Recent Hydrologic Change at Audubon's Corkscrew Swamp Sanctuary

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EXECUTIVE SUMMARY

Located in southwest Florida, Corkscrew Swamp is the largest remaining old-growth cypress swamp in the world. Daily water level monitoring began at Corkscrew Swamp Sanctuary (CSS) in 1959 when there had been relatively few hydrologic alterations in its watershed. Agricultural and residential development have since come to dominate the watershed, and a 55-year-long monitoring record has detected substantial changes in the swamp's hydrology.

Rainfall records indicate no significant changes from 1960 to 2015. Water level data indicate no decadal change in the timing or magnitude of peak wet season conditions or in the hydroperiods of upland habitats (hammock forests and pine forests) or wet prairies. Hydroperiods decreased 41% in marshes, 27% in bald cypress, and 23% in pond habitats, with the most notable change occurring between the 1990s and 2000s. The frequency of dry down at Corkscrew's Lettuce Lakes increased from 22% of years WY1960-1999 to 81% of years WY2000-2015, with the duration of dry down increasing 41%. Additionally, dry season biweekly water level recession rates increased 1.4-2.3X between these two time periods.

There are a number of likely interacting causes of the hydrologic changes we observed at CSS: (1) Upstream agricultural and residential development lowers wet season water levels by sending water downstream (to CSS), thereby eliminating wet season water storage that maintained downstream dry season water levels; (2) Population growth and agricultural expansion has required increasingly larger extractions from southwest Florida's freshwater aquifers underlying CSS; (3) Increased downstream drainage for residential development has increased hydrologic gradients, and thus outflows from Corkscrew Swamp; and (4) In undeveloped areas, decades of fire suppression has led to succession of open pine forests with a dense herbaceous groundcover and herbaceous marsh and wet prairie plant communities to dense, more-deeply rooted, multi-strata shrub and/or hardwood forests which could be increasing evapotranspiration rates.

The implications of the hydrologic change described in this study are vast. As wetland water levels are lowered and hydroperiods shortened, it is expected that plant communities along south Florida's very low topographic gradient will gradually move downslope, resulting in the partial or complete loss of wetlands, depending on their position along the topographic gradient and the severity of drainage. This change can happen slowly over long periods of time or very rapidly due to an altered fire regime on these drained sites. We predict the reduction in hydroperiod and more rapid dry season water level recession rates observed at CSS since 2000 will significantly reduce the standing stock of small fishes and freshwater shrimp, reducing the biomass of this critical prey source for wading birds, alligators, otters and other higher trophic level animals. In addition to stress associated with reduced availability of aquatic prey, a decline in flood conditions beneath Corkscrew's Wood Stork colony leaves this colony more vulnerable to mammalian predators. Reduced hydroperiod also changes alligator occupancy patterns across the landscape, moving them out of peripheral marshes into deeper habitats and ultimately concentrating alligators of different size classes in remaining water bodies and increasing competition for food resources, fighting, and incidence of cannibalism.

We further discuss ecological implications of this marked hydrologic change on CSS and the Corkscrew watershed and we demonstrate and underscore the value of long-term monitoring for detecting and documenting ecological change.

INTRODUCTION

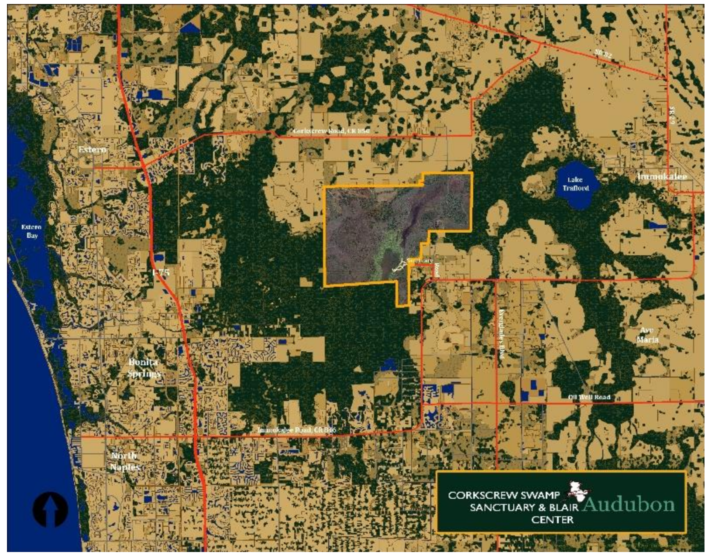

Figure 1. Location of Corkscrew Swamp Sanctuary (outlined in orange) within the Corkscrew watershed in Southwest Florida.

Corkscrew Swamp is the largest old-growth cypress swamp in the world. Located near the top of its watershed (Duever et al. 1976) the 13,000 acre National Audubon Society Corkscrew Swamp Sanctuary (CSS) is central to the 60,000 acre Corkscrew Regional Ecosystem Watershed (Figure 1), the largest intact watershed in southwest Florida. Recognized for its rich biodiversity and important ecological functions, Corkscrew is designated an Important Bird Area (Bird Life International), a National Natural Landmark (U.S. Department of the Interior) and a Wetland of International Importance (Ramsar Convention).

