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Mapped Fractures and Sinkholes in the Coastal Plain of Florida and Georgia to Infer Environmental Impacts from Aquifer Storage and Recovery (ASR) and Supply Wells in the Regional Karst Floridan Aquifer System

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Abstract

The regional Floridan aquifer system (FAS) extends from the submerged carbonate platform of the Atlantic Ocean, Gulf of Mexico, and Straits of Florida in the southeastern United States (US), throughout Florida and the coastal plain of Alabama, Georgia, and South Carolina. This carbonate aquifer system is characterized by bedding planes, fractures, dissolution cavities, and other karst features that result in preferential flow of ground water, particularly in response to anthropogenic perturbations such as groundwater withdrawals and aquifer injections. The FAS was divided into six sub-regions for groundwater-modeling purposes in 1989, with results concluding that breaches of those groundwater divides had occurred and those breaches were attributed to large withdrawals of ground water in the US southeastern coastal plain. Those results suggest the model did not elucidate preferential flow conditions through fractures and other karst conduits. We hypothesized that incorporating fractures and sinkholes into groundwater models could improve results and predict adverse impacts to environmentally sensitive areas. We analyzed extensive fracture networks and sinkholes previously mapped throughout Florida and in Dougherty County, Georgia. Some of those fractures extend from one sub-region into an adjacent sub-region of the FAS and may be facilitating the breaching of groundwater divides described in the 1989 groundwater model for this regional aquifer system. The greater total fractures and fracture density in Dougherty County (1,225 and 141.3/100 km^2, respectively) compared to 21 north-Florida counties (10-91fractures per county and 0.6-3.8/100 km^2, respectively) presumably is due to the scale of fracture mapping and shorter mean lengths of mapped fractures in Dougherty County (1.2 km), compared to north Florida counties (26-118 km), rather than to orders of magnitude increases in fracture densities in that part of the FAS. The number of sinkholes identified in Dougherty County in a recent, unrelated project using 2011 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images, was approximately an order of magnitude greater than the number of sinkholes mapped in analog form in that county and published in 1986. Extension of the dense network of those fractures that occurred within the boundaries of a Priority Amphibian and Reptile Conservation Area (PARCA) that encompassed Dougherty County covered the Elmodel Wildlife Management Area (WMA) and ASR demonstration well in Baker County, Georgia. Those extensions also passed through numerous agricultural areas with center-pivot irrigation wells in southwest Georgia; intersected other Georgia PARCAs near the Florida-Georgia state line; and clumped in two areas of dense sinkhole clusters in northwest Florida. No determination has been made regarding the contributions of pirated water from the Apalachicola-Chattahoochee-Flint (ACF) River Basins and Wakulla Springshed from the magnitude and extent of agricultural, municipal, and industrial groundwater withdrawals in Georgia's coastal plain, that exceed groundwater withdrawals in Florida for that area of the FAS, to the increase in sinkholes in Dougherty County and the dense clusters of sinkholes in northwest Florida, via preferential flow through fractures. Similarly, the survival and recovery of at least 24 animal species in Georgia that are either federally listed or high-priority state species may be jeopardized by adverse direct, indirect, and cumulative impacts from preferential flow through fractures, sinkholes, and other karst conduits in response to aquifer injections and withdrawals that have not been evaluated. Currently no regional groundwater model has been constructed to evaluate such preferential groundwater flow in the FAS. A model incorporating preferential flow via mapped fractures and sinkholes is essential to determine the magnitude and extent of environmental impacts from ASR wells and other supply and disposal wells in this regional aquifer system, such as pirated water from the ACF and other river basins, alterations in submarine groundwater discharge to Apalachicola Bay and other coastal areas, saltwater intrusion, upconing of saline ground water and resulting impacts to federally endangered and threatened species and high-priority state species.

Keywords: Apalachicola-Chattahoochee-Flint (ACF) River Basins, arsenic, breached groundwater divides, carbonate aquifer system, geographic information system (GIS), pirated water, saltwater intrusion, upconing

1. Introduction

1.1 Regional Floridan Aquifer System

The regional Floridan aquifer system (FAS) extends throughout Florida, the coastal plain of Alabama, Georgia, and South Carolina (Johnston & Bush, 1988) and offshore from those states, to the limits of the submerged carbonate platform of the Atlantic Ocean, Gulf of Mexico, and Straits of Florida in the southeastern US. This aquifer system is the primary source of municipal water for those states. It also is a critical source of water for environmentally sensitive public and private lands, federally endangered and threatened species, and high-priority state species, including coastal species, but groundwater quantity and quality are declining without acknowledging the role of preferential groundwater flow in those declines. Carbonate aquifer systems, including the FAS, are characterized by bedding planes, fractures, dissolution cavities, piping, and other karst features. These result in preferential flow of ground water, particularly in response to anthropogenic perturbations such as groundwater withdrawals and aquifer injections (Bacchus, 2002; 2007; Bacchus, Bernardes, Jordan, & Madden, 2014; Bacchus, Bernardes, Xu, & Madden, 2015a; Bush & Johnston, 1988; Ford, Palmer, & White, 1988; Ford & Williams; 1989; Kohout, 1967; Krause & Randolph, 1989; Meyer, 1989; Neuendorf, 2005; Popenoe, Kohout, & Manheim, 1984; Yassin, Muhammad, Taib, & Al-Kouri, 2014).

