Hydrologic Changes over 60 Years (1959-2019) in an Old-Growth Bald Cypress Swamp on a Rapidly Developing Landscape

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ABSTRACT

National Audubon Society's Corkscrew Swamp Sanctuary (Naples, Florida, USA), an ecological relic of Old Florida, protects the largest remaining old-growth bald cypress swamp in the world. A 60-year record of daily water level measurements revealed substantial changes in Corkscrew Swamp's hydrology as agricultural and residential development have grown to dominate the landscape surrounding the sanctuary. Between 1959 and 2019, surface water data indicate no decadal change in the timing or magnitude of peak wet season water levels or in the hydroperiods (days inundated per water year) of upland hammock and pine forests or wet prairies. Despite little change in rainfall patterns between the 1960s and 2010s, hydroperiods decreased 29% in marshes, 18% in old-growth bald cypress, and 17% in ponds, with the most notable change occurring between the 1990s and 2000s. Average dry season water level recession rate (decrease in water level over time) was 6.3 mm/d in the 2000s and 5.7 mm/d in the 2010s, 47% and 32% higher, respectively, than those seen in earlier decades. Analyses of groundwater data indicated a similar dry season decline between the 1990s and 2000s to that seen in surface water. Analyses of cumulative hydroperiod in surface and groundwater suggested markedly drier conditions began in the 2006 water year. While causes of the observed hydrologic changes are uncertain, likely interacting causes include reduced upstream wet season surface and groundwater storage, increased residential and agricultural extraction, increased downstream drainage, and increased evapotranspiration rates across the region as more deeply-rooted shrubs and trees replace more shallowly-rooted herbaceous plant communities. We discuss significant implications for plant and animal communities, particularly the historic Corkscrew wood stork colony, and discuss the role of long-term hydrologic monitoring for detecting and documenting ecological change.

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INTRODUCTION

Corkscrew Swamp is the largest old-growth bald cypress (*Taxodium distichum*) swamp in the United States. Located near the top of the Big Cypress Swamp watershed (Duever et al. 1976), the National Audubon Society Corkscrew Swamp Sanctuary (CSS) is central to the ~24,000 ha Corkscrew Regional Ecosystem Watershed. Recognized for its rich biodiversity and important ecological functions, CSS is designated an Important Bird Area (Bird Life International), a National Natural Landmark (U.S. Department of the Interior), a Wetland of International Importance (Ramsar Convention), and a Wetland of Distinction (Society of Wetland Scientists).

Like other parts of the Florida Everglades, Corkscrew Swamp has a rain-driven, seasonally-pulsed hydropattern that drives the ecology of its plant and animal communities (DeAngelis 1994; Duever et al. 1984; Davis 1943). The Sanctuary is dominated by wetlands, including herbaceous organic-soil marshes and mineral-soil wet prairies, as well as the old-growth bald cypress forest. Smaller areas of upland old-growth pine forests and hardwood hammocks add to the biological diversity. In the Western Everglades, these plant communities exist because of a combination of environmental factors, including the site's hydrologic and fire regimes and its substrates (Duever et al. 1984), particularly the organic soils that have been accumulating for the past 5,000 years (Gleason and Stone 1994; Kropp 1976). Wet season water levels sort the plant communities into upland, wetland, and aquatic communities. Within these groups, plant community structure is dictated by fire regime (Duever and Roberts 2013). A high fire frequency produces predominantly herbaceous communities. With decreasing fire frequency, herbaceous communities over time succeed to shrubby vegetation (>18 years), such as willow or wax myrtle, then to fire-tolerant forests of pine or bald cypress (>40 years), and finally to fire-intolerant hardwood forests (no fire).

The duration of inundation and timing of dry-season water level recession are critical factors for this ecosystem's animal communities. At the base of the aquatic food web, frequency and severity of drought are key drivers of aquatic fauna communities (Trexler and Goss 2009; Ruetz

TABLE 1. Characteristic composition of Corkscrew Swamp Sanctuary plant communities. The species in the hardwood hammock and old-growth bald cypress communities are those found in the canopy and sub-canopy. Shrubs and ground cover, particularly ferns, can be sparse to dense in these forests depending on canopy density and water depth. Pine forests have relatively open canopy with few shrubs and a groundcover of saw palmetto dominating on higher/drier sites and herbaceous vegetation on lower/wetter sites. Wet prairies and marshes have herbaceous plant communities. Wet prairies have very diverse plant communities with a relatively short, more open vegetative structure and the marshes have a relatively low plant diversity with a taller, denser vegetative structure.

Habitat	Characteristic vegetation
Hardwood Hammock	Swamp bay (*Persea palustris*) Red maple (*Acer rubrum)* Cabbage palm (*Sabal palmetto*) Laurel oak (*Quercus laurifolia*) Live oak (*Q. virginiana)* Myrsine *(Myrsine cubana)*
Pine Forest	Slash pine (*Pinus elliotti)* Saw palmetto (*Serenoa* repens) A highly diverse community of grasses, sedges, and forbs
Wet Prairie	A highly diverse community of sedges, forbs, and grasses
Young Bald Cypress	A dense, monospecific stand of bald cypress (*Taxodium distichum*)
Freshwater Marsh	Pickerelweed (*Pontederia cordata*) Bulltongue arrowhead (*Sagittaria lancifolia)* Maidencane (*Panicum hemitomon)* Carolina willow (*Salix caroliniana)* Sawgrass *(Cladium jamaicense)* Fireflag *(Thalia geniculata)*
Old-growth Bald Cypress	Bald cypress Dahoon holly (*Ilex cassine*) Red maple Swamp bay Strangler fig (*Ficus aurea*) Pond apple (*Annona glabra*) Pop ash (Fraxinus *caroliniana*)
Ponds	Open water or covered with floating plants, including: Water lettuce (*Pistia stratoides)* Water spangles *(Salvinia minima)* American waterfern (*Azolla filiculoides*)

et al. 2005) as inundated periods allow aquatic fauna to disperse throughout the landscape and increase biomass via growth and reproduction (Loftus and Eklund 1994). In Southwest Florida's dry season, recession rate of water levels and subtle variations in microtopography are critical drivers of the biomass of fish available to higher trophic levels (Botson et al. 2016). This dry-season concentration of aquatic prey in shallow to intermediate and then to long-hydroperiod wetlands is synchronized with annual cycles of wading bird nesting season (typically December-May), as wading birds depend on high concentrations of prey throughout the nesting season. Of particular importance are federally-threatened wood storks (*Mycteria americana*) that historically produced the largest breeding colony in North America at CSS (Ogden and Nesbitt 1979) and, like white ibis (*Eudocimus albus*) and snowy egrets (*Egretta thula*), employ a feeding strategy that makes them more dependent upon finding new, high-quality food patches than other wading bird species (Gawlik 2002).