Like all of the Big Cypress Swamp, Corkscrew Swamp has a rainfall-driven, seasonally-pulsed hydropattern that drives the ecology of its plant and animal communities (Duever et al. 1984). The sanctuary is dominated by wetlands, including herbaceous organic soil marshes and mineral soil wet prairies, as well as the old growth cypress forest. Smaller areas of upland 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 1984), particularly the organic soils that have been accumulating over the past 5,000 years (Kropp 1976, Gleason & Stone 1994). Wet season water levels sort the plant communities into upland, wetland, and aquatic communities. Within these groups, fire sorts out their vegetative structure (Duever & Roberts 2013). A high fire frequency produces predominantly herbaceous communities. With a decreasing fire frequency, over time the herbaceous communities first succeed to shrubby vegetation, such as willow or wax myrtle, then to fire-tolerant forests of pine or cypress, and finally to fire-intolerant hardwood forests.

The duration of inundation and timing of dry-season water level recession are critical factors for this ecosystem's animal communities, particularly Corkscrew's Wood Stork colony which was historically the largest breeding colony in North America. Inundation of the landscape in the wet season allows fish and crayfish communities to disperse and reproduce. The duration of inundation structures the aquatic community and ultimately controls the biomass of aquatic prey, with longer hydroperiods leading to larger fish and more prey biomass (Loftus & Eklund 1994). A slow recession of surface water throughout the dry season concentrates aquatic prey making them available for higher trophic levels like wading birds, whose nesting season is synchronized with this period of high food availability.

METHODS

Data Collection

Daily surface water depth was recorded beginning in November 1959 from a staff gauge at the sanctuary's Lettuce Lake, a deep pond (ground level = 4.60 m) within the bald cypress strand. All elevations stated in this paper are NGVD29. When possible, missing daily surface water data were estimated based on correlation with a second staff gauge approximately 200 m away from the first, near the outer edge of the cypress. Linear interpolation was used to supplement daily surface water depth data when water levels were above ground at both gauges and the number of consecutive missing values was <30. Despite these efforts, 9 data gaps (gap size = 38-267 days) remained in our 55-year daily surface water level data set which prohibited inclusion of 5 Water Years (WY) in most analyses of surface water level and hydroperiod: WY1960, WY1962, WY1971, WY1972 and WY1976. We defined a Water Year as June 1 of the previous calendar year to May 31 of the named calendar year.

A U.S. Geological Survey well (C-492) was installed in 1970 in the headquarters area at CSS, approximately 380 m southeast of the Lettuce Lake gauge. Mean daily groundwater level data for Well C-492 were obtained from the South Florida Water Management District DBHYDRO environmental database (https://www.sfwmd.gov/science-data/dbhydro). Data were obtained from October 1973 to present except for a gap from 10/1/1984 to 11/18/1986. The ground surface elevation at the well was surveyed at 5.61 m. The well was originally recorded as being 20.0 m deep and open to the aquifer from 18.3 to 20.0 m below the ground surface.

Daily rainfall at CSS was recorded beginning November 1959 using a standard rain gauge. While the exact location of the rain gauge changed over the years, all locations were within 100 m of the current location. Due to intermittent gaps in Corkscrew's rainfall data, total monthly rainfall for WY1960 through WY2015 were also obtained from the National Weather Service station at Page Field Airport in Fort Myers, approximately 28 km northwest of CSS (Menne et al. 2012).

Data Analyses

Staff gauge data were used to estimate daily water levels (WY1960-2015) at six elevations that correspond with Corkscrew habitats. Elevations were selected using WY1960-1979 surface water level data such that the average number of days per year that water levels were at or above each elevation matched published hydroperiods for these habitats (Duever et al. 1986). Selected habitats (and corresponding elevations) were pond (4.75 m), bald cypress (5.05 m), freshwater marsh and pond cypress (5.20 m), wet prairie (5.40 m), pine forest (5.50 m), and hammock forest (5.65 m). Hydroperiod for each habitat in each hydrologic year was estimated by calculating the total number of days the water level was greater than or equal to the corresponding elevation.

Well data were used to examine water levels at five elevations: 3.66 m, 3.96 m, 4.26 m, 4.57 m, and 4.87 m. Duration above each belowground elevation in each hydrologic year was calculated as the total number of days the water level was greater than or equal to the corresponding elevation.

Average bi-weekly dry season recession rates were calculated from staff gauge data ((depth day 15 - depth day 1) / 14) beginning week 27 of the hydrologic year (November 30-December 13). Analyses of recession rates omitted the late dry season (weeks 43-52 (March 22-May 30)) due to drying of staff gauge location and the resulting paucity of water level data during this time period in recent decades.

Analysis of variance (ANOVA) was used to examine temporal variation in peak wet season water level, hydroperiod, recession rates, and rainfall. Tukey pairwise comparisons were used to explicate significant results.

RESULTS

Annual Climate Variation

Annual rainfall at CSS averaged 151.5 ± 3.6 cm and did not vary across decades at CSS ($F_{5,45}$ = 1.66, P = 0.164) or Page Field ($F_{5,49}$ = 0.41, P = 0.841). Monthly rainfall totals did not vary across decades for any month at either location (all P > 0.05). Annual rainfall total and monthly rainfall patterns were similar to those described in other regions of the Everglades (Duever et al., 1994).