Krause and Randolph (1989) divided the FAS into six sub-regions for groundwater modeling purposes. They concluded that breaches of those groundwater divides had occurred, attributing the breaches to large withdrawals of groundwater in the US southeastern coastal plain. Breaching probably is the result of extensive networks of fractures that have been reported by the US Army Corps of Engineers (ACOE, 2004), and mapped by Florida Department of Transportation (FDOT, 1973), and Vernon (1951) throughout Florida, facilitated by remote sensing. In the northwestern extent of the FAS, Brook and Allison (1986) mapped similar extensive fracture networks in Dougherty County, Georgia, located in the northwest portion of the FAS. Remote sensing continues to be a useful tool for identifying fractures, including in non-karst and Cretaceous formations (Oden, Okpamu, & Amah, 2012).

1.2 Background

1.2.1 Terminology Related to Aquifer Storage and Recovery (ASR)

Bacchus et al. (2015a) provided definitions for terminology related to “aquifer storage and recovery” (ASR) that is used by regulatory agencies, municipalities, and representatives of the ASR industry. That terminology, created primarily by the ASR industry and regulatory agencies, generally does not conform to standard or scientific definitions or concepts and is misleading. Examples include “aquifer storage and recovery,” “bubble,” “confining,” “excess water,” “lost to tide,” “recharge,” “reservoir,” “restoration,” “target storage volume” (TSV), and “water banking” (Bacchus et al., 2015a). Neither definitions nor descriptions of some of these terms, as applied to ASR, have been included in scientific peer-reviewed publications with dictionaries or glossaries. Therefore, in some cases (e.g., “aquifer storage and recovery,” “target storage volume,” and “water banking”), the default sources for definitions and descriptions of terms are documents produced by representatives of the ASR industry. Because of those constraints, terms that are used in an unorthodox manner in regulatory and other documents referenced in this paper are provided in quotations marks, to avoid confusion and misrepresentation.

McNeill (2000) concluded that municipal sewage effluent injected into deep saline aquifers for decades at Miami-Dade, Florida’s South District Wastewater Treatment Plant (SDWWTP) was flowing vertically upward. More than a decade latter, Walsh and Price (2010) and Walsh (2012) concluded that “injectate remained chemically distinct as it migrated upwards through rapid vertical pathways via density-driven buoyancy” at that site. In fact, numerous hydraulic and geochemical effects of the waste injections into the FAS already had been documented by the early 1970s. Examples included: (1) reversal of natural hydraulic gradients, with establishment of potential for up-dip migration of fluids; (2) increased localized aquifer permeability and transmissivity; (3) dissolution of the carbonate aquifer and localized cavern development beneath the injection sites; (4) upward movement of wastes; and (5) evolution of high concentrations of hydrogen sulfide, nitrogen, methane, and other gases (Kaufman, 1973). Additional evidence that more buoyant, low-salinity water injected into saline aquifer zones discharges vertically into overlying surface waters was published by numerous scientists in the 1980s based on independent research, as described by Bacchus (2001; 2002). That extensive evidence spanning decades, that low-salinity water injected into saline aquifer zones flows vertically upward, was not addressed by Walsh and Price (2010) and Walsh (2012) in their conclusion that "only a one-time pulse of injectate into the overlying aquifers" occurred at Miami-Dade's North District Wastewater Treatment Plant (NDWWTP) "due to improper well construction" or the unsupported statement that "[D]eep well injection into non-potable saline aquifers of treated domestic wastewater has been used in Florida for decades as a safe and effective alternative to ocean outfall disposal (Walsh, 2010).