In this paper, we describe changes in hydrology at CSS from 1959 to 2019. By hydrology, we imply both natural surface water and surficial groundwater levels and flows, the realm of which are so uniquely interrelated in south Florida. Due to the paucity of ecological data from this region in the 1950s, 1960s and 1970s, this unique dataset provides valuable perspective on how hydrology has responded to the myriad changes on the landscape that have occurred with land development. We also discuss possible causes of hydrologic change, none of which are unique to this landscape. In addition to the inherent implications for CSS, we present these data to emphasize the importance of considering both wet and dry season functions in wetland conservation and management and to provide a compelling example of the importance and challenges of using monitoring data to dictate natural resource management, particularly in systems with a high degree of inter- and intra-annual meteorological and resultant hydrologic variability.

METHODS

Study Site

Corkscrew Swamp Sanctuary is a 5,260 ha preserve located in the Big Cypress Swamp, a component of the Everglades ecosystem in southwestern Florida (Figure 1). The climate of CSS is subtropical with distinct wet and dry seasons. The area receives approximately ~1,400 cm of rain annually with nearly 80% of rain occurring during the wet season (June – October). The sanctuary is comprised of a matrix of upland and wetland habitats, including: hardwood hammock, pine forest, wet prairie, young bald cypress, freshwater marsh, old-growth bald cypress, and ponds (Table 1) (Duever et al. 1986, 1984).

Data Collection

Rainfall was recorded daily at Corkscrew Swamp Sanctuary 11/1959-5/2019 using a standard rain gauge. While the exact location of the rain gauge changed through time, all locations were within ≈100 m of the current location (Figure 1). Daily surface water depth was recorded beginning in 11/1959 using two staff gauges (A and B) located ≈200 m apart and adjacent to a raised boardwalk within the Sanctuary's bald cypress slough. All elevations stated in this paper are National Geodetic Vertical Datum of 1929 (NGVD29). The B gauge, located in a deep pond (ground level=4.60 m NGVD29; Figure 1), was used primarily as it is located at lower elevation and inundated for longer periods. Daily depth at the B gauge was estimated based on correlation with the A gauge 11/1959 through 12/1962, prior to installation and final calibration of the B gauge. The B gauge was moved several times with changes in the Sanctuary's boardwalk, at which time the A gauge was used to ensure consistent readings upon re-installation. Groundwater data were obtained 10/1973 through 5/2019 from well C-492, a 19.5 m U.S. Geological Survey well located within the Sanctuary ≈380 m southeast of the B-gauge (Figure 1). Maximum daily groundwater level data for C-492 were obtained from the South Florida Water Management District DBHYDRO environmental database (https://www.sfwmd.gov/science-data/dbhydro).

Data Analyses

Gaps in daily surface water depth at the B gauge were filled through linear regression with the A gauge or linear interpolation of preceding and subsequent B gauge readings (when the number of consecutive missing values was <30). For days prior to and following Hurricane Irma (9/6/17-9/29/17), daily staff gauge readings were not recorded, so B gauge readings were estimated using linear regression with an immediately adjacent well fitted with a Rugged TROLL® 100 data logger (r^2=0.987). Despite this effort, 9 data gaps (range of gap size= 38-267 days) remained in our 60-year daily water level data set. Therefore, we excluded 5 water years (WY1960, 1962, 1971, 1972 and 1976) in analyses of surface water data. We defined a water year (WY) as June 1 of the previous calendar year to May 31 of the named calendar year.

In order to examine hydrologic variation along the topographic gradient in a way that was meaningful for land management and conservation, we estimated daily water levels (WY1960-WY2019) using B gauge data at six elevations that correspond with Corkscrew habitats. Elevations were selected using WY1960-WY1979 surface water level data such that the average number of days per year that water levels were at or above each elevation corresponded with published hydroperiods for these habitats (Duever et al. 1986). Selected elevations were 4.75 m (pond), 5.05 m

FIGURE 1. Corkscrew Swamp Sanctuary. (A) Location of Corkscrew Swamp Sanctuary in Southwest Florida; (B) extent of Corkscrew Swamp Sanctuary (outlined white); (C) location of long-term monitoring sites discussed in this study. Brown line represents Corkscrew's boardwalk and the Blair Audubon Center (far right).