Wet Season Surface Water Levels

No decadal variation was seen in the average date ($F_{5,45}$ = 0.76, P = 0.580, $\bar{x}$ = September 18) or magnitude ($F_{5,45}$ = 1.08, P = 0.383, $\bar{x}$ = 102.5 ± 1.8 cm) of Corkscrew's peak water level (Figure 2). We defined 'wet season' as the 4-month period of high water levels centered on this peak: July 18-November 18 (noting that this period is not consistent with the average period of peak rainfall that defines most wet season definitions in this system). Higher elevation habitats that are only inundated in the wettest part of the year saw no variation in hydroperiod across decades, including hammock forest, pine forest, and wet prairie (Table 1).

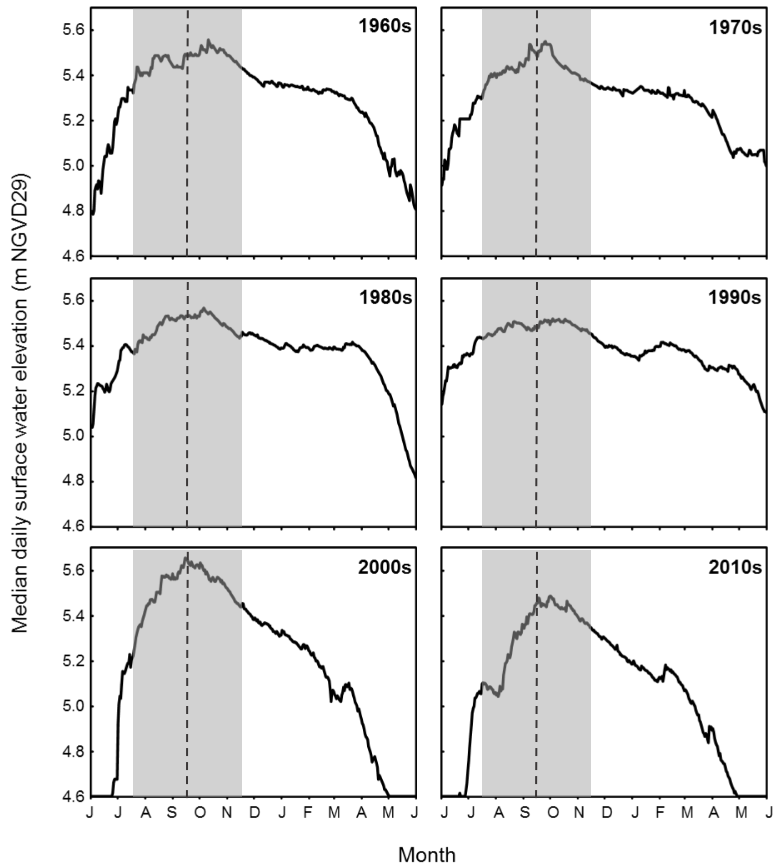

Figure 2. Median daily surface water elevation throughout the hydrologic year (June 1 through May 31) at Corkscrew Swamp Sanctuary's staff gauge (Lettuce Lake) for each decade WY1960 through WY2015. Dashed lines indicate the average date of peak annual water level across decades and shaded swaths (July 18-November 18) provide a 4-month period of peak water levels defining our 'wet season.' Ground level at staff gauge=4.6 m NGVD29.

Table 1. Analysis of variance across decades (1960s to 2010s) for estimated hydroperiod of wetland habitats within Corkscrew Swamp Sanctuary.

Habitat	*df*	*F*	*P*	Hydroperiod variation across decades
Hammock forest	5,49	1.29	0.284	No variation ($\bar{x}$ = 9.6 ± 2.8 d)
Pine forest	5,48	1.68	0.157	No variation ($\bar{x}$ = 57.6 ± 6.8 d)
Wet prairie	5,45	2.08	0.085	No variation ($\bar{x}$ = 132.6 ± 12.0 d)
Freshwater marsh/ Pond cypress	5,46	3.50	**0.009**	41% (3.8 mo.) decrease 1960s to 2010s
Bald cypress	5,47	4.35	**0.002**	27% (2.8 mo.) decrease 1960s to 2010s
Ponds	5,50	6.01	**< 0.001**	23% (2.6 mo.) decrease 1960s to 2010s