Walsh and Price (2010) and Walsh (2012) also concluded that no fracturing had been reported at either the SDWWTP or NDWWTP injection-well sites. Based on the locations of those injection wells in the FDEP UIC database, the SDWWTP site is located immediately northeast of a fracture mapped by FDOT (1973) and north of the intersection of fracture extensions from the FDOT (1973) fracture data set. The NDWWTP site is located immediately southwest of the extension of a fracture mapped by FDOT (1973), but that NDWWTP location does not appear to coincide with the location of the NDWWTP shown in Figure 1 of Walsh and Price (2010). It is important to note that the SDWWTP site is west of submarine groundwater discharge (SGD) sites "b" and "a," south of SGD site "a," and north of SGD "d," all of which are in Biscayne Bay, and both SDWWTP and NDWWTP sites are associated with extensions of a fracture mapped by FDOT (1973) that extends to a coral reef in the Florida Keys subjected to eutrophication (Bacchus et al., 2014). The data and samples analyzed by Walsh and Price (2010) and Walsh (2012) were from the existing UIC monitoring wells, rather than samples and data from fractures associated with those two aquifer-injection sites. It also is important to note that Walsh's (2012) conclusion regarding fractures was that "seismic data acquisition is recommended for any future injection sites, as it may be able to optimize location of future injection sites in areas where these subsurface features are not found." Since 2012, FDEP has issued 2,216 UIC permits, but none of those permits required seismic data acquisition (Joe Haberfeld, FDEP Geological Survey, UIC Program Geologist, pers. comm., 04/25/16 and 04/27/16). This deficiency does not appear to be confined to Florida. There was no evidence that seismic data acquisition was required prior to the permitting and construction of the recent ASR demonstration well in Georgia, the recent ASR wells in Hilton Head, South Carolina (Pyne, 2015) or any of the other ASR wells permitted in South Carolina. The analysis of ASR for Hilton Head Island does not even address the presence of fractures or the ability of ASR to increase saltwater intrusion, rather than provide a solution to that serious problem (Pyne, 2015).

1.2.2 The Theory of ASR

The theory of ASR is temporary artificial aquifer "recharge" that consists of three components: (1) aquifer injections of fluids ("recharge"); (2) withdrawals of the injected fluids ("recovery"); and (3) a period of time ("cycle") between the injections and withdrawals (Bacchus et al., 2015a). Bacchus, Bernardes, Xu, and Madden (2015b) discussed the difference between natural and artificial aquifer recharge and how natural recharge exceeds actual "recovery" documented from Florida ASR wells.

The period of time between aquifer injections and aquifer withdrawals from an ASR well is considered to be "storage" of the injected fluids. The injected water generally is termed "excess water." The concepts of "excess water" and water "lost to tide" during the wet season ignore the beneficial/essential roles of natural pulses of uncontaminated, nonsaline surface and ground water to coastal ecosystems. The source of this temporary artificial aquifer "recharge" includes: (1) stormwater runoff (containing agricultural, industrial and/or municipal contaminants) pumped out of canals, mine pits or other areas; (2) treated sewage effluent (also known as reclaimed water, reuse water, bright water) previously mined from the aquifer system and resulting in induced (forced) recharge; (3) surface water diverted or extracted from natural streams, lakes, and other surfacewater ecosystems during the wet season; and (4) ground water withdrawn from one layer or zone of the aquifer system and injected into another. "Augmentation" and "blending" are examples of terms applied to withdrawing ground water from one aquifer zone for injecting into another zone.

The US Environmental Protection Agency (USEPA) regulates these types of underground injections pursuant to the federal Safe Drinking Water Act (SDWA) Underground Injection Control (UIC) Program. Although the USEPA also is responsible for enforcing the federal Clean Water Act and complying with the federal Endangered Species Act, direct, indirect, and cumulative environmental impacts have not been evaluated for: (1) diverting natural surfacewater discharges during wet seasons; (2) aquifer-injections of water with different chemical composition than existing ground water; and (3) discharges of injected water into surface waters via fractures and other karst conduits (Bacchus, et al., 2014; Bacchus et al., 2015a; Bacchus et al., 2015b).

1.2.3 "Disposal" vs. "Storage" and Reported "Recovery" vs. Actual "Recovery"

Aquifer injections into the FAS for "disposal" of various contaminated fluids occur via wells at similar depths as the ASR "storage" and "recovery" wells. These fluids include sewage effluent treated to various degrees; contaminated stormwater runoff; and agricultural, industrial, and other municipal wastes (e.g., brine from reverse osmosis production of municipal water). Most "disposal" of contaminated fluids through aquifer injections are reported as exceeding "1 million gallons per day (MGD)." The presumption for these aquifer "disposals" of contaminated fluids through injection wells is that the contaminated fluids constantly flow away from the injection wells as additional injections of contaminated fluids occur. These "disposal" wells also are regulated under the SDWA by the USEPA's UIC program. The governing presumption of this regulatory program is that contaminated fluids injected into the aquifer do not flow vertically upward and into an overlying aquifer zone that is used or potentially available for potable water. Horizontal flow of those injected contaminants, which include discharges to inland and coastal surface waters, is ignored.

