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Not so Isolated: Isotopic and Hydraulic Evidence of Vertical Connectivity Between the Okefenokee Swamp and Floridan Aquifer

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Abstract

The Okefenokee Swamp has long been assumed to be hydraulically isolated from the Upper Floridan Aquifer (UFA) due to the intervening Hawthorne Formation, a Miocene-age confining unit. Here we test that assumption using stable water isotopes and multiyear time series of swamp and aquifer water levels. Isotope mixing model using $\delta^{18}O$ indicates that 27–95% of groundwater beneath the swamp is swamp-derived, with the remainder resembling regional UFA water. Coherence analysis and impulse-response modeling show that water level fluctuations propagate across the Hawthorne layer with a lag of ~30 days, yielding a vertical hydraulic diffusivity of ~291 m^2/d. These independent lines of evidence confirm that the swamp and aquifer are hydraulically connected through a semi-confining system. Vertical leakage from the swamp may represent 5–15% of annual rainfall and contributes to the isotopic enrichment of UFA waters downgradient. This overturns prevailing hydrogeologic conceptual models and suggests that wetland–aquifer interactions are more dynamic and consequential than previously recognized.

1. Introduction

Groundwater–surface water exchanges govern both water quantity and quality across climates, yet their spatial modes—whether diffuse or focused—remain difficult to quantify. Recharge occurs along a continuum between diffuse infiltration through soils and focused leakage via streams, depressions, or karst features. Climatic aridity and local hydrogeology largely determine where a system lies on that continuum. Observations across sub-Saharan Africa show that humid regions sustain diffuse, seasonally consistent recharge, whereas semi-arid areas experience threshold-controlled, episodic recharge through focused infiltration from ephemeral flows (Cuthbert *et al* 2019). Globally, field syntheses confirm that recharge fractions scale nonlinearly with aridity and that preferential flowpaths strengthen the connection between aquifers and surface fluxes beyond what global models typically resolve (Berghuijs *et al* 2022).

This connection has implications for vulnerability to surface-derived contaminants. Although deep aquifers often contain "fossil" water recharged during the late Pleistocene, half of such wells worldwide also contain tritium, indicating partial mixing with modern recharge (Jasechko *et al* 2017). Intensive groundwater pumping further deepens this penetration: across U.S. aquifers, modern water reaches greater depths where withdrawals are highest, showing that pumping can draw young, contaminant-prone water downward into previously isolated zones (Thaw *et al* 2022). Thus, thick confining units do not guarantee isolation; preferential pathways and hydraulic stresses can short-circuit stratified systems.

Stable isotopes of water (δ^2H, $\delta^{18}O$) are powerful diagnostics of such exchanges because evaporation imparts a distinct isotopic signature to surface waters (Ramchunder *et al* 2022, Evaristo *et al* 2015). In northern Finland, for example, line-conditioned excess (LCE) analysis has been used to identify wells affected by lakes, gravel pits, and drained peatlands, revealing subtle surface-water intrusions even where recharge is otherwise diffuse (Yapiyev *et al* 2023). Similarly, isotopic and microbial monitoring in shallow aquifers shows that wells isotopically resembling nearby ponds can derive 80–95 % of their water from those sources, despite distinct microbial communities (Lyons *et al* 2025). Such findings highlight the need to pair isotopic tracers with hydraulic observations to diagnose exchange mechanisms and intrusion risk.

1.1 Regional and historical context

The Floridan Aquifer System (FAS), extending across Georgia and Florida, is among the world's most productive carbonate aquifers. Its upper unit—the Upper Floridan Aquifer (UFA)—is overlain in southeastern Georgia by the Miocene Hawthorn Group, widely regarded as an effective confining layer. Consequently, overlying wetlands such as the Okefenokee Swamp have long been presumed hydraulically isolated. Yet isotopic and noble-gas evidence gathered since the 1990s challenges that assumption.

Plummer (1993) measured stable isotopes, radiocarbon, and dissolved gases along three UFA flow paths and found that late-Pleistocene (20–26 ka) waters were enriched in $\delta^{18}O$ by 0.7–2.3 ‰ relative to Holocene recharge. Because this enrichment was opposite to the depletion expected from glacial cooling, he proposed that recharge during the Last Glacial Maximum (LGM) derived from evaporatively enriched tropical-cyclone precipitation over the Atlantic Coastal Plain. That interpretation implicitly required negligible modern leakage through the Hawthorne confining unit.

Clark et al (1997) re-examined the same region using stable isotopes, radiocarbon, noble gases, and chloride, and came to a different conclusion. They showed that the UFA contains both regional (old) and local (young) flow systems, with locally recharged waters entering the top of the aquifer and remaining largely unmixed with the regional system (Clark *et al* 1997). Noble-gas thermometry indicated that the region was ~4 °C cooler during the LGM, yet the $\delta^{18}O$ enrichment observed down-gradient was best explained by modern shallow groundwater leaking downward rather than by paleoclimate effects (Clark *et al* 1997). Their tracer patterns, together with hydraulic modeling, revealed that southeastern Georgia's segment of the FAS is semi-confined, with localized downward flux through discontinuities in the Hawthorn Group. However, those studies did not include direct sampling of overlying wetlands—notably the Okefenokee Swamp—or pair chemical signatures with time-series head data. As a result, the magnitude, timing, and spatial organization of swamp–aquifer exchange remain unresolved.

1.2 Broader scientific problem

Globally, recent studies reveal that recharge processes are far more heterogeneous than long-assumed: diffuse and focused fluxes can coexist across small spatial scales, and even deep aquifers thought to contain ancient water can be dynamically connected to modern surface sources (Thaw *et al* 2022, Berghuijs *et al* 2022, Cuthbert *et al* 2019, Jasechko *et al* 2017). Yet empirical tests of these processes beneath large peat wetlands remain rare. Such systems are often treated as hydrologically self-contained, dominated by precipitation and evapotranspiration, with little consideration of vertical leakage. However, evidence from other environments—arid floodplains, ephemeral basins, glaciofluvial aquifers—demonstrates that focused recharge through localized windows can transmit surface signals deep into regional aquifers. Whether the Okefenokee Swamp functions purely as an evaporative terminus or as a zone of focused downward exchange thus remains a key uncertainty with implications for both groundwater budgets and contaminant pathways.

1.3 Objectives and approach

This study provides the first direct test of hydraulic connectivity between the Okefenokee Swamp and the UFA. We combine new δ^2H–$\delta^{18}O$ measurements (2025) from swamp waters and nearby wells with the historical 1990s tracer dataset of Clark et al. (1997) and analyze multi-year records of swamp stage and groundwater heads. Together, these datasets allow us to evaluate both spatial isotopic signatures and temporal coupling between surface and subsurface systems.

Our objectives are to:

1. Quantify the isotopic evidence for swamp-derived water within the UFA;
2. Determine whether exchange is diffuse or focused and identify likely pathways; and
3. Interpret the findings within the global context of groundwater–surface water coupling and intrusion vulnerability.

Guided by the global literature on preferential recharge and semi-confined systems, our working hypothesis is that the Okefenokee Swamp and the UFA are hydraulically connected, with exchange that is spatially heterogeneous, episodically focused, and potentially enhanced by pumping-induced gradients in adjacent areas.

This investigation thus revisits a long-standing assumption in southeastern Georgia hydrogeology—that the Okefenokee is hydrologically isolated—and reframes it within the broader understanding of how confining layers behave in real landscapes: leaky, patchy, and dynamically coupled to the surface despite their apparent continuity.