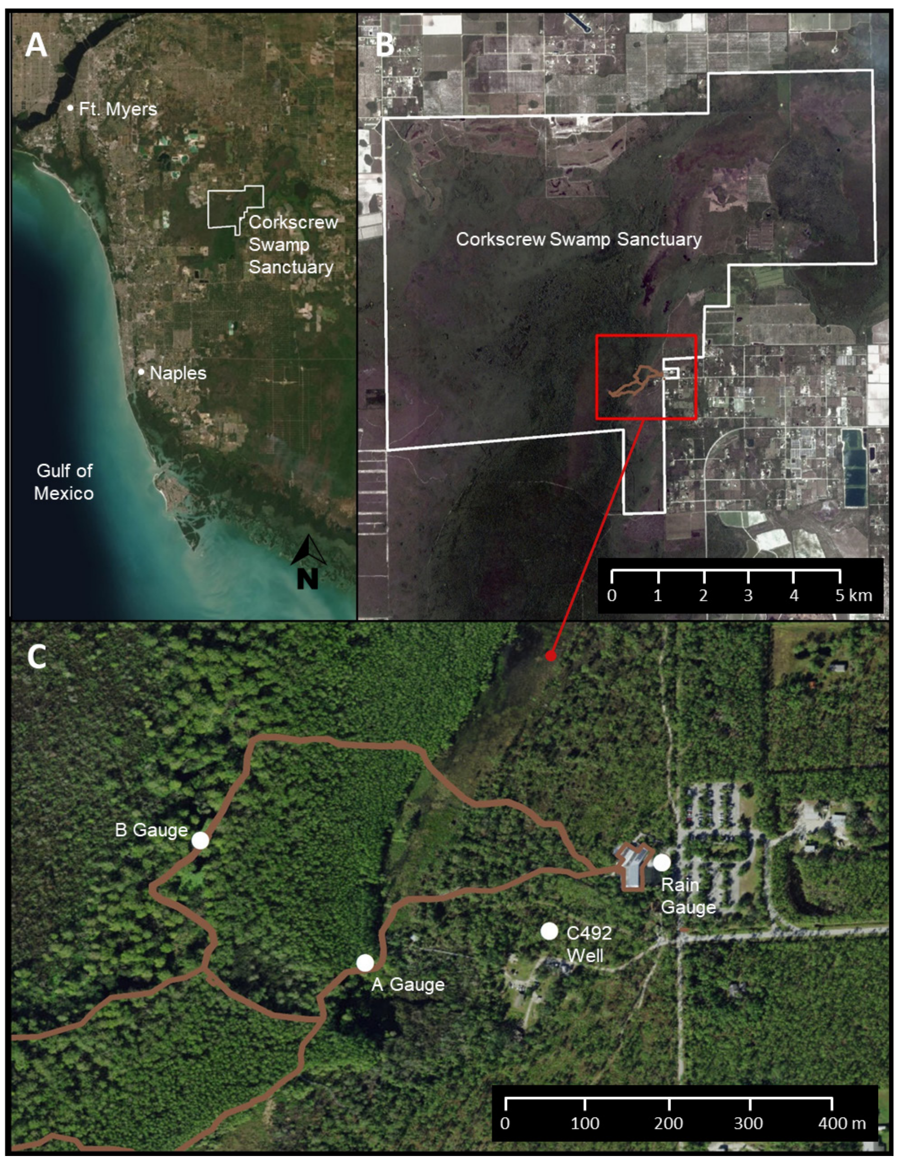


TABLE 2. Slope (m) and coefficient of determination (R2) for the cumulative days per year below elevation for surface water (B gauge, 5.05 m NGVD29) and groundwater (C-492 well, 4.50 m NGVD29). Time periods (A-D) reference those depicted in Figure 7. Slopes indicate similar patterns in surface and groundwater and notably shorter hydroperiod (higher slope) in both surface water and groundwater data 2006-2019, compared to any earlier time period.

	Surface water			Groundwater	
Period	m	R^2		m	R^2
1960-1988 (A)	36.9	0.974		16.2	0.891
1990-2000 (B)	26.1	0.879		7.8	0.695
2002-2006 (C)	43.6	0.990		24.8	0.926
2006-2019 (D)	131.1	0.974		83.7	0.970

(old-growth bald cypress), 5.20 m (freshwater marsh and small bald cypress), 5.40 m (wet prairie), 5.50 m (pine forest), and 5.65 m (hammock forest). Hydroperiod for each elevation in each water year was estimated by calculating the total number of days the water level was greater than or equal to the corresponding elevation. Recession rates were calculated from B gauge data ((depth day 15 - depth day 1) / 14) for weeks 27-52 of the water year. Negative recession rates (dry season reversal events) were excluded and bi-weekly rates were used to obtain an average dry season recession rate for each year. Well data were used to examine groundwater levels at the above-described five elevations. Annual duration above each belowground elevation was calculated as the total number of days per water year that the water level was greater than or equal to the corresponding elevation. Finally, we plotted the cumulative annual number of days water levels were below 5.05 m at the B gauge (surface water) and 4.50 m at the C-492 well (groundwater) to identify the timing of observed hydrologic change. Analysis of variance (ANOVA) was used to examine temporal variation in rainfall peak wet season water level, hydroperiod, and recession rate; Tukey pairwise comparisons were used to explicate significant results.

RESULTS

Rainfall

Annual rainfall at CSS averaged 153.5 ± 3.5 cm with no variation across decades ($F_{5,50}$ = 1.607, P = 0.175, R^2 = 0.138). Wet season (June-September) rainfall averaged 97.9 ± 2.7 cm, but varied across decades ($F_{5,51}$ = 3.499, P = 0.009, R^2 = 0.255) with the 2000s and 2010s receiving 24.5% (Tukey: P = 0.024) and 24.6% (Tukey: P = 0.035), respectively, more wet season rainfall than the 1990s (no variation seen among other decades, Tukey: P>0.05). No decadal variation was observed in dry season rainfall ($F_{5,50}$ = 2.329, P = 0.056, R^2 = 0.189). South Florida received record rainfall in summer 2017 (WY2018) (Abtew et al. 2019). CSS received 256.2 cm of rainfall in WY2018, 13% higher than the prior maximum (WY2010) and 64% higher than the average of the other 56 years on record. Consequently, WY2018 rainfall data were excluded from rainfall analyses and are not included in any reported means.

Water Levels

No decadal variation was seen in the average date ($F_{5,49}$ = 1.02, P = 0.417, $\bar{x}$ = September 20 ± 5 d) or magnitude ($F_{5,49}$ = 0.75, P = 0.590, $\bar{x}$ = 5.628 ± 0.017 m NGVD) of Corkscrew's peak water level (Figure 2). Higher elevation habitats that are only inundated in the wettest part of the year saw no variation in hydroperiod across decades, including hammock forest ($F_{5,49}$=1.192, P=0.327, $\bar{x}$=12.7 ± 5.0 d), pine forest ($F_{5,49}$=0.870, P=0.508, $\bar{x}$=79.6± 9.1 d), and wet prairie ($F_{5,49}$=1.901, P=0.111, $\bar{x}$= 144.8 ± 11.6 d).

The median daily water level for the 1960s, 1970s, 1980s, and 1990s was always above ground at the B gauge, while the median daily water level for 2000s and 2010s went below ground during the dry season for 55 and 39 d, respectively (Figure 2). A marked decrease in hydroperiod across decades was seen in all habitats that are typically inundated well into the dry season, including 5.20 m (freshwater marsh/small bald cypress; $F_{5,49}$=3.336, P=0.011, R^2=0.254), 5.05 m (old-growth bald cypress; $F_{5,49}$=3.104, P=0.016, R^2=0.241), and 4.75 m (wetland ponds; $F_{5,49}$=4.080, P=0.004, R^2=0.294)(Figure 3). On average, from the 1960s to the 2010s Corkscrew's hydroperiod decreased 29% (2.6 mo.) in marshes, 18% (1.9 mo.) in old-growth bald cypress, and 17% (2.0 mo.) in ponds.