Despite the established fact that fluids injected into the FAS flow away from the point of aquifer injection, federal and state regulatory agencies, and the ASR industry continue to claim that aquifer injections of water into ASR wells remain at the base of the well in a "bubble" waiting for withdrawal as "recovery" of the injected water (Bacchus et al., 2014; 2015a; 2015b). The reported "recovery" in the US Geological Survey (USGS) review of ASR wells and well data in Florida (Reese, 2002, Table 5) was based on the chloride concentration established under the SDWA for potable water (250 mg/L), rather than the much lower chloride concentration of the water injected into those ASR wells. Actual "recovery" was determined by adjusting the results of cycle testing conducted in ASR test wells constructed in south Florida to compensate for differences between chloride concentration of water injected into ASR wells and water withdrawn from those wells (i.e., reported chloride concentration/(recovered/injected concentration)), as summarized by Bacchus et al. (2014; 2015a; 2015b). Actual "recovery," based solely on chloride content of the withdrawn water adjusted to match the chloride content of the injected water ranged from 0% to 16.8% for "storage" periods of 15 and 8 days, respectively for those ASR wells (Table 3 of Bacchus et al., 2015a). That evaluation by Reese (2002) conducted at selected ASR wells appears to be the most extensive compilation of the chloride content of ground water at the ASR location and the chloride content of "recovered" water, which exceeded the chloride concentration of the ground water routinely, while still being considered as "recovered" water.

Those shocking results illustrate the lack of evidence supporting the presumption of "storage" or "recovery" of water injected into ASR wells and that ASR wells respond differently than aquifer disposal wells, despite agency and industry terminology that attempts to support distinct differences. After the evaluation of 18 ASR sites by Reese (2002, Table 5), in the USGS review of Florida's ASR wells, 13 of those sites were reported as abandoned by Bloetscher, Sham, Danko III, and Ratick (2014). That suggests percent "recovery" was misrepresented because water continued to be withdrawn after the chloride content of the withdrawn water was considerably greater than the chloride content of the water injected into ASR wells, making claims of the volume and duration of injected water "stored" questionable. Another ASR well site evaluated by Reese (2002, i.e., San Carlos) later was reported in the Florida Department of Environmental Protection (FDEP) database as inactive. The names of those 14 ASR sites are shown in bold in Table 1 (Bacchus et al., 2015b). Examples of other abandoned ASR sites in Collier, Lee, Miami-Dade, and Okeechobee Counties are shown in Table 1 of Bloetscher et al. (2014).

An additional process, gravity flow in shallow ground water of surficial aquifer zones in the FAS, is well documented as a transport mechanism for contaminants at locations such as non-human concentrated animal feeding operations (CAFOs) and similar human operations, such as the City of Tallahassee municipal sewage effluent sprayfield (Bacchus & Barile (2005); Kincaid, Davies, Hazlett, Loper, Dehan, & McKinlay (2004); and Kincaid, Davies, Werner, & DeHan (2012)). The established fact that ground water is not static but flows raises the question of how the same water that is injected into ASR wells can be "recovered." Similarly, the question arises regarding whether aquifer injections can be considered as artificial aquifer recharge, as ASR proponents claim, or if the injected water simply flows rapidly from the point of injection via karst conduits and then discharges to surface waters (Bacchus et al., 2015a; 2015b). We found no published literature or reports or permits for ASR wells in the FAS describing the chemical characterization or "fingerprinting" of the native ground water and water injected for "storage" and "recovery" that would support the claims of "storage" and "recovery."

1.3 Objectives

This investigation reports on the dynamics of potential pathways from the subsurface to the surface in Florida and the coastal plain of Georgia and South Carolina, all of which are underlain by the FAS. The first objective was to compare locations, lengths, and densities of the three referenced sets of fracture networks in Florida (ACOE, 2004; FDOT, 1973; Vernon, 1951) to the fracture networks in Dougherty County, mapped by Brook and Allison (1986) in the northwestern Georgia portion of the FAS. Those fracture networks, originally mapped in analog format, were georeferenced and converted to digital formats to update those previous studies and facilitate our comparisons. The second objective was to compare the proximity of those fractures and fracture extensions to permitted ASR wells in Florida, Georgia, and South Carolina, and relict and modern sinkholes mapped in Florida and Dougherty County, Georgia. The third objective was to compare the locations of those mapped fractures and extensions in Florida and Georgia to areas of federally listed or high-priority state animal species, selected federal and state lands, watersheds for the Apalachicola-Chattahoochee-Flint (ACF) River Basins (adapted from Seaber, Kapinos, & Knapp, 1987) and watersheds throughout the coastal plain designated by the USGS.

2. Study Area

Our study area covers the extent of the regional FAS from the submerged carbonate platform of the Atlantic Ocean, Gulf of Mexico, and Straits of Florida, throughout Florida and the coastal plain of Alabama, Georgia, and South Carolina in the southeastern US. Krause and Randolph (1989) divided the FAS into six sub-regions for groundwater modeling purposes. They identified those sub-regions as D, E, F, G, H, and an unnamed sub-region between D and H**,** where available data were insufficient for groundwater modeling. Figure 1A illustrates the approximate submerged extent of the Floridan aquifer system and the location of these six sub-regions, with the previously unnamed sub-region labeled U.