2. Methods

2.1 Site description

The Okefenokee Swamp lies in the low-relief Atlantic Coastal Plain, straddling the Georgia–Florida state line (**Figure 1A**). Three flowpaths (Flowpaths 1-3) of the UFA in southeast Georgia have been identified based on predevelopment potentiometric surface (Plummer 1993). The locations of UFA wells along these flowpaths are shown in in Figure 1A, and their corresponding elevations above mean sea level (AMSL) are shown in **Figure 1B-D**. The swamp occupies a saucer-shaped topographic depression; swamp water surface elevations range from about 38 m AMSL at the northeastern rim to ~33–34 m AMSL at the southwestern outflow near Fargo, Georgia, USA (**Figure 1D**). The interior is characterized by peat accumulations (up to several meters thick) in broad prairies and cypress swamps, interspersed with slightly elevated sand "islands." The swamp's surface area expands and contracts seasonally, but generally covers ~1,500–1,800 km^2 of wetland. The climate is humid subtropical, with mean annual precipitation on the order of 1300 mm. Rainfall and runoff from a small upland catchment to the north provide nearly all water inputs, whereas losses occur via evapotranspiration and surface outflows. On a long-term basis, approximately 80 % of rainfall over the Okefenokee Swamp is lost to evapotranspiration, and the remaining 20 % exits as surface flow (Rykiel 1977), chiefly through the Suwannee River, which drains the western and northern parts of the basin, and the St. Marys River, which drains the southeast. Because this surface-water budget appeared to account for nearly all inflows, direct groundwater recharge from the swamp was long considered negligible (Georgia EPD, 2024). The prevailing interpretation held that the Miocene Hawthorn Formation formed an effective confining layer that isolated the swamp from the underlying Upper Floridan Aquifer.

Beneath the swamp's peat and sand deposits, the geologic framework consists of an unconfined surficial aquifer underlain by the Hawthorne Group, which in turn overlies the UFA (Thom 2015, Clarke *et al* 1990). The Hawthorne Group (Miocene age) is a sequence of clay and interbedded sand/carbonates that acts as a regional confining unit, limiting vertical flow. It is present throughout the Okefenokee Basin (Thom 2015) and ranges up to ~70 m in thickness in this area (as inferred from well logs in surrounding regions). Under the Hawthorne lie the Eocene limestones of the Floridan Aquifer, a karstic, high-permeability unit that is the principal groundwater source in southeastern Georgia and Florida. In and around the Okefenokee, the Floridan Aquifer is generally confined by the Hawthorne Group, and artesian conditions historically existed (Thom 2015, Clarke *et al* 1990). This stratigraphy gave rise to the assumption of hydraulic isolation: most studies have treated the Hawthorne confining beds as a barrier separating the swamp's shallow water from the Floridan Aquifer (Rykiel 1977). Nevertheless, the possibility of breaches or windows in the confining layer has been noted about 100 km west of Okefenokee in Valdosta, Georgia (Plummer *et al* 1998). The swamp's geologic history includes subsidence and perhaps karst activity; indeed, localized sinkhole-like features in the swamp's substratum have been hypothesized, which could facilitate focused seepage through the Hawthorne Group (Priest 2004, Loftin 1998, Rykiel 1977). Additionally, Trail Ridge – a Pleistocene sand ridge forming the eastern boundary of the swamp (Thom 2015) – creates a hydrologic divide; west of Trail Ridge, groundwater gradients would direct flow toward the swamp, while to the east groundwater flows away. This raises the complexity that any vertical exchange might vary spatially across the swamp.

The UFA in southeast Georgia and north Florida has seen significant anthropogenic drawdown over the past half-century due to municipal and industrial pumping in coastal Georgia (e.g., Brunswick) (Krause and Clarke 2001, Clarke *et al* 1990). The swamp's water level (surface elevation ~36–38 m AMSL in wetter periods) is typically higher than the potentiometric surface of the Floridan Aquifer beneath by several meters (Kitchens and Rasmussen 1995). Historically, artesian pressure may have approached the swamp surface, but today, the head in the UFA is considerably lower, establishing a downward hydraulic gradient virtually year-round (Kitchens and Rasmussen 1995). Thus, if permeable pathways exist, Okefenokee's waters would be expected to percolate into the aquifer. Conversely, upward discharge of Floridan water into the swamp is not observed – consistent with geochemical evidence (the swamp lacks the calcium-rich signature of Floridan spring water) (Yu 1986, Kitchens and Rasmussen 1995). In summary, the setting is one of a large, shallow wetland underlain by a regional aquifer with a confining layer that is generally of low permeability, but with a persistent head difference that drives potential downward leakage.

The Suwanee and St. Marys River basins encompass nearly twice the swamp's area, so basin-average yields (291 and 310 mm/yr, respectively) cannot isolate the swamp's contribution. Nearby non-swamp basins yield similar values (262-345 mm/yr), making it unlikely that surface yield alone distinguishes swamp vs. upland behavior. Instead, any residual must be evaluated through mass balance and tracer constraints.

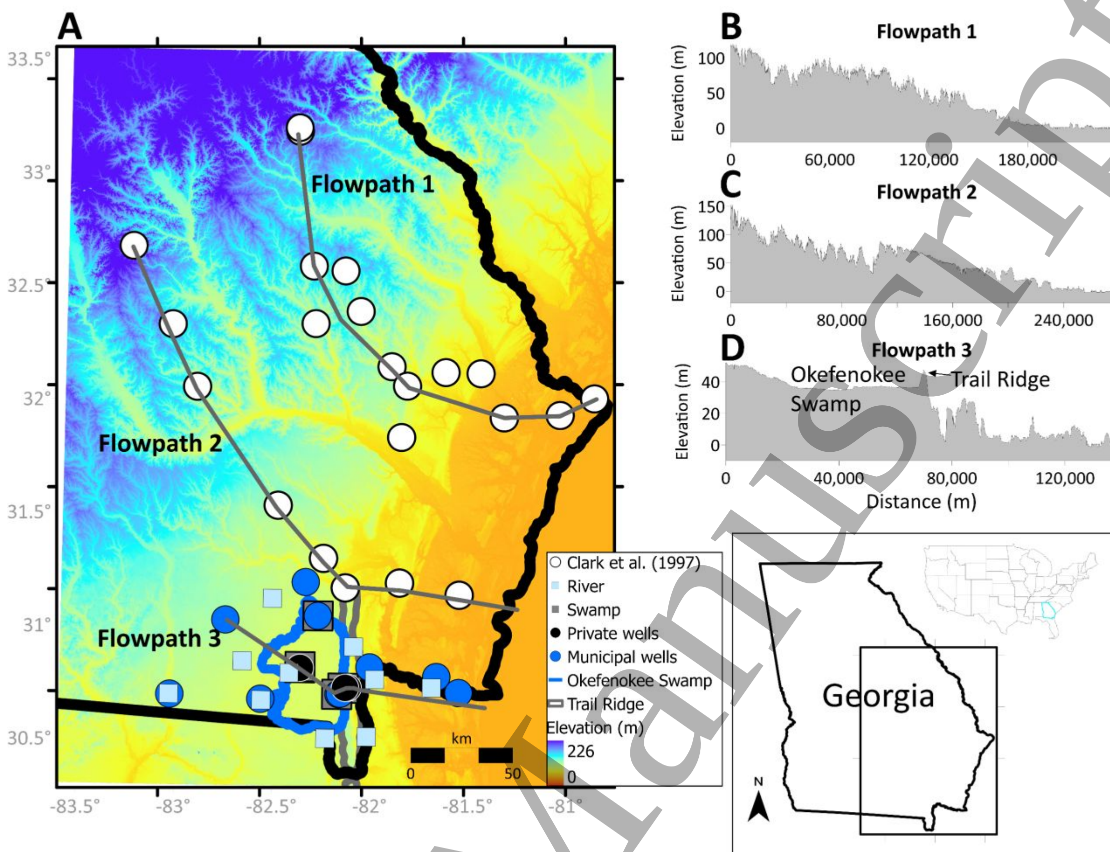


Figure 1. Study site. (A) Map of a section of southeast Georgia, USA (see inset) showing the Okefenokee Swamp, Trail Ridge, well locations open to the UFA from Clark et al. (1997; *n* =15) and this study (*n*=16); also shown are locations of our river and swamp samples as are Flowpaths 1-3 as delineated by Plummer (1993). The polygon on the inset shows the spatial extent of the map shown in **(A)**. **(B-D)** Elevation cross-section profiles of respective flowpaths shown in (A); Okefenokee Swamp and Trail Ridge are annotated in (D).