Average dry season recession rate varied significantly among decades ($F_{5,54}$=3.748, P=0.006, R^2=0.258). Recession rates in the 2000s and 2010s were 47% and 32% higher, respectively, than the average recession rate of the other decades which were similar (Figure 4). Notably, similar strength, landfall location, track (within 5 km of CSS), and rainfall amounts of Hurricane Donna (9/10/1960) and Hurricane Irma (9/10/2017) provided an anecdotal opportunity to compare water level recession in the 1960s versus present. Rainfall from each storm caused CSS water levels to rise to near-record levels, with maximum post-storm water levels in 1960 (WY1961) and 2017 (WY2018) within 5 cm of each other. Recession of surface water tracked quite similarly until late December, after which time average WY2018 recession rate was 67% higher than that of WY1961 (Figure 5).

We observed significant decadal variation in the average number of days/year groundwater levels were above 4.25 and 4.50 m NGVD29 (4.25m: $F_{4,37}$=3.263, P=0.022, R^2=0.261;

4.50 m: $F_{4,37}$=2.645, P=0.049, R^2=0.222); while not statistically significant, similar trends were seen at 4.00, 4.75, and 5.00 m (4.00 m: $F_{4,37}$=1.749, P=0.160; 4.75 m: $F_{4,37}$=1.747, P=0.160; 5.00 m: $F_{4,37}$=2.234, P=0.084) (Figure 6).

Visually-identified inflection points in plots of the cumulative annual number of days water levels were below 5.05 m at the B gauge and 4.50 m at the C-492 well (Figure 7) were similar. For each data set, slope (average duration water levels were below elevation) was relatively consistent WY1961-1988, WY1990-2000, and WY2002-2006 (Figure 7, Table 2), although WY1990 -2000 was slightly wetter. Short periods of drier conditions (higher slope) were seen WY1989-1990 and WY2000-2001. Conditions were markedly drier WY2006-2019, as slopes were 3.6X and 5.2X higher than those seen through WY1988 in surface water and groundwater, respectively.

DISCUSSION

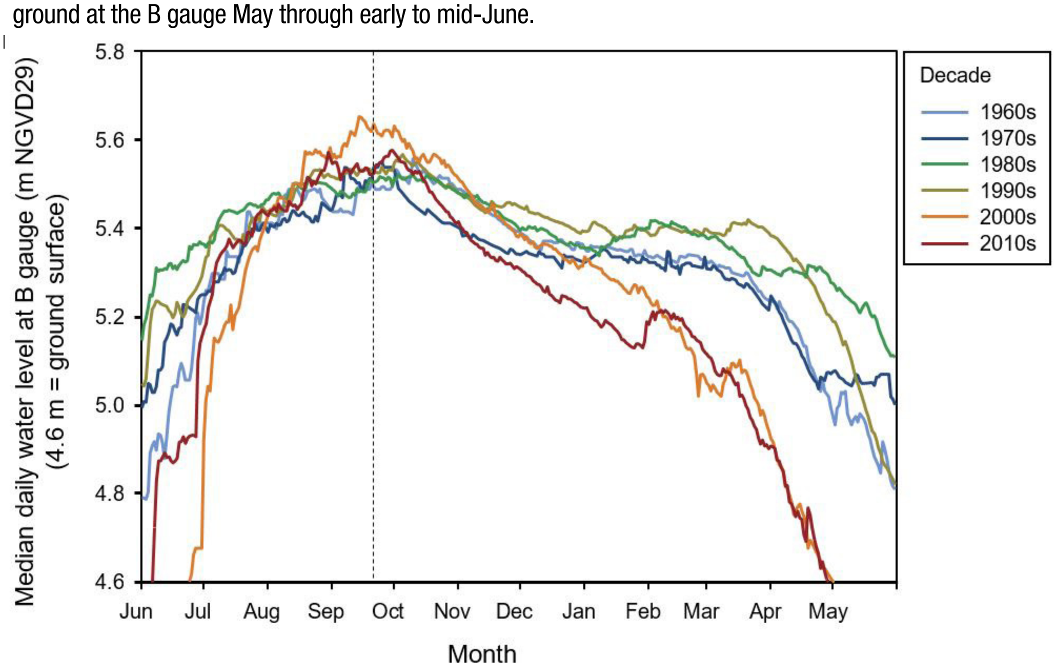
Daily water level monitoring began in 1959 at Corkscrew Swamp Sanctuary to identify adverse changes in its hydrologic regime. Long-term hydrologic monitoring data allowed us to clearly document significant hydrologic changes in recent decades. These changes are probably due to a suite of environmental changes, which have been steadily increasing over the last 60 years as the region developed. Despite the dramatic change in hydrology we observed in the early 2000s, this system's marked inter-and intra-annual variation in hydropatterns made it difficult to detect change prior to this analysis of this long-term data set. This underscores both the importance and limitations of long-term ecological monitoring, particularly in systems with a high degree of inherent variability. Analysis of rainfall at Corkscrew Swamp Sanctuary over the past 60 years shows little change over time, while water level data from both the B gauge and the USGS Surficial Aquifer well C-492 show dramatic reductions in hydroperiods and dry season water levels in the last 15-20 years. Over the 60-year period of record that water levels have been measured at CSS, dramatic changes in land use have occurred across the region which have the potential to significantly contribute to the recently observed dry season hydropattern changes.

Possible Causes for Dry Season Water Table Decline

Agricultural and residential development have steadily increased in southwest Florida since the 1950s. These activities have necessitated extensive drainage of the developed landscape and the withdrawal of large quantities of water for irrigation and domestic water supplies from the Surficial Aquifer underlying the region. While data are not currently available to elucidate and weigh the relative importance of many of the factors that we discuss, the likelihood that they are contributing factors is strong and modelling efforts have begun to quantitatively examine and evaluate them.