More detailed focus in the study area (Figure 1B) included the ACF River Basins, Dougherty County, and adjacent counties in Georgia where fractures and sinkholes have been mapped and preferential flow documented through fractures (Brook, 1985; Brook & Allison, 1986; Brook, Carver, & Sun, 1986; Brook & Sun, 1982; Brook, Sun, & Carver, 1988)**.** The headwaters of the Chattahoochee and Flint Rivers originate in Alabama and Georgia, north of the northern extent of the Florida aquifer system, and were not considered in our study. Those rivers, however, flow into the Apalachicola River and eventually discharge into Apalachicola Bay and the Gulf of Mexico. The counties in Georgia and South Carolina included in the study also were based on the location of an ASR demonstration well recently constructed in Baker County, Georgia and counties in South Carolina where ASR wells have been installed.

A

B

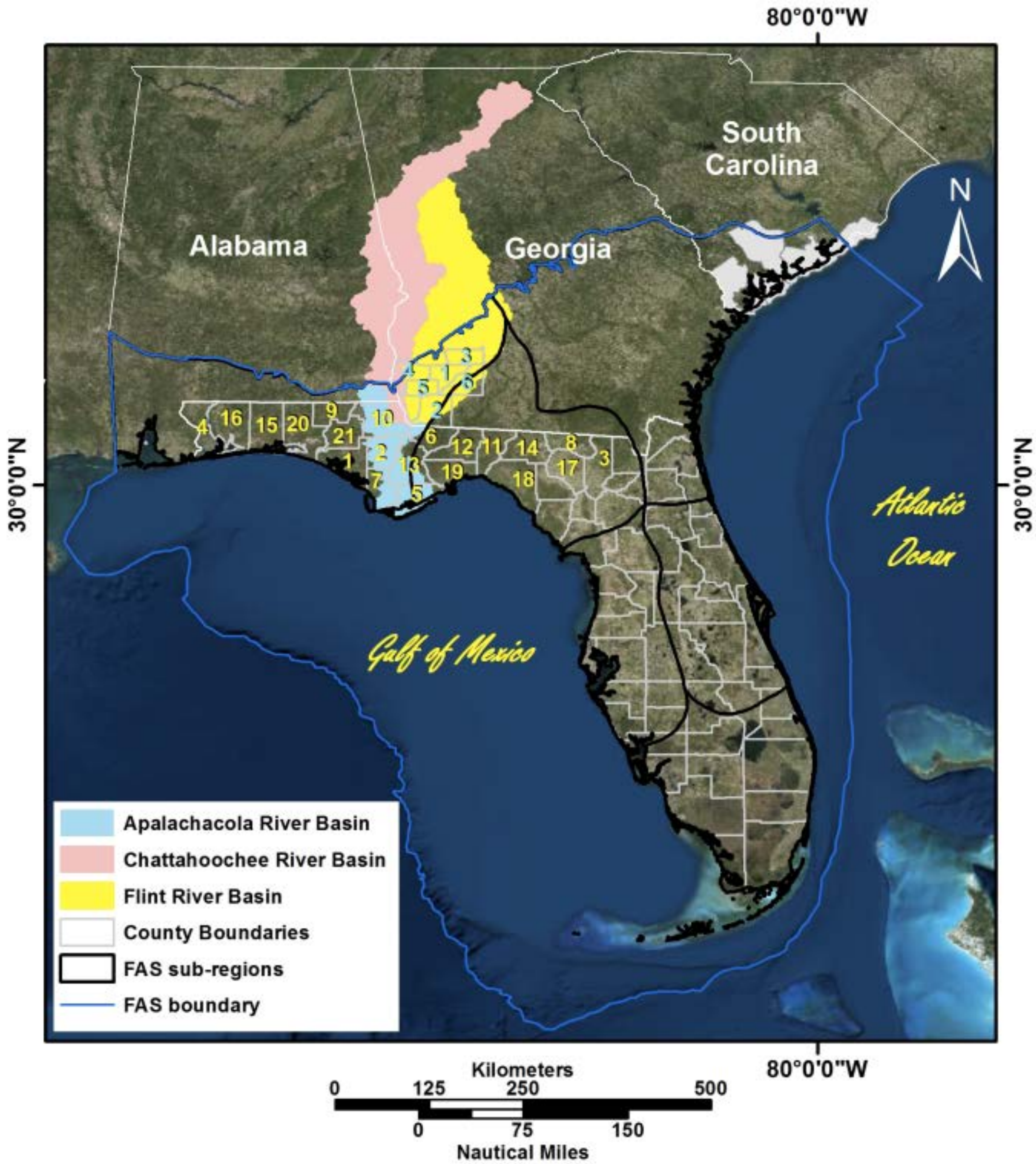


Figure 1. Approximate submarine extent of the Floridan aquifer system in the Atlantic Ocean and Gulf of Mexico, and throughout Florida and southeastern coastal plain of Alabama, Georgia, and South Carolina, with:

A. the six sub-regions (D, E, F, G, H, and unnamed (U)) designated by Krause & Randolph (1989), and

B. detailed view showing the Apalachicola-Chattahoochee-Flint (ACF) River Basin, and counties in north Florida (numbered), Georgia, and South Carolina with mapped fractures, relict sinkholes or ASR wells included in the study

Having such a large data set allowed us to evaluate the relationship of fractures and sinkholes to key watersheds of concern, as well as sub-regions of the regional aquifer system designated by the USGS. Our large data set also facilitated evaluating the relationship of fractures and sinkholes to examples of federal and state lands in Florida, Georgia, and South Carolina**,** and selected Priority Amphibian and Reptile Conservation Areas (PARCAs) as part of our study. Table 1 lists the counties, and federal and state lands in north Florida, Georgia, and South Carolina that were evaluated in more detail in our study area.

Table 1. Counties in north Florida, Georgia, and South Carolina in the Floridan aquifer system with more detailed analysis of mapped fracture data, permitted ASR wells, and federal and state lands, and towns in the vicinity of those fractures or ASR wells.

ID	North Florida Counties	Federal and State Lands and Towns
1	Bay	Panama City
2	Calhoun	Blountstown
3	Columbia	Lake City
4	Escambia	Pensacola
5	Franklin	Apalachicola NF[1], Tate's Hell State Forest[2]
6	Gadsen	Quincy
7	Gulf	Port St. Joe
8	Hamilton	Jasper
9	Holmes	Bonifay
10	Jackson	Marianna
11	Jefferson	St. Marks National Wildlife Refuge (NWR)[3]
12	Leon	Apalachicola NF[1]
13	Liberty	Apalachicola NF[1], Tate's Hell State Forest[2]
14	Madison	Madison
15	Okaloosa	Crestview
16	Santa Rosa	Milton
17	Suwannee	Live Oak
18	Taylor	St. Marks NWR[3]
19	Wakulla	Apalachicola NF[1], St. Marks NWR[3], Wakulla Springs SP
20	Walton	DeFuniak Springs
21	Washington	Chipley
	Georgia Counties	
1	Baker	Elmodel Wildlife Management Area, ASR demonstration well
2	Decatur	Bainbridge
3	Dougherty	Albany, Pretoria, Putney
4	Early	Damascus
5	Miller	Cooktown
6	Mitchell	Camilla
	South Carolina Counties	
	Beaufort	Pinckney Island NWR
	Charleston	Charleston, Kiawah, Mt. Pleasant
	Colleton	Edisto Beach[4]
	Jasper	Savannah NWR, Tybee NWR

[1]Apalachicola National Forest is the largest U.S. National Forest in Florida at 2,561.2 km^2 (988.9 mi^2) and includes Bradwell Bay Wilderness Area, Mud Swamp/New River Wilderness Area and Leon Sinks Geological Area.
[2]Tate's Hell SF encompasses 819 km^2 (316.2 mi^2).
[3]St. Marks National Wildlife Refuge includes the estuaries of seven north Florida streams and encompasses 280 km^2 (108.1 mi^2).
[4]Proposed ASR well and RO facility.

3. Methods

3.1 Shapefiles and Data from Other Sources

3.1.1 Shapefiles and Data for Florida

The locations of the Florida ASR wells permitted by the FDEP were created from location information included in the FDEP database and provided by that agency. Locations of all aquifer injection wells permitted by the FDEP in Florida are available online (http://ca.dep.state.fl.us/mapdirect/?focus=uic). The locations for modern sinkholes (used synonymously with subsidence features) reported in Florida were created from the FDEP Florida Geological Survey (FGS) shapefile for subsidence features mapped in Florida through October 2014. Shapefiles not available from the Army Corps of Engineers (ACOE) for the lineaments representing extensive networks of fractures shown as the "Lineament map of south Florida" (Figure 3-7 in ACOE (2014), originally from ACOE (2004)), were created by converting the analog file to a digital file as described in Bacchus et al. (2015a). The acquisition methods for the FDOT (1973) and Vernon (1951) lineaments in Florida were described in Bacchus et al. (2014) and Lines et al. (2012).