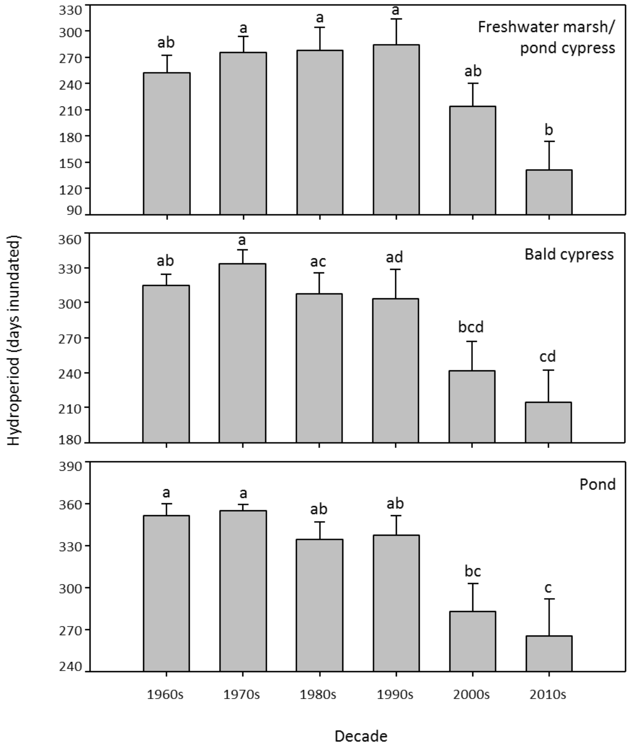

Figure 3. Estimated hydroperiod (days inundated) at three wetland habitats within Corkscrew Swamp Sanctuary (pond=4.75 m NGVD29, bald cypress=5.05 m NGVD29, freshwater marsh/pond cypress=5.20 m NGVD29) based on staff gauge data WY1960 through WY2015. Different letters represent significant differences within each habitat (Tukey $P \le 0.05$) and error bars represent 1 SE.

Dry Season Surface Water Levels and Recession

While water levels went below ground at the Lettuce Lake staff gauge during some individual years, the decadal average daily water level from WY1960 to WY1999 was always above ground. The decadal average water levels from WY2000 to WY2015 indicated water levels going below ground for over two months (Figure 2). A marked decrease in hydroperiod across decades was seen in all lower elevation habitats that are typically inundated well into the dry season, including freshwater marsh/pond cypress, bald cypress, and ponds (Table 1, Figure 3). The most marked change in hydroperiod was seen between the 1990s and 2000s. From the 1960s to the 2010s Corkscrew's hydroperiod decreased 41% (3.8 mo.) in marshes, 27% (2.8 mo.) in bald cypress, and 23% (2.6 mo.) in ponds.

Water levels dropped below ground at the Lettuce Lake staff gauge in 22% of years WY1960-1999 and 81% of years WY2000-2015. In the years the Lettuce Lakes did dry (water level ≤0 at the staff gauge), the average duration of dry down increased 41%, from 58 days in WY1960-1999 to 82 days in WY2000-2015. Focusing on months that were constantly inundated in all years, average September, October and November water levels were unchanged from WY1960-1999 to WY2000-2015 while average December and January water levels decreased 11.5% and 18.8%, respectively (Table 2).

Table 2. Analysis of variance between WY1960-1999 and WY2000-2015 for the average monthly water level. Analyses focused only on months that were constantly inundated in all years.

Month	*df*	*F*	*P*	Variation in average monthly water level from WY1960-1999 to WY2000-2015
September	1,52	0.04	0.834	No change
October	1,50	0.01	0.918	No change
November	1,52	1.99	0.165	No change
December	1,53	5.71	**0.020**	Decrease 11.5% (8.9 cm)
January	1,53	10.33	**0.002**	Decrease 18.8% (14.0 cm)

Based on the timing of observed hydroperiod changes we compared dry season recession rates prior to marked changes in hydrology (WY1960-1999) with those of more recent years (WY2000-2015). Average recession rates were different among these time periods in 7 of the 8 bi-weekly periods examined, with recent rates 1.4X to 2.3X higher than those seen previously (Table 3, Figure 4). The percentage of dry season weeks experiencing reversal events (bi-weekly recession rate <0) did not vary between WY1960-1999 and WY2000-2015 ($F_{1,54} = 1.49$, $P = 0.227$, $\bar{x} = 33.3 \pm 4.3$ %).

Table 3. Analysis of variance across decades (1960s to 2010s) for bi-weekly dry season water level recession rates (mm/d).

Bi-weekly period	*df*	*F*	*P*
11/30 - 12/13	1,42	8.37	**0.006**
12/14-27	1,40	4.84	**0.034**
12/28 – 1/10	1,38	1.60	0.214
1/11-24	1,40	20.48	**< 0.001**
1/25 – 2/7	1,39	6.75	**0.013**
2/8-21	1,40	5.30	**0.027**
2/22 – 3/7	1,36	11.09	**0.002**
3/8-21	1,38	12.34	**0.001**

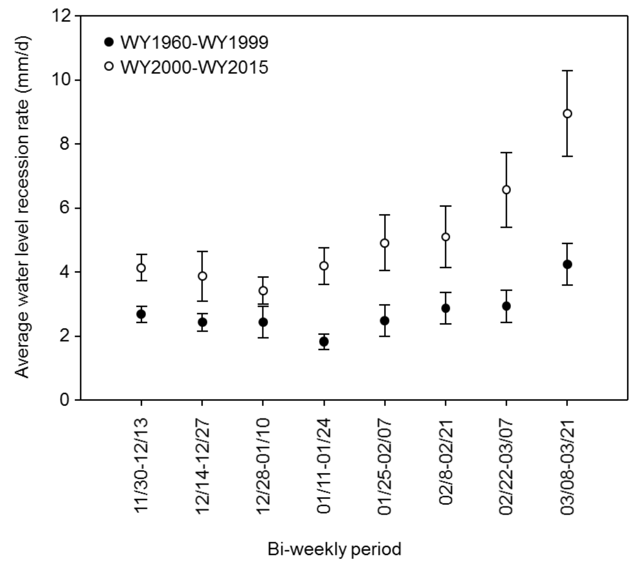

Figure 4. Average bi-weekly dry season water level recession rates (mm/d) WY1960-1999 (closed circles) and WY2000-2015 (open circles). Error bars represent 1SE.