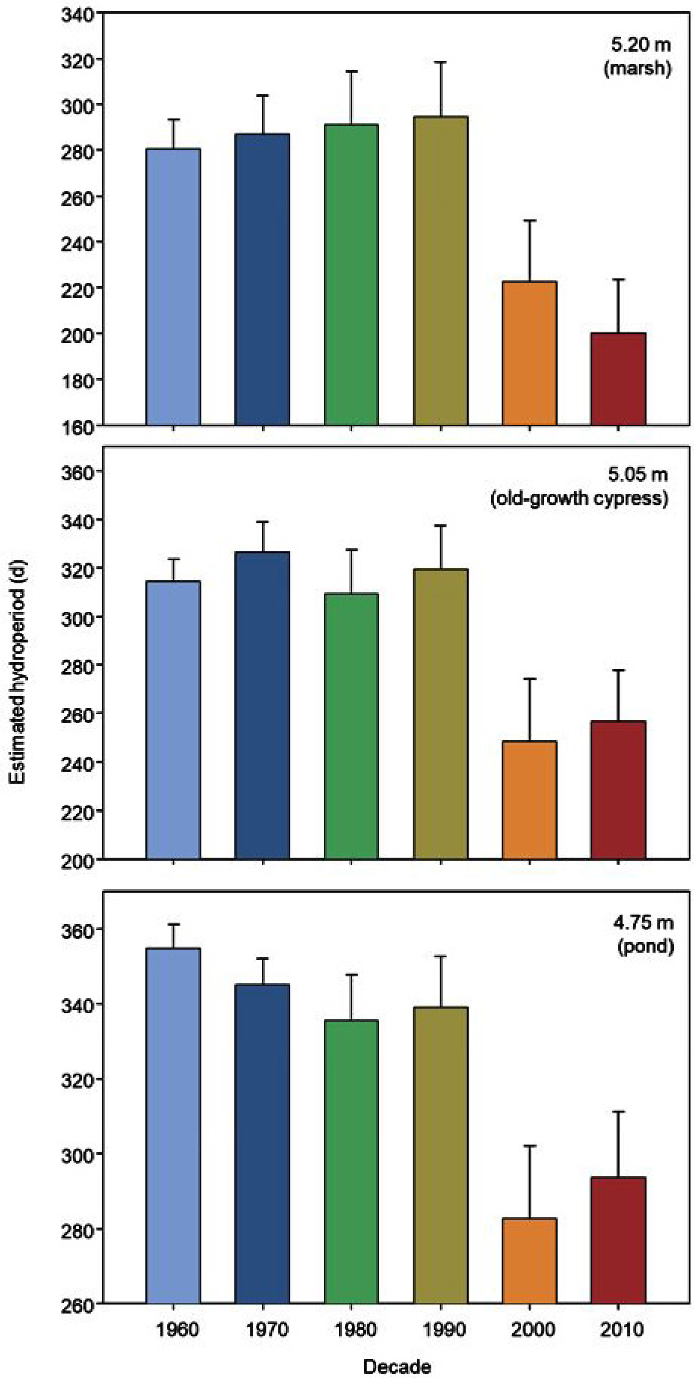
Landscape drainage. Until the 1950s most of the agricultural activity in southwest Florida was open range for cattle. Irrigated cropland acreage in Collier County, FL increased nearly 5 times (5,534 ha to 27,093 ha) from 1954 to 2012 (U.S. Bureau of the Census 2014, 1956). Expansion and intensification of agricultural development throughout this region has resulted in a lower wet season water table at varying depths below ground over large

FIGURE 2. Median daily surface water level through the water year for each decade, WY1960-WY2019 . Dashed vertical line represents the average day of peak water level (September 20). Ground level at the B gauge is at 4.60 m. Surface water levels are consistently in the same range during the summer/fall wet season in all decades. Median water levels in the 1960s through the 1990s were consistently and dramatically higher throughout the spring dry season than they were in the 2000s and 2010s, when they were below ground at the B gauge May through early to mid-June.



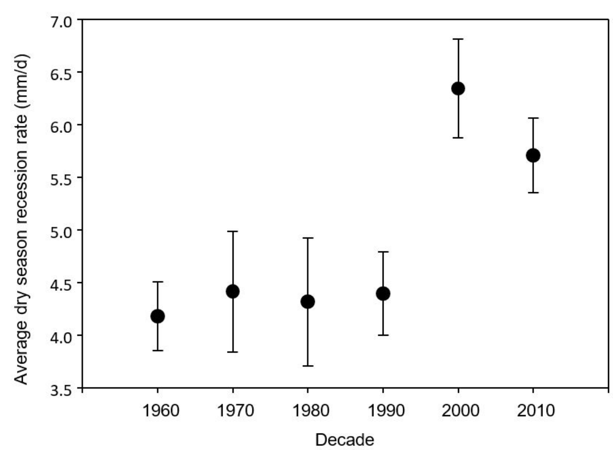
areas. In areas with some relief, systems of ditches drain large areas directly into major wetlands. In areas with little relief, pumps are used to remove water from farm fields and lower surface and shallow groundwater to depths of 45-60 cm below ground to provide sufficient aerated soil for the roots of the vegetable and tree crops (Edward Hanlon, personal communication). Pumped water is sent directly into adjacent wetlands or into retention areas, from which it drains into nearby flowways and increases wet season flows through these wetlands. This practice greatly reduces the amount of upstream surface water and shallow groundwater present when the dry season begins. Loss of upstream wet season storage would inevitably contribute to the dry season water table decline we are seeing at CSS. It is also likely that agricultural pumping causes CSS to receive increased water in the wet season, allowing higher elevation habitats (those inundated only in the wet season: hammock forest, pine flatwoods, wet prairie) to maintain historic hydroperiods in a drained landscape.

FIGURE 3. Average estimated hydroperiod (days inundated per water year) by decade, WY1960-2019, at three lower elevation habitats at Corkscrew Swamp Sanctuary. Despite no appreciable variation in rainfall, hydroperiods in the 1960s through 1990s were significantly longer than they were in the 2000s and 2010s. No decadal variation was observed in higher elevation habitats.