3.1.2 Shapefiles and Data for Georgia and South Carolina

Locations for fractures and relict sinkholes in Dougherty County were based on analog versions identified by Brook and Allison (1986), who used topographic maps and 1:24,000 scale, color infrared images to identify sinkholes, based on surfacewater features, vegetation and soil moisture patterns, and topographic expression. Mapped sinkhole distribution and color infrared images then were used to map fractures and compare the mapped fracture orientations with regional trends for that area. Modern sinkholes in Dougherty County were identified independently, by the NASA DEVELOP National Program for Georgia Disasters and Water Resources for the period of 2002 to 2011, identifying as many as 18,557 sinkholes in 2011 for that county

(Cahalan, Amin, Berry, Xu, Hu, & Milewski, 2015). The methods used for that NASA DEVELOP project were the same methods used to evaluate sinkholes in a smaller area in southeast Dougherty County (Cahalan, Milewski & Durham, in press). Relict sinkholes mapped by Brook and Allison (1986) were digitized to convert from analog to digital format.

We located the ASR demonstration well in the Elmodel Wildlife Management Area (WMA), in Baker County, Georgia in the approximate center of the boundaries of the Elmodel WMA, because specific location information (i.e., latitude and longitude or shapefile) for that ASR well was not provided by the Georgia Department of Natural Resources (GDNR) that permitted that well (Jim Kennedy, GDNR, State Geologist, pers. comm., 12/15) or the Georgia Environmental Finance Authority (GEFA) Program that funded that well (Shane Hix, Director of Public Affairs, pers. comm., 12/15). Specific location information also was not available from the public and private utility companies in South Carolina for the 68 ASR wells permitted in that state, but a spreadsheet for those ASR wells, including the latitude and longitude coordinates for each well, was provided by the South Carolina Department of Environment and Health Control (SCDEHC, Christopher Wargo, pers. comm., 3/16). We converted the coordinates for those ASR wells into point-files. Funding of a proposed ASR well and associated reverse osmosis (RO) system in Edisto Beach, South Carolina is pending approval by the Edisto Beach council and mayor. Therefore, that pending ASR well was not included in the spreadsheet provided by the SCDEHC, but Colleton County, where the pending ASR well would be located, was included in the figures we created for this paper.

A shapefile for the locations of the Georgia PARCAs from Figure 1 of Jenson (2015) was provided by J.J. Apodaca (Professor of Conservation Biology at Warren Wilson College, in Asheville, North Carolina) to facilitate our determination of the proximity of those PARCAs to mapped fractures and fracture extensions. Shapefiles for the USGS watershed basin dataset (WBD) hydrologic unit codes (HUC) that intersect the state boundaries of Georgia are those used by the River Basin Center (RBC), University of Georgia**,** Odum School of Ecology in Athens, Georgia, as extracted from http://nhd.usgs.gov/wbd.html, and were provided by Duncan Elkin (RBC Postdoctoral Research Associate). He also provided the shapefile for the ACF River Basins (adapted from Seaber et al., 1987) that extend from Georgia through northwest Florida.

3.1.3 Shapefiles for Federal and State Lands, and Basemaps for Figures

Shapefiles for federal and state lands (e.g., National Wildlife Refuges and state Wildlife Management Areas) were obtained online from http://gapanalysis.usgs.gov/padus/data/download/. The basemap source for Figures 1A and 6A was provided as “Esri, HERE, DeLorme, TomTom, Intermap, GEBCO, USGS, FOA, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance, Survey, Esri Japan, METI, Esri China.” The basemap source for Figures 1B, 2A-B, 3A-B, and 6B-C was provided as, “Esri, Digital Globe, GeoEye, i-cubed, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.”

3.2 Analog to Digital Conversion of Mapped Sinkholes and Lineaments Representing Fractures and Data Analysis

Geospatial analysis to assess fracture lineaments, sinkholes, and wells was conducted in ArcGIS Version 10.2, as described in Bacchus et al. (2015a). Sub-regions of the FAS were delineated by following widely-accepted map vectorization procedures, including the control-point based georeferencing of the sub-regions map in Krause and Randolph (1989) and the heads up digitizing of the resulting georeferenced map image. Political boundaries from the US Census Bureau, including county limits, were used as reference during georeferencing. Spatial frequency analysis of previously mapped linear features indicative of fractures also was conducted as described in Bacchus et al. (2015a).

Brook and Allison (1986) used topographic maps and 1:24,000 scale, color infrared images to create analog maps of sinkholes and fractures, based on the presence of surface water features, vegetation and soil moisture patterns, and topographic expression, and to compare the mapped fracture orientations with regional trends. We used ArcGIS to georeference their analog maps for Dougherty County. During georeferencing, 25 evenly distributed control points were identified over a digital copy of the fractures map and the county boundary reference layer. The resulting georeferenced map was then used to manually trace the fractures using the "Create Features" tool in ArcMap.

