief periods of surface connection to the overall wetlandscape water balance and the episodic nature of the bypassing of groundwater export versus surface flow.

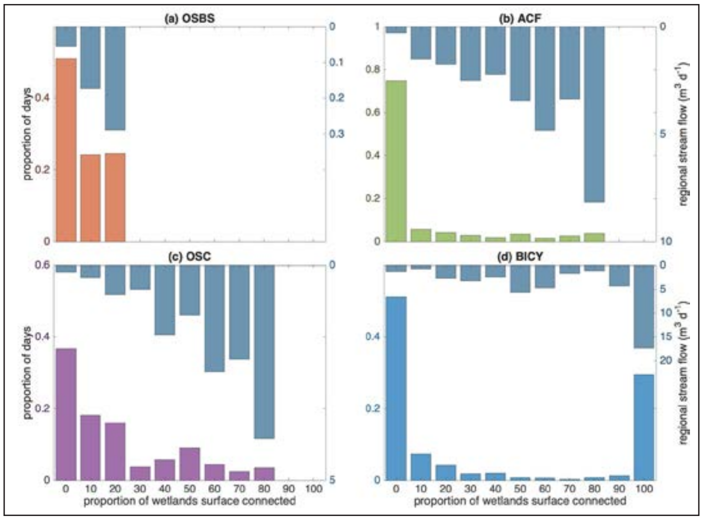

Figure 6. Proportion of days (left y-axis) with varying levels of wetlandscape surface connectivity, along with regional stream flow from a downstream flow gauge (right y-axis, reverse direction). The proportion of surface connected wetlands is calculated by dividing surface connected wetlands (stage ≥ hcrit) on each day by the number of study wetlands. Note that the timing and duration of data collection vary across the wetlandscapes (Table 1) with the resulting frequencies affected by weather variability over the study period.

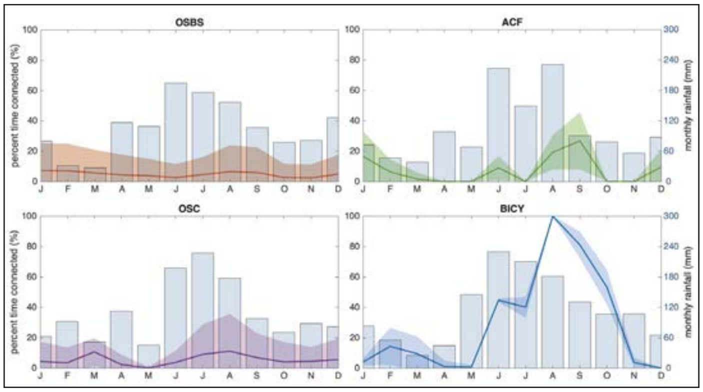

Figure 7. Seasonality in percent time surface connected (wetland stage ≥ hcrit; colored solid line with shade; left y-axis) plotted with monthly rainfall (bar; right y-axis). Percent time surface connected indicates the portion of days with surface connectivity in each month. Shaded area indicates the standard deviation across the study wetlands in each wetlandscape.

ET in the adjacent upland forest surrounding each wetland, quantified based on measured leaf area index (LAI) (Acharya et al., 2022), varied widely but did not significantly influence wetland nighttime groundwater export in any of the wetlandscapes. Results suggest that, in these coastal plain wetlandscapes, local ET does not directly impact groundwater recession. Deeper wetlands export water more rapidly via subsurface pathways than shallower wetlands, as documented in Supporting Information in the online version of Lee et al., 2023. The magnitude of this effect is notable: a 1 cm increase in wetland depth increases groundwater losses by 0.01 cm d^{-1} (in ACF and OSC) and 0.02 cm d^{-1} (in BICY) (Supporting Information Lee et al., 2023) so that a wetland 20 cm deeper than another is expected to lose water nearly 2 to 4 mm per day faster, which is roughly equivalent to daily ET losses. One explanation for this arises from differences in ecosystem specific yield (McLaughlin & Cohen, 2014), which describes depth-dependent controls on vertical amplification of water volume changes. Depressional wetlands are typically bowl-shaped with gradual slopes from the wetland bottom to the spill elevation (Lane & D'Amico, 2010). Rapid head equilibration observed between the standing water in a wetland and the adjacent aquifer in these settings (McLaughlin & Cohen, 2014) creates an effective specific yield that amplifies ET or groundwater losses as a function of stage.