Large areas downstream of Corkscrew Swamp have been converted to low density residential development, made possible by a grid of canals that rapidly drain wet season surface water and groundwater from the adjacent landscape and carry it to coastal estuaries (SFWMD 2017). While the canals have numerous weirs intended to slow flows during drier parts of the year, the transmissivity of porous sand and limestone substrates allows water to steadily drain the landscape through the seven month dry season by simply going around or under the weirs. The upper ends of the Golden Gate Main and Faka Union canals do not reach directly into CSS; however, the Corkscrew Canal and the flowways leading to the Cocohatchee Canal do extend into the lower end of the Bird Rookery Swamp, an integral component of Corkscrew Swamp. These canals and flowways directly drain wet season surface waters. In

FIGURE 4. Average dry season recession rate (mm/d) of surface water at the B gauge each decade WY1960-2019. Error bars represent ±1 SE. Significantly higher recession rates in 2000s and 2010s resulted from water levels reaching the same wet season peak but then falling to markedly lower dry season water levels. A long, slow recession of water levels during the dry season concentrates aquatic fauna in shallow water and is critical for making food available for higher trophic levels, particularly nesting wading birds.



order to enhance flood protection for the rapidly urbanizing watersheds, the flow conveyance capacities of several of these canals were increased by additional channelization during the last two decades. This included extensive channel improvement and culvert replacements in the Corkscrew Canal in 2006 and resulted in a noticeable increase in peak wet season stages and lower dry season stages in the following decade downstream of CSS (Ananta Nath, personal communication).

Additionally, ditches associated with the construction of logging trams in the 1950s that extend into the southern end of CSS help rapidly convey wet season surface water flows to the canals. The southwesterly flow gradient of the surficial aquifer continues to recharge the base flows of the canals and wetland sloughs as the surface water levels begin receding during the onset of the dry season. This year-round wet and dry season drainage steepens the downstream gradient and very likely contributes to the lowered dry season water levels recorded at CSS. It is important to note that a detailed study of CSS environmental conditions was conducted in the mid-1970s (Duever et al. 1978, 1976, 1975, 1974). At that time there was relatively little agricultural activity or residential development in the upstream or downstream Corkscrew watershed and the recently completed Golden Gates Estates canal system (which terminated about 3 km south of the Sanctuary) appeared to be having minimal impacts on the ecology of CSS.

Dry season groundwater levels within CSS are likely to have also had an impact due to the swamp's geological setting. Corkscrew Swamp lies in an elongated mineral-substrate depression. The eastern edge of the depression is located at the eastern edge of the old-growth bald cypress forest ~6 m above MSL (mean sea level) and its bottom is located in the center of Corkscrew Swamp at ~3-4 m above MSL. While seasonal water level profiles along a transect crossing this depression show a relatively flat wet season water surface (Duever 1988), there is a distinct drawdown (up to 1 m) in the water level profile in the vicinity of an extensive shell bed on the east side of the bald cypress forest during the dry season. This suggests that there are groundwater flows out of CSS through the shell bed that are likely being intercepted by the downstream canals (Duever et al. 1986).

Water Supply Withdrawals. The primary aquifer influencing water levels at Corkscrew Swamp is the Surficial Aquifer, which includes the water table aquifer and the Lower Tamiami Aquifer (SFWMD 2017). In 2001 the South Florida Water Management District adopted a Minimum Flows and Levels rule specifying a minimum water level for the Lower West Coast Surficial Aquifer System that must equal the structural top of the aquifer. As of 2009, approximately 50% of the Public Water Supply was being provided by the Surficial Aquifer, which was maximizing its potential supply, so that additional increases in allocations are limited. In 2014 agricultural uses were 64% of the southwest Florida water supply (SFWMD 2017), and aside from rainfall, groundwater is the only source of water available within the Corkscrew watershed. Winter vegetables and citrus are the major agricultural crops throughout southwest Florida and in the Corkscrew watershed. Winter vegetables typically require drainage from late summer into winter, and irrigation from early

FIGURE 5. Daily surface water level (m NGVD29) at Corkscrew's B gauge WY1961 and WY2018. Dashed vertical line represents the landfall date (September 10) of both Hurricane Donna (WY1961) and Hurricane Irma (WY2018). Ground level at the B gauge is 4.60 m. The similar timing and rainfall inputs of these two storms provided an opportunity to compare dry season water level recession patterns before and after the hydrologic changes described in this study.

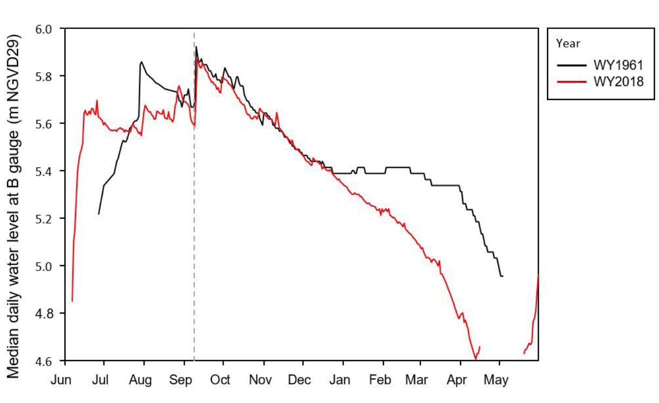
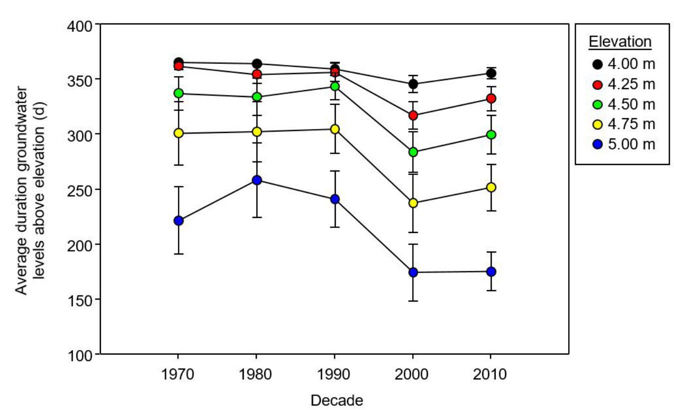


FIGURE 6. Average annual duration (days per year) groundwater levels were above elevation at 4.00, 4.25, 4.50, 4.75, and 5.00 m NGVD29 each decade WY1960-2019. Error bars represent ±1 SE. At 4.25 m and 4.50 m, groundwater levels were significantly lower in the 2000s and 2010s than previous decades. A similar trend was seen at other groundwater elevations and patterns are analogous to those seen in hydroperiod of surface water.