2.2 Stable isotope sampling and analysis

We analyzed stable isotopes of hydrogen and oxygen (δ^2H and $\delta^{18}O$) in water samples from both surface waters and groundwater wells to evaluate water sources and mixing between the swamp and aquifer. We compiled isotope data from a 1997 study (Clark *et al* 1997) for baseline comparison (N=15) and collected new samples in the vicinity of the swamp in February 2025 (N=32). The Clark et al. (1997) dataset included δ^2H and $\delta^{18}O$ measurements from UFA wells following flowpaths 1 and 2 **(Figure 1A)**, as delineated by Plummer (1993). Those samples were originally analyzed via isotope-ratio mass spectrometry; the reported analytical precision was on the order of ±0.1‰ for $\delta^{18}O$ and ±1‰ for δ^2H. For our 2025 sampling, we selected representative locations in and around the swamp: (i) open-water swamp surface at several sites (interior prairies and near the outflows; $n = 4$), (ii) wells open to the UFA directly beneath or immediately adjacent to the swamp ($n = 4$), (iii) spatially distributed tapwaters supplied by municipal wells that are also open to the UFA ($n = 12$), and river water ($n = 12$). All water samples were collected in 20 mL high-density polyethylene bottles with minimal headspace, sealed and kept cool to prevent evaporation.

Isotopic analysis of the 2025 samples was performed using a Picarro L2140-i cavity ring-down laser spectrometer at the Evaristo Lab at the University of Georgia. Each sample was injected nine times, and the first six injections were discarded to eliminate memory effects. The spectrometer was calibrated using three standards (USGS 46-48) that spanned the range of expected terrestrial $\delta^{18}O$ and $\delta^{2}H$ values, all cross-referenced to the VSMOW-SLAP international scale. Results are reported in permille (‰) notation relative to VSMOW. The analytical precision (1σ) for the 2025 measurements was approximately ±0.025‰ for $\delta^{18}O$ and ±0.1‰ for $\delta^{2}H$, better than the 1997 data quality.

We performed a two-endmember mixing analysis (also see Supporting Information) to quantify the contribution of swamp water to the UFA, treating swamp surface water as one endmember ($n = 4$) and regional groundwater ($n = 15$) as the other endmember. The groundwater endmember consists of wells that are open to the UFA from Flowpaths 1 and 2 in the Clark et al. (1997) dataset. For each UFA well, the fraction of swamp water, f_{swamp}, was computed as:

$$f_{swamp} = \frac{\delta_{well} - \delta_{regional}}{\delta_{swamp} - \delta_{regional}} \qquad \text{(Eq. 1)}$$

using $\delta^{18}O$ values (and cross-checked with $\delta^{2}H$ for comparison). In Equation 1, δ_{well} is the $\delta^{18}O$ isotope value in sampled wells and tapwaters, δ_{swamp} is the value in swamp water (-1.7 ± 0.58; $n = 4$), and $\delta_{regional}$ is the value in UFA wells along Flowpaths 1 and 2 in the Clark et al. (1997) dataset (-3.86 ± 0.43; $n = 15$). This linear mixing approximation assumes that isotope effects like evaporation only modify the swamp endmember and that there are no other distinct sources (e.g., no significant paleowater component with a vastly different signature beyond the chosen endmembers). The range of f_{swamp} across sites provides an estimate of how much of the UFA water under the swamp is derived from swamp infiltration. We performed this analysis for each of the two field campaigns.

The 'offset' of a water sample from the (local meteoric water line, LMWL) has been shown useful in characterizing the magnitude of evaporative enrichment (Evaristo *et al* 2015). To quantify the offset between UFA water, swamp water, river water and precipitation, we calculated the line-conditioned excess (LCE):

$$LCE = [\delta^{2}H - a\delta^{18}O - b]/S \qquad \text{(Eq. 2)}$$

where *a* and *b* are the slope and y-intercept, respectively, of the LMWL $\delta^2H = 7.15\ \delta^{18}O + 9.28$ (R^2 0.93, n =145) from (Klaus *et al* 2015). This LMWL was derived from the Upper Fourmile Branch at the Savannah River Site, South Carolina. Like our study site in SE Georgia, the Savannah River Site is also in the Coastal Plain physiographic region of the Upper Atlantic, and thus (in the absence of locally derived, SE Georgia MWL) represents the best and most applicable LMWL there is to date.

2.3 Water level data and analysis

We analyzed daily water level records from 1978 to 2025 for two USGS groundwater wells—27G003 near Waycross and 27E004 at Jones Island—and for surface water in Jones Island Swamp, within the Okefenokee region (Okefenokee National Wildlife Refuge 2025). Elevation data were converted to meters above mean sea level and resampled to a common daily time base using vectorized interpolation to address temporal gaps and averaging algorithms to resolve duplicate values.

To assess hydrologic connectivity between swamp and aquifer, we applied complementary statistical tools. Pearson correlations captured linear covariation, while dynamic time warping quantified pattern similarity independent of time shifts (Hemri and Klein 2017, Sammour *et al* 2019). Frequency-dependent coherence was evaluated using magnitude-squared coherence computed via Welch's method (Malekpour *et al* 2018). Directional dependencies were probed using simplified Granger causality (Guo *et al* 2010, Shojaie and Fox 2022, Tuttle and Salvucci 2017), and mutual information (Tiwari *et al* 2020)—estimated from histogram-based distributions—provided a nonparametric measure of shared variability. We focused detailed analysis on the most complete and continuous data interval (July 2017 to August 2020; n = 1,135 days), maximizing statistical power and minimizing interpolation artifacts.

We estimated aquifer hydraulic properties by modeling the impulse response between surface and groundwater levels at Jones Island (Strupczewski *et al* 2003, Lu *et al* 2022). The response function is estimated using ordinary-least-squares regression deconvolution (Rasmussen and Mote 2007, Toll and Rasmussen 2007, Rasmussen and Crawford 1997). The analytical response function is,

$$R(\tau) = 1 - \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\exp\left[-(2n+1)^2\pi^2\tau\right]$$

(Eq. 3)

where τ is the dimensionless time defined by $\tau = \frac{D}{tb^2}$. Here, t is the elapsed time (days), *D* is the vertical hydraulic diffusivity (m^2/d), and b is the vertical thickness (m) of the leaky layer through which vertical flow occurs (see Supporting Information). This formula represents the aquifer's theoretical response to a unit step change in swamp head: at $\tau = 0, R = 0$; as $\tau \rightarrow \infty$, the exponential terms vanish and $R \rightarrow 1$ (complete transmission). Curve matching at the inflection point (τ* = 30 days) yielded *D* = 290.96 m²/d, assuming *b* = 151.8 m. This provides a physically grounded estimate of vertical leakage and quantifies swamp–aquifer connectivity in this low-relief coastal plain system.

