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

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