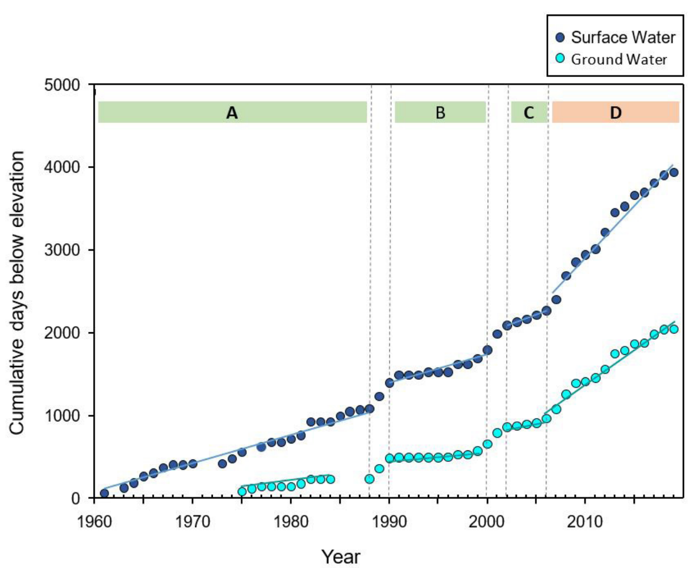


winter into mid-spring. Citrus farming, which expanded into south Florida in the 1980s following severe freezes in central and north Florida (Shukla et al. 2006), requires year-round drainage and irrigation to consistently maintain groundwater levels ≈60 cm below ground (Edward Hanlon, personal communication).

Population has steadily increased in southern Florida in recent decades, with southwest Florida cities frequently leading the state in growth. Between 1950 and 2010, Collier County population increased 50X (6,488 to 321,520) and Lee County population increased 26X (23,404 to 618,754) (U.S. Bureau of the Census 2010; Forstall 1995). Groundwater withdrawals have necessarily increased to support the needs of this increased population and its associated landscaping practices, which currently use about 31% of southwest Florida's water supply (SFWMD 2017). Given the increasingly large extractions of water from the Surficial Aquifer over the past 60 years for urban uses, it is likely that these water withdrawals contribute to the dry season water level drawdowns observed at CSS.

Evapotranspiration. Evapotranspiration (ET) was the primary natural mechanism controlling the outflow of water from predevelopment southwest Florida. A recent three-year study of ET losses from natural southwest Florida plant communities showed annual ET losses from four of five different Big Cypress Swamp plant communities averaged

FIGURE 7. Cumulative days below elevation each year WY1960-2019 in surface water (5.05 m NGVD29) and groundwater (4.50 m NGVD29) data. Missing years resulted from data gaps (see Methods). Dashed vertical lines indicate inflection points. Regression lines for surface and groundwater data during each of four time periods (A-D) are shown and described in Table 2. While drought years resulted in short periods of increased slope/drier conditions (~1990, ~2000), increased slope/drier conditions were seen consistently beginning in 2006.



73-81% of annual rainfall (Shoemaker et al. 2011). The majority of the Corkscrew watershed was originally dominated by wetlands, with smaller areas of uplands that had a water table close to the ground surface in the wet season. Decades of fire suppression have facilitated natural plant community succession from a shallowly-rooted herbaceous vegetation dominated ecosystem (open pine forests, herbaceous marshes, wet prairies) to one dominated by dense, multistrata shrub and/or pine and hardwood forests with deeper roots that provide greater access to the dry season water table. Carolina willow has extensively invaded freshwater marshes throughout South Florida and with its deeper roots has been shown to increase wetland ET water loss (Budny and Benscoter 2016, McLaughlin et al. 2011). Additionally, a recent study by McCollom et al. (2017) documented a large increase in slash pine and laurel oak density over ≈40 years at a site near CSS. This conversion of herbaceous plant communities to communities that are denser, with more deeply-rooted woody vegetation and more species with greater leaf area has significant potential to increase dry season ET rates . Increasing air temperatures associated with climate change (Allen et al. 2018) has also increased ET rates.

Implications for Plant Communities and Fire

Links between hydrology, plant communities, and fire in this ecosystem are critical for understanding the implications of the hydrologic change recorded at CSS. The relationship between hydrology and fire can easily be seen along the westward-sloping topographic gradient at CSS, from the Blair Audubon Center to the old-growth bald cypress swamp (Duever 1988; Wharton et al. 1977). From the fire-tolerant pinelands that exist on higher and drier ground, elevation decreases and fire-tolerant pinelands give way to herbaceous wet prairie at an intermediate elevation, too wet for pines and burning too frequently for bald cypress. Farther west, a gradient of smaller, denser bald cypress trees near the edge of the forest to larger, more-scattered trees in the center of the forest reflects the age structure of the forest (Duever 1988; Duever et al. 1984), with the strong positively-correlated size/age structure established by the site's hydrology and fire regimes in relation to the depth of organic soils, that have accumulated over the past 5,000 years in the mineral substrate depression that underlies the bald cypress forest (Duever et al. 1982). The depth of the organic soil ranges from a few centimeters at the edge of the depression to over two meters in its center. As the water table retreats below ground during the dry season, more and more of the organic soil profile loses contact with the water table and more of the forest becomes vulnerable to severe fires.

The fine structure of Corkscrew's organic soils allows water to wick upward from the water table, making moisture more readily available to the roots of vegetation (Duever

1988; Duever et al. 1984). The combination of evaporation from this relatively moist substrate and transpiration from vegetation creates a moist microclimate below the forest canopy, which helps to protect it from damaging fires. This moist microclimate also supports a highly-diverse understory plant community that includes a number of critically imperiled or endangered sub-tropical epiphytes (Wilder and McCollom 2018). Many of these epiphytes, like the ghost orchid (*Dendrophylax lindenii*), may be at increased risk without standing water to buffer low temperatures during the winter and low humidities during the dry season (Houlihan et al. 2019).