Ground Water Levels

We saw little significant variation among decades in the average annual duration water levels were above our five groundwater elevations (Table 4A), although differences between 1970s-1990s and 2000s-2010s were suggested at several elevations. Direct comparison of these two time periods indicated that at 3.66 m the average annual duration water levels were above elevation WY2000-2015 was similar to WY1975-1999, but they were shorter than WY1975-1999 at all other elevations tested (Table 4, Figure 5).

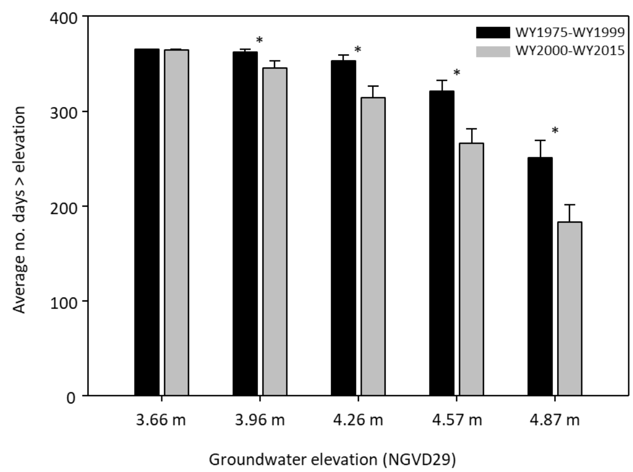

Figure 5. Average annual number of days above elevation (m NGVD29) for two time periods at five elevations in the C-492 groundwater well located at Corkscrew Swamp Sanctuary. Asterisks (*) indicate significant variation (P≤0.05) among time periods for each elevation and error bars represent 1 SE.

Table 4. Analysis of variance across decades (A) and between WY1975-1999 and WY2000-2015 (B) for the duration groundwater levels were above specified elevation. Asterisk (*) indicates that despite model significance (P < 0.05), Tukey pairwise comparisons indicated *P* > 0.05 for all pairs.

	A. Variation among decades			B. Variation before/after 2000			
Elevation (m)	*df*	*F*	*P*	*df*	*F*	*P*	Variation in duration above elevation
3.66	4,32	1.11	0.368	1,35	2.21	0.146	No variation ($\bar{x}$ = 364.6 ± 0.3 d)
3.96	4,32	1.76	0.161	1,35	4.64	**0.038**	4.7% shorter WY2000-2015
4.26	4,32	2.78	**0.044***	1,35	10.46	**0.003**	10.9% shorter WY2000-2015
4.57	4,32	1.89	0.137	1,35	8.16	**0.007**	16.9% shorter WY2000-2015
4.87	4,32	2.29	0.081	1,35	6.41	**0.016**	27.0% shorter WY2000-2015

Timing of Hydrologic Change

Cumulative annual number of days at or below 5.05 m at the Lettuce Lake staff gauge and 4.50 m at the C-492 well were plotted to pinpoint the timing of observed hydrologic change (Figure 6). Inflection points along this curve were similar for both data sets indicating at least some degree of connection between the Lower Tamiami and Surficial Aquifers. Average duration of dry down was consistent WY1960-1988 and WY1991-2000 (surface water $\bar{x}$ = 32.5 dry d/yr, ground water $\bar{x}$ = 11.9 dry d/yr) and was considered the baseline condition. Two periods had markedly drier-than-average conditions (WY1989-1990, WY2001-2002) and one period (WY2003-2005) was only slightly drier than average. From WY2006 to WY2015 the duration of annual low water levels was 4.0 mo. (4.5x) and 2.8 mo. (8.2x) longer than baseline conditions for surface and ground water, respectively.

DISCUSSION

The rainfall-driven seasonally pulsed hydrology of the Florida Everglades is a driving force in the system's ecology (DeAngelis 1994). Hydroperiod is a key factor controlling nearly all aspects of the distribution and abundance of Everglades plant and animal communities (Davis 1943, Duever 1984). It is important to note that a detailed ecosystem study of CSS was conducted in the mid-1970s to document the environmental conditions of an old-growth cypress swamp forest and its surroundings, particularly the relationships between plant communities and the dominant natural processes that controlled their character and distribution (Duever et al. 1974, 1975, 1976, 1978). At that time there was relatively little agricultural activity or residential development in the upstream and near-downstream CSS watershed and the recently completed Golden Gates Estates canal system (which terminated about 2 miles south of the Sanctuary) was having minimal impacts on Corkscrew Swamp.