All data processing and analyses were performed using Matlab. The isotope mixing calculations were straightforward algebraic derivations from the measured values. Uncertainty in the computed swamp-water fraction, f_{swamp}, was evaluated by propagating the standard deviation of the δ values following Genereux (1998):

$$W_{f_{swamp}} = \left\{\left[\frac{\delta_{regional}-\delta_{well}}{(\delta_{regional}-\delta_{swamp})^2} W_{\delta_{swamp}}\right]^2 + \left[\frac{\delta_{well}-\delta_{swamp}}{(\delta_{regional}-\delta_{swamp})^2} W_{\delta_{gw}}\right]^2 + \left[\frac{-1}{(\delta_{regional}-\delta_{swamp})} W_{\delta_{well}}\right]^2\right\}^{\frac{1}{2}} \quad \text{(Eq. 4)}$$

3. Results

3.1 Stable isotopic evidence of vertical exchange

The stable isotope measurements show a clear fingerprint of Okefenokee Swamp water in the underlying Upper Floridan Aquifer. **Figure 2A** shows a crossplot of $\delta^{18}O$ and $\delta^{2}H$ of regional UFA groundwater from Flowpaths 1 and 2 in (Clark *et al* 1997), and swamp surface waters and groundwater from UFA beneath or near the swamp collected in 2025. Several notable patterns emerge. First, the swamp surface water is relatively enriched in heavy isotopes ($\delta^{18}O \approx -1.7 \pm 0.6$, $\delta^{2}H \approx -7.0 \pm 3.1$) compared to regional groundwater ($\delta^{18}O \approx -3.9 \pm 0.4$, $\delta^{2}H \approx -22.6 \pm 2.7$). By contrast, groundwater from the UFA beneath or near the swamp is significantly different ($\delta^{18}O \approx -2.6 \pm 0.38$, $\delta^{2}H \approx -9.8 \pm 1.9$) from regional background. In 2025, wells tapping the UFA near the swamp were found to be even more enriched, with one well measuring $\delta^{18}O \approx -1.8$ ‰, $\delta^{2}H \approx -7$ ‰ – nearly indistinguishable from the swamp surface water values. These data strongly indicate mixing of swamp-derived water into the aquifer. Groundwater in the aquifer directly beneath the swamp has an isotopic signature shifted toward that of swamp water, whereas regional groundwater remains distinctly lighter. This spatial isotopic contrast – heavy under the swamp vs. lighter away – is exactly what one would expect if swamp water were leaking downward and dominating the recharge under the swamp.

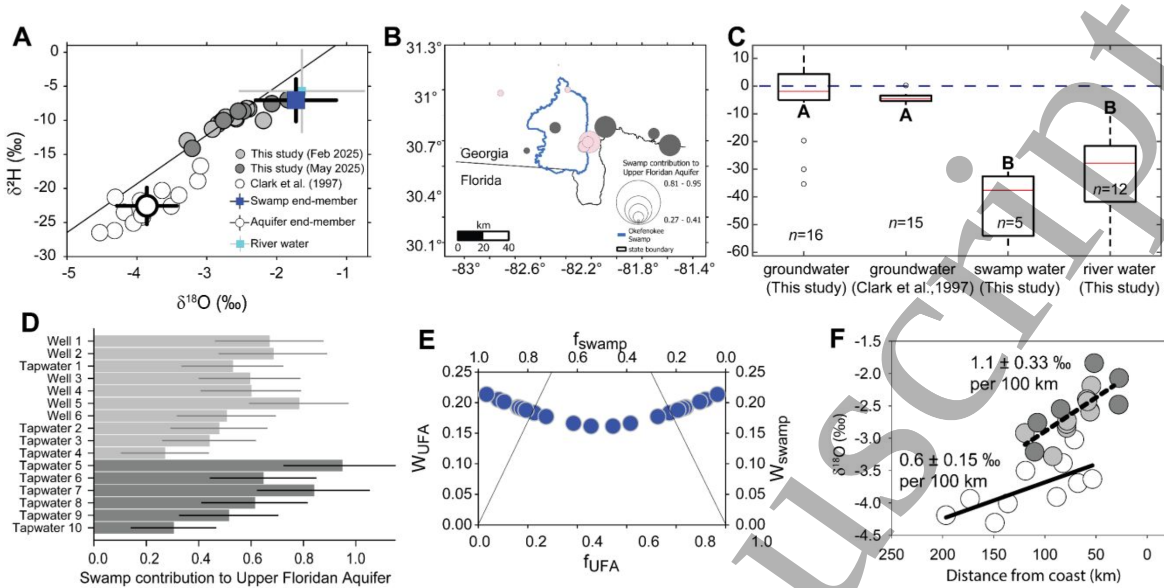
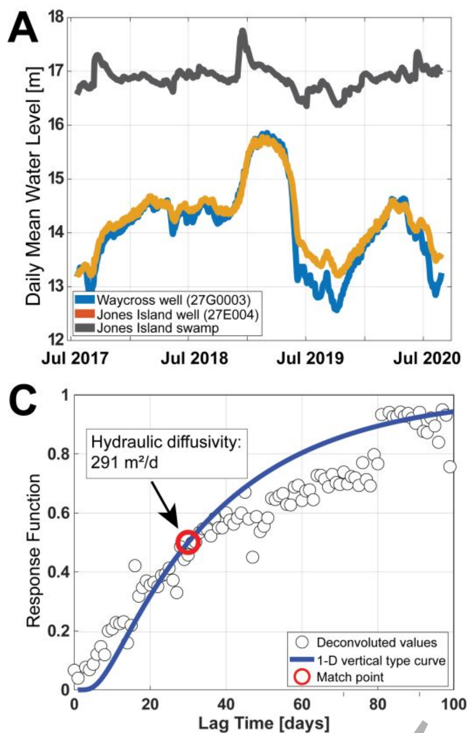


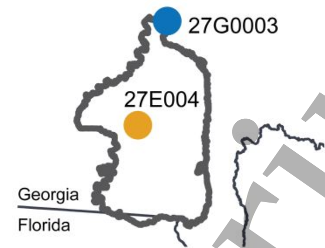
Figure 2. Endmember mixing results. (A) $\delta^{18}O$- $\delta^{2}H$ crossplot of UFA groundwater samples from Clark et al. (1997; *n=15*) and this study (*n*=16); also shown are aquifer and swamp endmember mean values (error bars represent one standard deviation) and river water and LMWL. **(B)** Dots map of swamp water contributions to UFA samples collected in this study; bubble size denotes the fraction of swamp water contribution to UFA. **(C)** LCE box plots of UFA groundwater from this study, Clark et al. (1997), swamp water and river water; boxplots that are not connected by the same letter are significantly different (using Steel-Dwass nonparametric all-pairs comparison, $p<0.05$). **(D)** Bar plot of swamp water contributions to UFA samples collected in this study; the error bars represent the calculated uncertainties using Eq. (4). **(E)** Calculated uncertainty *W* in fractions of swamp water (f_{swamp}) and UFA (f_{UFA}) contributions to UFA samples collected in this study (following Genereux, 1998); the concave up curve shows that the lowest uncertainties are associated with increasingly equal proportions of swamp water and UFA water contributions to UFA samples collected in this study. **(F)** Crossplot of $\delta^{18}O$ and distance from the coast; the open circles are from Clark et al. (1997); the grey-filled circles are from this study. The trendlines represent inland gradients of $\delta^{18}O$ from Clark et al. (1997) (0.60 ±0.15 ‰ per 100 km) and this study (1.10 ±0.33 ‰ per 100 km).