The potential for changes in the hydrologic regime to dramatically change the character of this system can be seen through CSS's geologic history. Corkscrew's central marsh is higher than the surrounding old-growth bald cypress forest (Duever et al. 1974), so the water table there falls below ground sooner than in the adjacent bald cypress forest. This allows more frequent surface fires that have limited the invasion of woody vegetation, just as is seen in the wet prairies on the outside of the bald cypress forest. Soil cores from the central marsh indicate the presence of charcoal throughout the 5,000 year record (Stone and Gleason 1976). Radio-carbon dating of the organic material on top of an ash layer at the bottom of one of the small lakes in the old-growth bald cypress forest indicated the lake was created by a fire that occurred over 500 years ago (Duever 1988; P.A. Stone personal communication). Interestingly, based on ring counts of bald cypress tree cores, the oldest bald cypress trees at Corkscrew Swamp are a little over 500 years old. This suggests a severe drought and fire may have eliminated most, if not all, of the Corkscrew Swamp bald cypress forest and created the many small lakes that are still present in today's forest. However, most of the organic soils were still present after the fire, and when the rains returned the forest eventually reestablished the structure we see today in response to the long-term, natural hydrologic and fire regimes.

Given these relationships between hydrologic processes, fire, and substrates, it is clear that changes in hydrology can have major effects on the character and even the existence of plant communities in natural areas like Corkscrew Swamp. These changes can range from slow long-term shifts in plant communities along the hydrologic gradient to the complete elimination of one or more of the existing communities as a result of a major fire event (Duever and Roberts 2013). These kinds of changes can be clearly seen in the nearby Golden Gate Estates and Picayune Strand State Forest where deep canals severely drained the landscape which has resulted in a range of transitions in plant communities as a function of depth of organic soils, degree of drainage severity, and spatial variation in the occurrence and severity of fire events.

Implications for Animal Communities

Throughout the Everglades, reducing wetland hydroperiod changes the structure of fish communities and reduces the standing stock of large and small fishes and freshwater shrimp (e.g., Trexler et al. 2005; Chick et al. 2004; Loftus and Eklund 1994). We predict the reduction in the seasonal duration of standing water observed at CSS since 2006 would significantly reduce the standing stock of small fishes, freshwater shrimp, and crayfish that form the base of the aquatic food web and support higher trophic levels. Reduced aquatic prey production is of particular concern for wading birds and alligators in this ecosystem. Decreased food availability decreases wading bird productivity in the Everglades (Frederick et al. 2009) and has likely decreased wading bird populations at CSS. While dry season recession rates are a key factor in the creation of the high-density prey patches wading birds rely on (Botson et al. 2016), the dry season recession rates seen at CSS in recent years are notably faster than those typically seen in other parts of the Everglades. It is uncertain how both the refuge-seeking aquatic prey and prey-searching wading birds respond when water levels are falling so quickly. In addition to stress associated with reduced availability of aquatic prey, flooded conditions in old-growth bald cypress areas beneath the Corkscrew colony are necessary to attract alligators who protect nests from mammalian predators (Nell et al. 2016). While even relatively shallow water beneath nesting sites can restrict travel by mammalian predators (e.g., raccoons, foxes, and rats) (Frederick and Collopy 1989), the hydroperiod reduction observed in Corkscrew's bald cypress has put the Corkscrew wood stork colony at increased risk of predation, particularly in dry years. While causation cannot be determined or implied, the Corkscrew wood stork colony has markedly declined in recent decades concurrent with the changes in wetland hydrology described in this study (S.E. Clem, unpublished data). Reduction of the aquatic prey base may also significantly decrease alligator body condition (Brandt et al. 2016). Shortened hydroperiod can also change alligator occupancy patterns across the landscape, moving them out of peripheral marshes and into deeper habitats, and concentrating alligators of different size classes in remaining water bodies, ultimately increasing competition for food resources, fighting, and incidence of cannibalism (Mazzotti and Brandt 1994).

CONCLUSION

Analyses of a 60-year water level monitoring dataset indicated no major changes in the CSS hydrologic regime for the first 40 years followed by a dramatic lowering of the dry season water table over the past 20 years. This change resulted in a markedly shortened hydroperiod in all wetland habitats that typically hold at least some water well into the dry season (i.e., marshes, old-growth bald cypress forests and ponds). Dry season groundwater levels on the sanctuary were also lower for longer periods of time. The magnitude of this change is such that CSS's Lettuce Lake, an important dry season aquatic refuge along the iconic boardwalk, dried down approximately once every five years from 1960-1999 and more recently, approximately four of every five years 2000-2019.

The altered dry season hydrology documented at CSS has significant implications for wildlife, native plant communities, and wildfire risk. Of particular importance (and at particular risk) are federally-threatened wood storks, an indicator species in the Everglades that has historically nested at CSS in very large numbers, and depend on (1) high densities of aquatic prey available in the surrounding landscape throughout their nesting season, and (2) standing water beneath the CSS old-growth bald cypress forest where they nest. The hydrologic changes documented in this study reveal deleterious reductions in both wetland hydroperiods, which reduces prey availability, and dry season inundation of the CSS old-growth bald cypress. The timing of these changes aligns with the decline in the CSS wood stork colony that has been observed in recent decades. Additionally, the drier organic soils and associated vegetation is making CSS's old-growth bald cypress much more vulnerable to catastrophic wildfires.

In this paper we focused on three possible causes for the severe dry season water level drawdowns that we have clearly documented at CSS: landscape drainage, water supply withdrawals, and increased evapotranspiration associated with succession of a primarily herbaceous landscape to an increasingly densely forested landscape. For some of these factors we were able to provide good support for the nature and magnitude of potential impacts they could have on local hydrology, while for others we have relied on more limited information. While we chose these factors because we know they have all been occurring in southwest Florida over the last 60 years concurrent with the described CSS hydrologic changes, our intent was to provide a starting point for modelling and additional research aimed at quantifying and evaluating the relative contribution of each of these factors. Currently, an effort is underway to integrate this information into a hydrologic model that will facilitate an evaluation of the relative importance and spatial extent of each of these human influences. We are hopeful that this will ultimately lead to better long-term management of our southwest Florida landscape.

Despite the dramatic hydrologic changes we documented in the early 2000s, this system's marked inter- and intra-annual variation in hydropatterns obscured the change until they were put into the context of a long-term data set. This underscores both the importance and some of the limitations of long-term ecological monitoring, particularly in systems with a high degree of inherent variability and a wide variety of factors simultaneously affecting the site. ■

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