In this study we found the hydroperiod of freshwater marsh and pond cypress, bald cypress and pond habitats at Corkscrew Swamp Sanctuary decreased 23-41% since the 1960s and 1970s. With rainfall patterns and the timing and magnitude of peak wet season water levels unchanged through time, the amount of surface water and groundwater our system loses during the dry season has increased markedly in recent years (Figure 2). This increased dry season water loss can be seen through dry season recession rates which are as high as 2.3x what was seen prior to WY2000 (Figure 4). Decadal analyses indicated the most abrupt decrease in hydroperiods occurred between the 1990s and the 2000s (Figure 3).

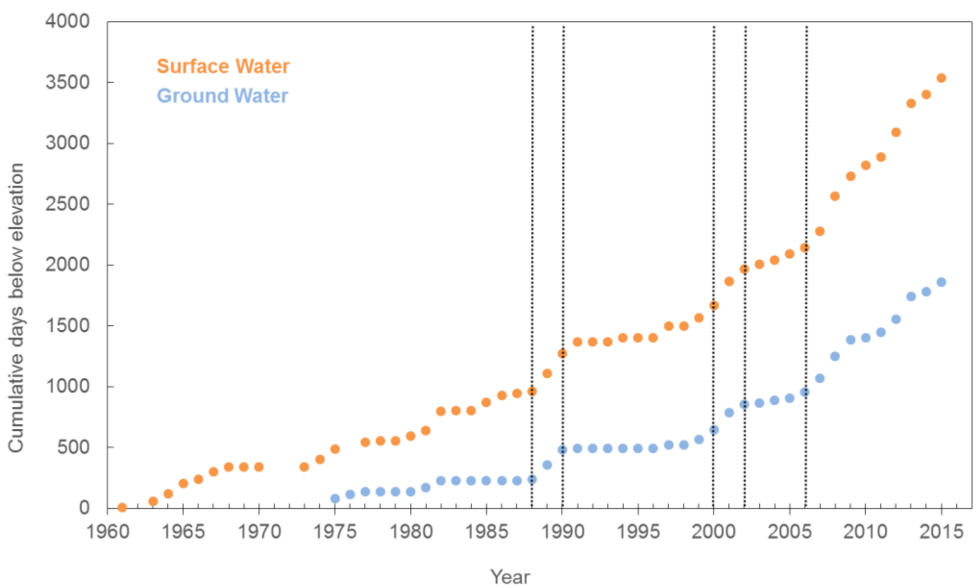

Figure 6. Cumulative annual days from 1960 to 2015 at or below elevations of 5.05 m in Corkscrew's bald cypress forest and 4.50 m in the C-492 well. Dotted vertical lines indicate visually apparent changes in the slope that represent changes in annual hydrologic patterns.

Links Between Hydrology, Plant Communities, and Fire

Understanding the links between hydrology, plant communities and fire in this ecosystem is critical in understanding the implications of the hydrologic change we've described at CSS. The relationship between hydrology and fire could easily be seen along the topographic gradient at CSS where the fire-tolerant pinelands exist on the high and drier ground around the Blair Audubon Center (Wharton et al. 1976, Duever 1988). Westward, toward the cypress, the elevation decreases and fire-tolerant pinelands give way to herbaceous wet prairie. The wet prairie is at an intermediate elevation, too wet for pines and burning too frequently for cypress. Farther westward, at lower elevations, interactions between hydrology and fire strongly influence the structure of the cypress forest. A gradient of smaller, denser cypress trees near the edge of the forest and larger, more-scattered trees in the center of the forest reflects the age structure of the forest (Duever et al. 1984, Duever 1988). The highly positively correlated size/age structure is established by the site's hydrology and fire regimes in relation to the depths of the organic soils that have accumulated over the past 5,000 years in a Pleistocene tidal channel that underlies the cypress forest (Duever et al. 1982).

The fine structure of 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. However, the depth of organic soil also exists on an underlying mineral soil topographic gradient from the edge of the tidal channel, where its thickness is only a few inches, to the center of the channel, where it can have a thickness of over 6 feet. Thus, as the water table declines below ground during the dry season, more and more of the organic soil along the gradient into the cypress forest losses contact with the water table and more and more of the forest becomes increasingly vulnerable to severe fires. Thus, the decreasing frequency of severe fires from the edge to the center of the cypress strand that have occurred over centuries has created the size and age structure of the Corkscrew Swamp cypress forest.

The hydrology-fire-organic soil relationship can also be seen in the presence of charcoal throughout 5,000 year-old soil cores taken from the Central Marsh, which is surrounded by Corkscrew's old-growth cypress forest (Stone & Gleason 1976). The Central Marsh exists because its surface is higher, like an island in the surrounding cypress forest (Duever et al. 1974), so the water table there falls below ground sooner than in the adjacent cypress forest. This allows more frequent fires that have limited the invasion of woody vegetation, just as was seen in the wet prairies on the outside of the cypress forest.

A radio-carbon date of the organic material that has accumulated on top of an ash layer at the bottom of one of the small lakes in the old-growth cypress forest indicate that the lake was created by a fire that occurred over 500 years ago (Duever 1988, PA Stone pers. comm.). Interestingly, based on ring counts of cypress tree cores, the oldest 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 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.