Photo by University of Florida

Implications for Conservation

Wetland surface connectivity has previously been indirectly inferred based on the proximity to adjacent downstream water bodies (Calhoun et al., 2017; Lane & D'Amico, 2016). This study extracted spill depth from the inflection point of water level recession rates as a function of stage to infer the timing, duration, and importance of surface connectivity. Study findings highlight the important role that short-lived but rapid surface connectivity plays in wetlandscape-scale hydrologic and aquatic habitat services, consistent with the role of high-flow states in overall catchment water and solute export (Jawitz & Mitchell, 2011). Periods of surface connectivity exhibit close temporal alignment with regional flow patterns (Figure 6), during which most of the solutes (e.g., nutrients, salts, dissolved organic matter) are exported to the larger downstream flow network and organisms are transported between aquatic habitats (Marton et al., 2015).

Spatial variation in surface connectivity patterns is relevant to conservation planning. This study highlights the aggregated effects of fill and spill heterogeneity for landscape functions that are unlikely to be informed from individual wetland-scale analyses. This heterogeneity is important for wildlife populations since small and shallow wetlands with shorter hydroperiods discourage populations of predatory fish that consume amphibian larvae and invertebrate biomass and thus are environments favorable for amphibians (e.g., salamanders; Jones et al., 2018) and migratory waterfowl (Morin, 1983; Semlitsch & Bodie, 1998; van der Valk, 2005; Wilbur, 1987). Biogeochemical processing (Marton et al., 2015) and landscape nutrient retention (Cheng & Basu, 2017; Cheng et al., 2022) are enhanced by the slow subsurface hydrologic connectivity of some wetlands that extends residence times. In contrast, short-lived periods of surface connectivity, observed consistently across most wetlandscapes in this study, are crucially important for landscape hydrological function, increasing the downstream daily flux rate by 350% to 800% compared with subsurface flowpaths. This increased connectivity is important for dispersal of aquatic organisms and plant propagules, increased export of flood waters, and maintenance of downstream surface flows.

Within-landscape variation in connectivity was also observed, with important implications for local conservation efforts, for example in prioritization for stormwater storage, nutrient mitigation, or habitat provision (Fisher et al., 2004; Leibowtiz, 2003; Pringle, 2003). Due to the landscape hydrologic buffering by the small, deep wetlands at OSC, loss of a single wetland there is likely to be more consequential for wetlandscape ecological function than a single wetland in BICY where the wetland responses are more homogeneous (McLaughlin et al., 2019). The low redundancy of OSBS wetlands supports the argument that the loss of heterogeneity in hydrologic storage capacity, recession rates, and timing and incidence of surface connections would collectively be more substantial than impacts of wetland removal based simply on wetland area lost. Thus, avoiding removal of non-redundant functions is relevant for conservation planners and land managers concerned about patterns of water storage and release, provision of wildlife habitat, enhancement of carbon sequestration, or mitigation of landscape nutrient exports (Amezaga et al., 2002; Dos Santos & Thomaz, 2007; Snodgrass et al., 2000).

Most of Florida's freshwater wetlands are forested, occurring in wet flatwoods comprised of forested depression and bottomland wetlands within a pine upland mosaic, as well as in small depressions and ponds.
Photo By: University of Florida

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Conservation Effects Assessment Project: Translating Science into Practice

The Conservation Effects Assessment Project (CEAP) is a multi-agency effort led by USDA's Natural Resources Conservation Service (NRCS) to build the science base for conservation. Project findings help guide USDA conservation policy and program development and support farmers and ranchers in making informed conservation choices.

One of CEAP's objectives is to quantify the environmental benefits of conservation practices for reporting at the national and regional levels. CEAP Wetland Assessments complement National Assessments for cropland, wildlife, and grazing lands to support conservation actions on a variety of landscapes.

This project was conducted through a collaborative effort by CEAP and the University of Florida. Primary authors of this Conservation Insight were Dr. Esther Lee with the University of Florida School of Forest, Fisheries, and Geomatics Sciences and Dr. Joseph (Joe) Prenger, CEAP Wetland Assessment Leader with NRCS.

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