From the isotopic mixing analysis (**Figure 2B**), we estimate that the fraction of swamp-origin water in the UFA beneath the Okefenokee ranges from roughly 0.27 to 0.95 in our 2025 samples. The LCE values of UFA water from this study and from Clark et al. (1997) are significantly different from the LCE values of swamp and river water (**Figure 2C**) (Steel-Dwass nonparametric all-pairs comparison, $p<0.05$). In all but two UFA samples within the perimeter of the swamp (**Figure 2D**), the groundwater compositions are so close to swamp water that 44-95% of it appears to be derived from swamp infiltration. The swamp contribution is on the order of 65–84% in the other two UFA samples away from the swamp (**Figure 2C, 2D**). The finding that much of the groundwater beneath the swamp consists of water that has passed through the swamp's surficial system directly refutes the notion of an impermeable separation. Instead, it confirms strong vertical connectivity: the swamp is actively recharging the Floridan Aquifer. Implementing the isotope mixing model using $\delta^{18}O$ results in more conservative estimates of swamp water contributions to UFA waters (0.60 ± 0.18) than when using $\delta^{2}H$ (0.82 ± 0.12). **Figure 2E** shows the estimated uncertainties in the computed swamp-water fractions. The symmetrical, concave-up shape of the curve indicates that the highest certainty in mixing fractions occurs when f_{swamp} and f_{UFA} are present in equal amounts. The triangular regions on the far left and right sides of the curve indicate areas where the uncertainty in the mixing fractions exceeds the value of the smaller fraction (with f_{UFA} on the left and f_{swamp} on the right) (Genereux 1998).

It is worth noting that the swamp water samples plot slightly to the right of the LMWL on a $\delta^{2}H$–$\delta^{18}O$ diagram (**Figure 2A**), consistent with evaporative enrichment. This is also shown in the LCE value of swamp (-42 ± 12) (**Figure 2C**). The groundwater beneath the swamp plots on a mixing line between the swamp water and the regional groundwaters, reinforcing the interpretation that it is a mixture of the two endmembers. We find no evidence of an isotopically distinct old groundwater component (i.e., LGM recharge expected to be lighter than Holocene after glacial-ocean correction and consistent with cooler recharge temperatures) in Floridan wells near the swamp; their δ-values are too heavy for ancient meteoric inputs and instead indicate modern, evaporatively enriched sources (Clark *et al* 1997). Thus, the stable isotope evidence indicates an active, relatively rapid exchange between the swamp and the aquifer in contemporary times.

As shown in **Figure 2F**, $\delta^{18}O$ values of deep wells (> 50 m) increase systematically toward the coast. Our data reproduce the isotopic enrichment pattern of the Upper Floridan Aquifer (UFA) first reported by (Clark *et al* 1997), but with nearly twice the slope: 1.1 ± 0.33 ‰ per 100 km, compared with their 0.6 ± 0.15 ‰ per 100 km. This steeper gradient indicates that evaporatively enriched water from the Okefenokee Swamp likely contributes to local recharge of the UFA, thereby amplifying the isotopic enrichment relative to the case of a fully disconnected system.





B

Site Pair	Pearson r	DTW
Waycross well–Jones well	0.980	69.0
Waycross well–Jones swamp	0.539	403.9
Jones well–Jones swamp	0.509	400.5

Figure 3. Hydraulic connectivity, impulse-response dynamics, and statistical dependencies among groundwater and surface water sites at Waycross and Jones Island. (A) Daily mean water levels from July 2017 to July 2020 for groundwater wells (Waycross 27G003, Jones Island 27E004) and Jones Island swamp surface water. Groundwater sites show highly synchronous fluctuations. Surface water displays distinct temporal dynamics, suggesting differing hydrologic processes. Inset map (upper right) shows locations of USGS groundwater wells 27G003 (Waycross) and 27E004 (Jones Island) within the Okefenokee region along the Georgia–Florida border. **(B)** Summary statistics highlighting linear correlation (Pearson's r) and similarity in temporal dynamics (Dynamic Time Warping; DTW). Granger causality analysis reveals that groundwater fluctuations at Waycross significantly predict groundwater levels at Jones Island (Waycross→Jones GW, lag = 1 day; F = 103.1, $p < 0.001$), supporting a directional hydraulic gradient. Mutual information (MI) quantifies nonlinear dependence, with higher values indicating stronger shared information between groundwater wells (Waycross–Jones GW MI = 2.33) and comparatively lower shared information with surface water (Waycross–Jones SW MI = 1.15; Jones GW–Jones SW MI = 1.16). **(C)** Groundwater impulse-response function determined via deconvolution (open circles), fitted with a one-dimensional vertical diffusivity type curve (blue line). The optimal diffusivity match (red circle) yields a diffusivity of approximately 291 m^2/d, indicative of rapid hydraulic responses and strong aquifer connectivity.

3.2 Hydraulic connectivity and response analysis

Daily water levels from July 2017 to July 2020 **(Figure 3A)** show synchronous fluctuations between the Upper Floridan Aquifer wells at Waycross (27G003) and Jones Island (27E004), with nearly overlapping patterns in both amplitude and phase. By contrast, the Jones Island swamp surface water exhibits damped variability and smoother transitions, consistent with differing short-term hydrologic responses.

The linear correlations and temporal alignments among the three monitoring sites (summarized in **Figure 3B**) show strong covariation, indicating coherent hydraulic responses across the swamp and aquifer. The Pearson correlation between the two groundwater wells is 0.980, indicating near-perfect linear covariation. Comparisons involving the swamp yield lower correlation values ($r = 0.539$ and $r = 0.509$). Dynamic time warping (DTW) distances show a similar pattern: the Waycross–Jones well pair has a much smaller DTW value (69.0) than either aquifer–swamp pair (>400), reflecting greater dissimilarity in temporal patterns involving the swamp.

To quantify the system's hydraulic responsiveness, we estimated the impulse response function between swamp surface water (input) and aquifer levels at Jones Island (output). As shown in **Figure 3C**, the deconvoluted response function increases monotonically and asymptotes over a ~100-day lag time. Fitting these values to a one-dimensional vertical flow model through a leaky aquitard yields a best-fit diffusivity of 291 m^2/d. The match point used for the fit occurs at a lag time of ~30 days, corresponding to the inflection point in the observed response.

These results **(Figure 3C)** quantify the strength and timing of hydrologic signal transmission between the swamp and underlying aquifer, and serve as the basis for the discussion of vertical connectivity and aquitard properties in Section 4.

Together, the results from Figure 3A–C—spanning time series behavior, statistical dependencies, and hydraulic modeling—converge on a coherent interpretation: the Okefenokee Swamp is hydraulically connected to the underlying Floridan Aquifer. This vertical exchange, while temporally damped, is physically significant and occurs through a leaky confining system. These findings reinforce and extend the isotopic evidence in Section 3.1, and underscore that swamp–aquifer connectivity must be reconsidered in regional water budget and groundwater resource assessments.

The residual water budget estimates (see Section 4.1) – 130 to 220 mm/yr – is consistent with the vertical leakage required to explain the enriched isotope signatures observed in the Floridan Aquifer beneath the swamp. This downward flux aligns with independent estimates from Darcy-based calculations using observed head gradients and reasonable ranges of vertical hydraulic conductivity. The match across independent lines of evidence – stable isotopes, water level lags, and water budget residuals – strongly supports swamp-to-aquifer recharge.

4. Discussion

Our analyses reveal that the Okefenokee Swamp is not hydraulically isolated from the Upper Floridan Aquifer, as long presumed. Instead, water stable isotope data (Figure 2A–F) and hydraulic time series (Figure 3A–C) both demonstrate vertical connectivity through the intervening Hawthorne Group. Together, these independent lines of evidence show that the swamp and aquifer exchange water and transmit pressure signals across a nominally confining system, over distances of tens of kilometers and time lags of about one month. This overturns long-held assumptions in the region's hydrogeologic conceptual model and has implications for water budgets, ecological dynamics, and groundwater management.

4.1 The confining layer permits vertical flux

Isotopic enrichment in aquifer samples beneath the swamp (δ^2H, $\delta^{18}O$) points to mixing with evaporatively enriched swamp water (Figure 2A–B). Modeled swamp contributions reach 27-95% (Figure 2D), far exceeding what would be expected under an impermeable boundary. These values align with residual water budget estimates (130–220 mm/yr;Rykiel, 1977) and reinforce a view of substantial vertical drainage. Moreover, the aquifer's hydraulic response to swamp-level changes follows a smooth, cumulative function that is well-fit by a leaky aquitard model (Figure 3C), with an estimated diffusivity of 291 m^2/d. This value implies that pressure perturbations cross the confining layer within a month—consistent with the observed lag in aquifer levels and with Kitchens & Rasmussen (1995)'s early observations.