Implications for Animal Communities

Aquatic fauna. A number of uncertainties remain regarding the relationship between aquatic fauna populations and hydrology (hydroperiod, water depth, recession rates) in the less-studied Western Everglades (Duever 2005, Liston & Lorenz 2011). However, with similar aquatic fauna and driving environmental factors, our understanding of Everglades ridge-and-slough marshes can likely be applied to this paper. In the Everglades, frequency and severity of drought are a key drivers of aquatic fauna communities (Ruetz et al. 2005, Trexler & Goss 2009). Inundated periods allow aquatic fauna communities to disperse throughout the landscape and increase in biomass (via growth and reproduction) while dry season water level recessions concentrate them in long hydroperiod wetlands, depressions (e.g., alligator holes), and ponds. Decreasing the hydroperiod of Everglades marshes changes the structure of fish communities and reduces the standing stock of large and small fishes, crayfish, and freshwater shrimp (e.g., Loftus and Eklund 1994; Chick, Ruetz & Trexler 2004; Trexler, Loftus & Perry 2005). In addition to reduced production of aquatic prey, dry season recession rate and microtopography are critical drivers of the biomass of fish available to higher trophic levels in the dry season (Botson, Gawlik & Trexler 2016). We predict the reduction in hydroperiod observed at Corkscrew Swamp Sanctuary since 2006 would significantly reduce the standing stock of small fishes and freshwater shrimp, reducing the biomass of this critical prey source for wading birds, alligators, otters and other higher trophic level animals. It is unclear what effect the observed increased recession rates have on dry season aquatic fauna concentrations (e.g., whether fish are able to keep up with the rapid drying rates to reach deeper pools).

Wading birds. Reduced aquatic prey production is of particular concern for wading birds who depend on high-density concentrations of prey throughout their nesting season (typically December-May in this region). This may be most important for White Ibis, Wood Storks, and Snowy Egrets whose 'searching' feeding strategy is more dependent on finding new high-quality food patches than other waders (e.g., Glossy Ibis, Great Egrets, Tricolored Herons, Great Blue Herons and Little Blue Herons) whose strategy is based on exploiting a feeding site before abandoning it (Gawlik 2002). While dry season recession rates are important for creating the high-density prey patches wading birds rely on (Botson, Gawlik & Trexler 2016), the dry season recession rates seen at Corkscrew in recent years are notably higher than those typically seen in other parts of the Everglades and it is uncertain how both the refuge-seeking aquatic prey and prey-searching wading birds respond when water levels are falling so quickly. Certainly, with deep water refuges within Corkscrew drying (where they did not dry in historic years) and long-hydroperiod wetlands drying earlier than they did historically, wading birds nesting within Corkscrew must respond by flying farther from nest sites to forage (thereby requiring increased energy expenditure). In addition to stress associated with reduced availability of aquatic prey, flooded conditions at Corkscrew's nesting sites are necessary to attract alligators who help protect nests from mammalian predators (Nell et al. 2016). While only small amounts of water beneath nesting sites can restrict travel by mammalian predators (e.g., raccoons, foxes, rats)(Frederick & 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.

Alligators. American alligators (*Alligator mississippiensis*) are a keystone species in the Everglades and are considered a biological indicator due to their role as top predators and their sensitivity to hydrologic conditions (Mazzotti et al. 2009). While the hydrologic change we have detected and described at Corkscrew to-date is unlikely to affect alligator nesting (June-September), the water level changes observed later in our hydrologic year may significantly impact the growth and survival of this species. Increased frequency and/or duration of dry downs can significantly decrease alligator body condition (Brandt et al. 2016). The prey base of both small alligators (with a diet similar to that of wading birds) and larger alligators (consuming fish, turtles, snakes, small mammals, etc.) is reduced with a shortened hydroperiod. Reduced hydroperiod also changes alligator occupancy patterns across the landscape, moving them out of peripheral marshes into deeper habitats and ultimately concentrating alligators of different size classes in remaining water bodies which increases competition for food resources, fighting, and incidence of cannibalism (Mazzotti and Brandt 1994).

Ecological Implications for Corkscrew Swamp Sanctuary and the Corkscrew Watershed

Given the previously described relationships between hydrology, fire, and substrates, changes in hydrology can have major effects on the character and even the existence of plant communities in natural areas. Alterations in hydrology can include changes in wet season and dry season water levels, hydroperiods, flow rates, and water quality, and any one of these can have significant impacts on the plant and animal communities within the Sanctuary and regionally.

Plant communities on the low relief Southwest Florida landscape exist along shallow hydrologic gradients. If the water table is significantly lowered, over time the altered hydrologic, fire, and substrate conditions will result in upland plant communities moving downslope and replacing adjacent shallow wetlands, which in turn can replace deeper wetlands (Duever & Roberts 2013). The lower water levels allow plant species that had been occupying more upslope sites to colonize and come to dominate the now relatively drier downslope sites. These plant community shifts can be accelerated by the new fire regime associated with the drier conditions. The original species on the site were adapted to wetter conditions and less intense and frequent fires, while the colonizing species would not only be more tolerant of the drier conditions, but the new fire regime as well. Finally, shallow organic substrates can completely decompose or be consumed by wildfires under the new drier conditions, resulting in a mineral substrate more suitable for the previously more upslope communities. These kinds of changes can be clearly seen in the nearby Golden Gate Estates and Picayune Strand State Forest where deep canals have severely drained the landscape, and the subsequent very intense and frequent fires have decimated many of the pre-development plant communities, including most of the organic substrates that supported these communities. We do not want to see this happen to Corkscrew Swamp, but it could with the reduced water levels and hydroperiods that have been occurring there since 2000.

Possible Causes for Water Table Decline

Analysis of rainfall at Corkscrew Swamp Sanctuary over the past 55 years shows no change over time and water level data from both the Lettuce Lake staff gauge and the USGS well C-492 (in the Lower Tamiami Aquifer) show dramatic reductions in dry season water levels and hydroperiods in the last 15-20 years. For these reasons it is imperative that we understand what could be causing these changes, particularly due to the acceleration that is apparent around 2000. At present, there may be a number of possible explanations for these changes, although there could be others of which we are not yet aware. Describing the spatial extent of this hydrologic change would also be helpful for identifying and addressing the factor(s) responsible for this marked hydrologic change.

Changes in land use. As agricultural and residential development has expanded and intensified in southwest Florida from the 1950s to the present, the surficial water table has been substantially lowered to varying depths below ground over large areas, greatly reducing the amount of upstream surface water and shallow groundwater present when the dry season begins. Loss of this upstream storage could help explain the more rapid and deeper dry season water table decline seen at CSS. It may also be maintaining Corkscrew's wet season water levels in a more drained landscape, as large amounts of water are being added to Corkscrew Marsh and Corkscrew Swamp to drain upstream lands during the wet season.

Water supply withdrawals. Population growth has been rapidly accelerating in Southwest Florida in recent decades, with Southwest Florida cities frequently leading the state in growth. Between 1950 and 2010, Collier County population increased 50X and Lee County population increased 26X (Forstall 1995, U.S. Census Bureau 2000, 2010; Figure 7). Groundwater withdrawals have necessarily increased proportionately (at a minimum) to support the needs of this increased population. Given the increasingly large extractions of water from the Lower Tamiami and Surficial Aquifers over the past 55 years by both agricultural and local and urban residential users, the water level drawdowns observed at CSS may have been increased by these extractions.

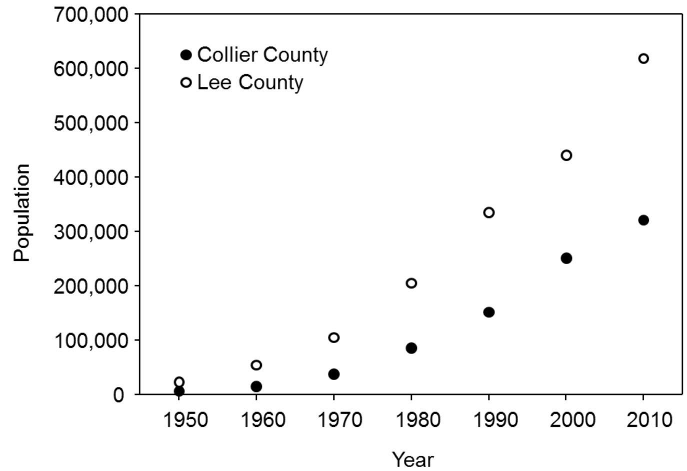

Figure 7. Population of Collier and Lee Counties 1950 -2010 as reported by the U.S. Census Bureau.

Water management. Increased downstream drainage could be influencing water levels at CSS. Maintenance of lowered water levels appropriate for downstream and adjacent residential areas are likely to be increasing the hydrologic gradient, and thus outflows from Corkscrew Swamp.

Changes in plant communities. In areas not converted to agriculture and urban development, succession of open pine forests and herbaceous marsh and wet prairie plant communities to dense, multi-strata shrub and/or hardwood forests due to decades of fire suppression could be increasing evapotranspiration rates, which is the primary natural mechanism controlling the outflow of water from southwest Florida. For example, studies of willow forests that have invaded marshes have shown an increase in water loss from willows as compared to the marsh vegetation they replaced (Budny & Benscoter 2016).

Importance and Limitations of Monitoring

This study clearly emphasizes the value and limitations of long term monitoring for the protection of an ecologically important natural area. For many years we did not see significant changes in Corkscrew's Swamp's hydrology, which is the cornerstone of maintaining its integrity. However, long-term hydrologic monitoring data have allowed us to document significant hydrologic change in recent years. The most obvious change is lower dry season groundwater levels and drastically shortened hydroperiods for most of the wetlands. There is some indication that while wet season water levels may have increased slightly, and the more rapid recession rates are associated with more rapid flow rates through the swamp. While over 30 years of monitoring did not show major changes in the sanctuary's hydrology, it did provide a strong baseline for identifying these changes when they did occur. While it's unfortunate that it took more than a decade of monitoring to clearly show that the changes were a continuing trend and not just variability in the data, it will potentially allow us to minimize further impacts.

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