Taken together, the isotope data quantify the flux, and the hydraulic response quantifies the transmissivity. The combined interpretation is clear: the Hawthorne Group, while impeding flow, does not prevent it. Its behavior is more consistent with a semi-confining system that allows significant distributed leakage, rather than an intact seal.

Figure 4 illustrates this conceptual framework, showing the vertical and lateral fluxes that govern the Okefenokee–Floridan system. The persistent head difference of up to 21 meters between swamp surface and aquifer potentiometric levels, combined with residual water budget imbalances (~130–220 mm/yr), provides a sustained downward driving force. The schematic also highlights the dominance of evapotranspiration, the influence of Trail Ridge, and the relative positions of key stratigraphic units and monitoring wells. While simplified, this cross-section captures the essential structure and hydrologic functioning of the system: a rain-fed wetland perched above a leaky aquitard, losing water to one of the most productive aquifers in North America.

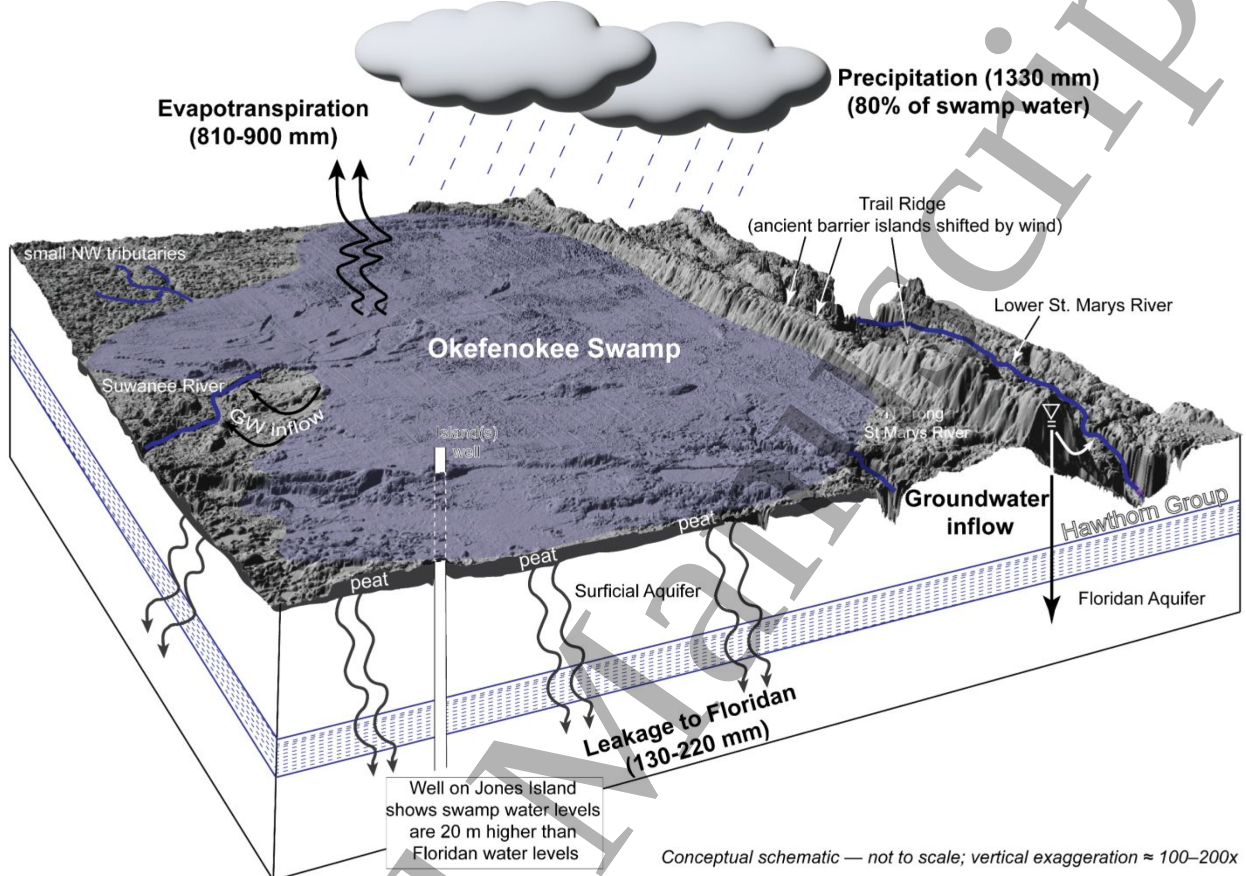


Figure 4. Conceptual 3D block diagram of the Okefenokee Swamp system showing dominant hydrologic fluxes, stratigraphy, and groundwater flow paths. Precipitation (~1330 mm yr^{-1}) sustains the swamp, with most water lost via evapotranspiration (810–900 mm yr^{-1}) and surface discharge to the Suwannee and St. Marys Rivers. Residual water exits primarily as vertical leakage (130–220 mm yr^{-1}) through the Hawthorn Formation into the Upper Floridan Aquifer. Head differences between the swamp and aquifer—up to 21 m—produce a persistent downward gradient. The Hawthorn acts as a semi-confining unit rather than a hydraulic barrier. Regional flow directions, hydrostratigraphic units, and topography are shown schematically. The diagram is not to scale and employs an approximate vertical exaggeration of 100–200x to emphasize relative hydrologic and geomorphic relationships rather than precise spatial dimensions.

4.2 Recontextualizing prior observations and assumptions

Our results resolve longstanding ambiguity in the swamp–aquifer relationship. Earlier tracer studies suggested swamp influence on aquifer chemistry (Plummer 1993, Clark

479 *et al* 1997), but lacked direct sampling of the swamp itself. Others, like Kitchens & Rasmussen (1995), proposed swamp-to-aquifer flow based on lagged water levels. We confirm both claims with a new, integrated dataset that includes isotopes, water levels, and response modeling. At the same time, our results contradict recent regulatory assertions that "the Okefenokee Swamp is not hydraulically connected to the Floridan aquifer" (Georgia EPD, 2024). This discrepancy highlights how hydrogeologic paradigms—such as "thick clay equals isolation"—can persist in the absence of site-specific testing. Our findings call for an update to regional groundwater models to explicitly include swamp-sourced recharge and leaky confinement.

4.3 A coastal signature of swamp recharge

Figure 2E shows that $\delta^{18}O$ values in UFA groundwater increase systematically with distance from the coast. This inland enrichment gradient is roughly double the magnitude originally reported by Clark et al. (1997), suggesting that swamp recharge plays a more dominant role than previously recognized. Since the swamp occupies the headwaters of the Suwannee and St. Marys basins, its influence on aquifer composition may extend tens to hundreds of kilometers downgradient. The heavy isotope signal propagated downstream is unlikely to result from paleoclimate inputs (cf. L. Niel Plummer 1993), given the modern and evaporative nature of the swamp water. This coastal enrichment trend provides independent, spatial evidence of sustained vertical and lateral aquifer transport of swamp-derived recharge.

4.4 Water budget and ecological implications

Our findings imply that a meaningful portion of the swamp's water exits not through rivers or evapotranspiration, but through vertical leakage into the Floridan Aquifer—behavior that is consistent with long-standing syntheses showing that wetlands can recharge groundwater where hydraulic gradients allow (Winter *et al* 1998). This flux could account for 5–15% of annual rainfall when scaled across the swamp area, i.e., comparable to surface runoff, and is consistent with field studies documenting focused downward exchange beneath wetlands in permeable or fractured settings (Oxtobee and Novakowski 2002). During drought, persistent head gradients and aeration may shift peatlands toward recharge behavior and trigger biogeochemical changes—notably enhanced DOC release and carbon losses—via the well-documented 'enzymic-latch' mechanism and post-rewetting pulses (Fenner and Freeman 2011, Freeman *et al* 2001). As a result, the swamp acts as a recharge wetland, not just a surface reservoir. During drought, persistent head gradients could pull water downward and further draw down swamp levels, potentially aerating underlying peat and driving chemical shifts. Indeed, declining water tables and observed increases in acidity, mercury, and lead in swamp biota (Kitchens and Rasmussen 1995) are consistent with such a mechanism. This hydraulic pathway provides a plausible causal link: aquifer drawdown or drought accelerates vertical seepage, leading to peat and sulfur oxidation that leads to contaminant mobilization. Swamp hydrology and chemistry, therefore, may respond not only to surface water fluctuations but also to subsurface pressure gradients.

4.5 Management considerations

Our findings provide a new understanding of hydraulic connectivity between the Okefenokee Swamp and the Floridan Aquifer, which should inform future water resource management and environmental protection in the region. For instance, proposals for heavy mineral sand mining near Trail Ridge or large-scale groundwater pumping in the vicinity should be evaluated with the knowledge that the swamp is not an isolated “bathtub,” but rather a leaky reservoir intimately linked to the Floridan Aquifer. A stress to one will affect the other. Previous environmental assessments may have underestimated swamp vulnerability by assuming the confining layer prevents any aquifer-surface water interaction. Our data suggest any activity that lowers Floridan Aquifer levels (such as pumping) could induce greater vertical flow from the swamp, potentially dewatering it. Conversely, extreme high water in the swamp (e.g., after hurricanes) will recharge the aquifer significantly, which could be beneficial for aquifer storage. This interplay should be incorporated into hydrologic models and management plans. In quantitative terms, the swamp’s leakage could represent on the order of 5–15% of annual rainfall (~50–150 mm/yr out of ~1300 mm/yr) if our flux estimates are scaled across the swamp – a non-trivial quantity that should be factored into water budgets.

4.6 Uncertainties and future work

While our study demonstrates vertical hydraulic connectivity, there remain uncertainties regarding the spatial variability and controls of the leakage. It is still unclear whether exchange is dominantly diffuse and uniform or concentrated along preferential flowpaths—perhaps beneath prairie depressions, forested slough margins, or reactivated tectonic features. Recharge studies elsewhere show that such distinctions are often climate- and geology-dependent: as Cuthbert et al (2019) observed across sub-Saharan Africa, humid settings tend toward diffuse infiltration through soils, whereas semi-arid landscapes rely increasingly on focused recharge via ephemeral surface flows and topographic lows.

Our 2025 isotope results already hint at analogous heterogeneity here—some wells showing markedly higher swamp fractions than others—suggesting that vertical connectivity may be organized around localized “hot spots” of permeability rather than a spatially uniform leak. Mapping the confining layer’s integrity using geophysical methods or exploratory borings could help identify such zones of focused exchange.

The risk of surface-water intrusion into shallow wells is another uncertainty. Yapiyev et al (2023) used LCE to flag wells influenced by lakes, gravel pits, or peatland drainage in Finland, showing that shallow unconfined aquifers—even where recharge is largely diffuse—can still experience focused incursions from nearby surface waters. Lyons et al (2025) demonstrated that isotope similarity between wells and ponds may indicate up to 80–95 % surface-water contribution, even when microbial assemblages remain distinct. Their study underscores that physicochemical indicators alone may not fully capture intrusion dynamics. Applying similar isotopic and microbiological screening in the Okefenokee system could thus constrain both recharge mode and contamination vulnerability.

Time-series analysis should also be extended, both temporally and spatially, to refine hydraulic parameters and diagnose feedbacks. Joint analyses of swamp stage, river discharge, and aquifer response could reveal lags or threshold behavior akin to the precipitation–recharge hysteresis documented by Cuthbert et al (2019). Environmental tracers spanning different timescales— tritium/helium, noble gases, etc.—could estimate the residence time of water beneath the swamp; young apparent ages would corroborate rapid vertical exchange. The presence of any older component, as seen in many fossil-water systems (Jasechko *et al* 2017), would imply partial isolation and limited flushing.

Modern groundwater has been shown to penetrate deeper under heavy pumping (Thaw *et al* 2022), suggesting that intensified withdrawals near the Okefenokee margin could draw swamp-derived water—and its solute or microbial load—further into the Floridan system than natural gradients alone would allow. This reinforces the need to couple isotopic and hydraulic observations with pumping-stress analyses to quantify intrusion risk.

At the broader scale, recent global syntheses indicate that groundwater–surface-water coupling is stronger than previously represented in models (Berghuijs *et al* 2022), emphasizing that even subtle diffuse fluxes can integrate into substantial cross-system exchange. Our assumption of a two-endmember isotope mix may therefore oversimplify reality: minor paleowater components or seasonal isotopic shifts could contribute. More frequent sampling—quarterly or event-based—would help determine whether swamp–aquifer exchange varies seasonally or during extreme wet–dry transitions.

A major limitation remains the absence of direct evapotranspiration measurements within the swamp. Eddy-covariance data would constrain the largest flux term in the water budget and reduce uncertainty in the residual attributed to groundwater loss. Without such constraints, swamp-specific budgets remain underdetermined. Despite these open questions, the fundamental conclusion remains robust: the Okefenokee Swamp and the Floridan Aquifer are hydraulically and chemically interconnected, but that connection is spatially heterogeneous—diffuse in some sectors, distinctly focused in others—and potentially susceptible to intrusion under altered hydraulic gradients.

5. Conclusion

Contrary to long-standing assumptions of hydraulic isolation, the Okefenokee Swamp is hydraulically connected to the underlying Upper Floridan Aquifer. Independent lines of evidence—stable isotopic enrichment in groundwater and lagged aquifer responses to swamp-stage fluctuations—demonstrate significant vertical exchange through the intervening Hawthorne Formation. Isotopic mixing models indicate that up to 92% of groundwater beneath the swamp is swamp-derived, and hydraulic response analysis yields a vertical diffusivity of ~291 m^2/d, consistent with monthly-scale signal transmission across a semi-confining layer.

These findings necessitate a revised conceptual model of the Okefenokee as a recharge wetland, not a hydraulically isolated basin. They also reveal that the Hawthorne Group functions as a leaky barrier, allowing appreciable vertical fluxes that alter both swamp water balances and regional aquifer composition. The swamp's role in sustaining Floridan groundwater resources—especially under climate variability and anthropogenic stress—warrants explicit consideration in regional water management and ecological forecasting.

6. References

Anon Response to Comments on Draft GW Permits 016-0013 and 016-0014_2024-10.pdf - Google Search Online: https://www.google.com/search?q=Response+to+Comments+on+Draft+GW+Permits+016-0013+and+016-0014_2024-10.pdf&rlz=1C1GCFA_enUS1115US1115&oq=Response+to+Comments+on+Draft+GW+Permits+016-0013+and+016-0014_2024-10.pdf&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIGCAEQRRg80gEHNTM5ajBqN6gCALACAA&sourceid=chrome&ie=UTF-8#vhid=zephyr:0&vssid=atritem-https://epd.georgia.gov/document/document/response-comments-draft-gw-permits-016-0013-and-016-00142024-10/download

Berghuijs W R, Luijendijk E, Moeck C, van der Velde Y and Allen S T 2022 Global Recharge Data Set Indicates Strengthened Groundwater Connection to Surface Fluxes *Geophys Res Lett* **49**

Clark J F, Stute M, Schlosser P, Drenkard S and Bonani G 1997 A tracer study of the Floridan Aquifer in southeastern Georgia: Implications for groundwater flow and paleoclimate *Water Resour Res* **33** 281–9 Online: /doi/pdf/10.1029/96WR03017

Clarke J S, Hacke C M and Peck M F 1990 GEOLOGY AND GROUND-WATER RESOURCES OF THE COASTAL AREA OF GEORGIA *Georgia Department of Natural Resources, Environmental Protection Division, Georgia Geologic Survey* 134 Online: https://ga.water.usgs.gov/www2/publications/ggs/bull-113/

Cuthbert M O, Taylor R G, Favreau G, Todd M C, Shamsudduha M, Villholth K G, MacDonald A M, Scanlon B R, Kotchoni D O V, Vouillamoz J M, Lawson F M A, Adjomayi P A, Kashaigili J, Seddon D, Sorensen J P R, Ebrahim G Y, Owor M, Nyenje P M, Nazoumou Y, Goni I, Ousmane B I, Sibanda T, Ascott M J, Macdonald D M J, Agyekum W, Koussoubé Y, Wanke H, Kim H, Wada Y, Lo M H, Oki T and Kukuric N 2019 Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa *Nature* **572**

Evaristo J, Jasechko S and McDonnell J J 2015 Global separation of plant transpiration from groundwater and streamflow *Nature* **525** 91–4 Online: http://www.nature.com/doifinder/10.1038/nature14983

Fenner N and Freeman C 2011 Drought-induced carbon loss in peatlands *Nature Geoscience 2011 4:12* **4** 895–900 Online: https://www.nature.com/articles/ngeo1323

Freeman C, Ostle N and Kang H 2001 An enzymic "latch" on a global carbon store *Nature* **409** 149 Online: https://doi.org/10.1038/35051650

Genereux D 1998 Quantifying uncertainty in tracer-based hydrograph separations *Water Resour Res* **34** 915–9

Guo S, Ladroue C and Feng J 2010 Granger Causality: Theory and Applications

Hemri S and Klein B 2017 Analog-Based Postprocessing of Navigation-Related Hydrological Ensemble Forecasts *Water Resour Res* **53**

Jasechko S, Perrone D, Befus K M, Bayani Cardenas M, Ferguson G, Gleeson T, Luijendijk E, McDonnell J J, Taylor R G, Wada Y and Kirchner J W 2017 Global aquifers dominated by fossil groundwaters but wells vulnerable to modern contamination *Nat Geosci* **10**

Kitchens S and Rasmussen T C 1995 *Hydraulic Evidence For Vertical Flow From Okefenokee Swamp To The Underlying Floridan Aquifer In Southeast Georgia* (Georgia Institute of Technology) Online: http://hdl.handle.net/1853/44003

Klaus J, McDonnell J J, Jackson C R, Du E and Griffiths N A 2015 Where does streamwater come from in low-relief forested watersheds? A dual-isotope approach *Hydrol Earth Syst Sci* **19**

Krause R E and Clarke J S 2001 Coastal ground water at risk — Saltwater contamination at Brunswick, Georgia and Hilton Head Island, South Carolina *Water-Resources Investigations Report* Online: https://pubs.usgs.gov/publication/wri014107

Loftin C S 1998 . *Assessing Patterns and Processes of Landscape Change in Okefenokee Swamp, Georgia.* (Gainsville, FL: University of Florida, Gainesville, FL.)

Lu M, Rogiers B, Beerten K, Gedeon M and Huysmans M 2022 Exploring river-aquifer interactions and hydrological system response using baseflow separation, impulse response modeling, and time series analysis in three temperate lowland catchments *Hydrol Earth Syst Sci* **26**

Lyons K J, Yapiyev V, Lehosmaa K, Ronkanen A K, Rossi P M and Kujala K 2025 Physicochemical and isotopic similarity between well water and intruding surface water is not synonymous with similarity in prokaryotic diversity and community composition *Water Res* **269** 122812 Online: https://www.sciencedirect.com/science/article/pii/S0043135424017111?via%3Dihub

Malekpour S, Gubner J A and Sethares W A 2018 Measures of generalized magnitude-squared coherence: Differences and similarities *J Franklin Inst* **355**

Okefenokee National Wildlife Refuge 2025 Okefenokee Surface Water Level Data

Oxtobee J P A and Novakowski K 2002 A field investigation of groundwater/surface water interaction in a fractured bedrock environment *J Hydrol (Amst)* **269**

Plummer L N 1993 Stable isotope enrichment in paleowaters of the southeast Atlantic coastal plain, United States *Science (1979)* **262** 2016–20 Online: /doi/pdf/10.1126/science.262.5142.2016

Plummer L N, Busenberg E, McConnell J B, Drenkard S, Schlosser P and Michel R L 1998 Flow of river water into a Karstic limestone aquifer. 1. Tracing the young fraction in groundwater mixtures in the Upper Floridan Aquifer near Valdosta, Georgia *Applied Geochemistry* **13**

Priest S 2004 *Evaluation of Ground-Water Contribution to Streamflow in Coastal Georgia and Adjacent Parts of Florida and South Carolina*

Ramchunder S J, Voutchkova D D, Estrada E S, Chuah C J, Evaristo J, Ng D, Cai Y, Koh R Y T and Ziegler A D 2022 Flowpath influence on stream acid events in tropical urban streams in Singapore *Hydrol Process* **36** e14467 Online: /doi/pdf/10.1002/hyp.14467

696 Rasmussen T C and Crawford L A 1997 Identifying and removing barometric pressure effects in confined and unconfined aquifers *Ground Water* **35**

698 Rasmussen T C and Mote T L 2007 Monitoring Surface and Subsurface Water Storage Using Confined Aquifer Water Levels at the Savannah River Site, USA *Vadose Zone Journal* **6**

701 Rykiel Jr , E J 1977 *The Okefenokee Swamp watershed: water balance and nutrient budgets.* (Athens: University of Georgia)

703 Sammour M, Othman Z A, Rus A M M and Mohamed R 2019 Modified dynamic time warping for hierarchical clustering *Int J Adv Sci Eng Inf Technol* **9**

705 Shojaie A and Fox E B 2022 Granger Causality: A Review and Recent Advances *Annu Rev Stat Appl* **9**

707 Strupczewski W G, Weglarczyk S and Singh V P 2003 Impulse response of the kinematic diffusion model as a probability distribution of hydrologic samples with zero values *J Hydrol (Amst)* **270**

710 Thaw M, GebreEgziabher M, Villafañe-Pagán J Y and Jasechko S 2022 Modern groundwater reaches deeper depths in heavily pumped aquifer systems *Nat Commun* **13**

713 Thom T A , K J H and J Faustini 2015 *Water Resource Inventory and Assessment: Okefenokee National Wildlife Refuge Ware, Charlton, and Clinch Counties, Georgia Baker County, Florida* (Atlanta, GA)

716 Tiwari S, Jha S K and Singh A 2020 Quantification of node importance in rain gauge network: influence of temporal resolution and rain gauge density *Sci Rep* **10**

718 Toll N J and Rasmussen T C 2007 Removal of barometric pressure effects and earth tides from observed water levels *Ground Water* **45**

720 Tuttle S E and Salvucci G D 2017 Confounding factors in determining causal soil moisture-precipitation feedback *Water Resour Res* **53**

722 Winter T C, Harvey J W, Franke O L and Alley W M 1998 Ground water and surface water: A single resource *Circular* Online: https://pubs.usgs.gov/publication/cir1139

724 Yapiyev V, Rossi P M, Ala-Aho P and Marttila H 2023 Stable Water Isotopes as an Indicator of Surface Water Intrusion in Shallow Aquifer Wells: A Cold Climate Perspective *Water Resour Res* **59**

727 Yu K B 1986 *The Hydrology of the Okefenokee Swamp Watershed with Emphasis on Groundwater Flow* (Athens, GA: University of Georgia)

729