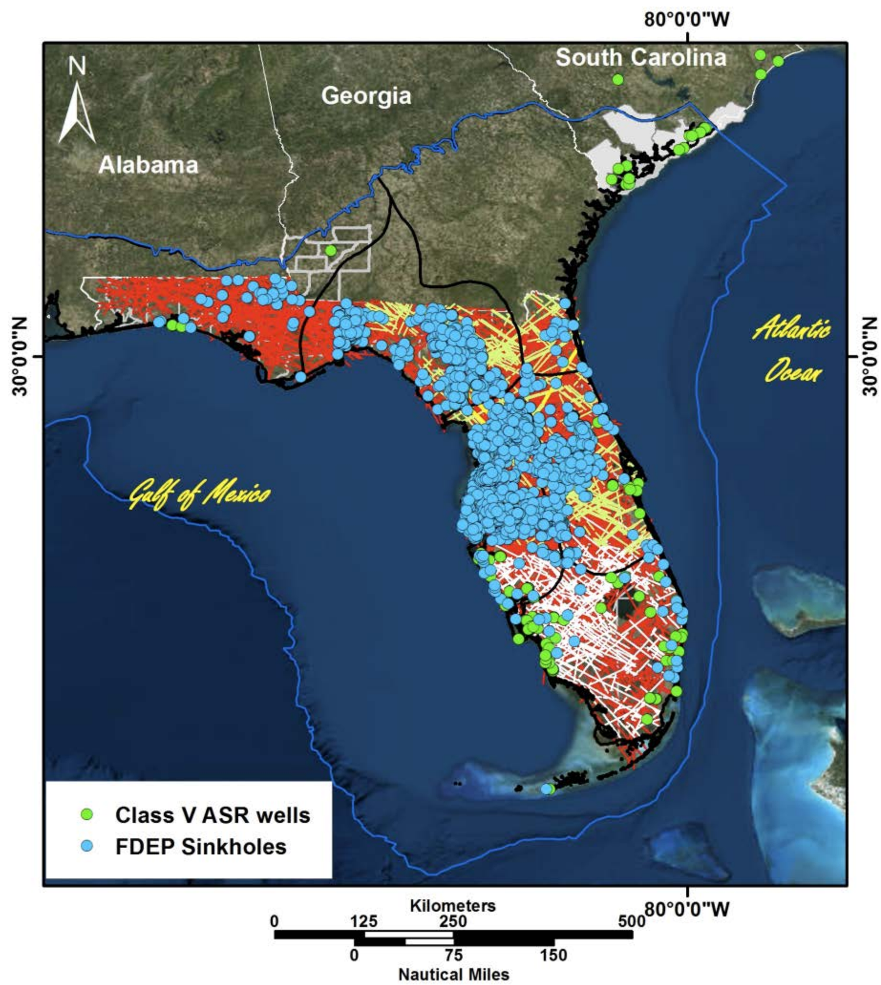
4. Results

4.1 Previously Mapped Fractures, Sinkholes, and ASR Wells in the FAS Sub-Regions

Figure 2A shows the locations of fractures mapped by Vernon (1951), the Remote Sensing Section of FDOT (1973), and unidentified source(s) originating in an unauthored draft report by ACOE (2004) and included in the ACOE Final TDR (2014) in southern Florida. Also shown in Figure 2A are the modern sinkholes in the Florida database (FDEP) and the ASR wells permitted throughout Florida, in Baker County, Georgia, and throughout South Carolina, in addition to the boundaries of the six sub-regions of the FAS. The FDOT (1973) fractures were mapped throughout Florida, in all six sub-regions of the FAS. The Vernon (1951) fractures were mapped only in sub-regions E and F and the Florida portion of sub-regions D and U. The ACOE (2004; 2014) fractures were mapped primarily in sub-region G, but also extended into sub-regions E and F. Dense clusters of modern sinkholes reported to the FDEP in Florida have been mapped in sub-regions E, F and U.

Fractures mapped in Florida that occurred in proximity to Florida ASR wells were extended to the submerged and landward FAS boundaries. Figure 2B shows the locations of these fracture extensions. The northern extension of one of the fractures mapped by FDOT (1973), that is in the immediate vicinity of a Florida ASR well in sub-region E, also is associated with the operational ASR wells in Hilton Head, Long Cove, and Palmetto Bay in South Carolina The northern portion of other fracture extensions from the Florida boundary of sub-region U continues through the Georgia counties surrounding the Baker County ASR demonstration well (Figure 2B). The absence of lineaments representing fractures in the center of south Florida coincides with the location of Lake Okeechobee and results from the inability to detect linear features within water bodies remotely, with aerial photography and satellite images used for those data sets. Therefore, the absence of mapped lineaments in that area of Figures 2A and B does not imply that fractures do not underly Lake Okeechobee.

A



B

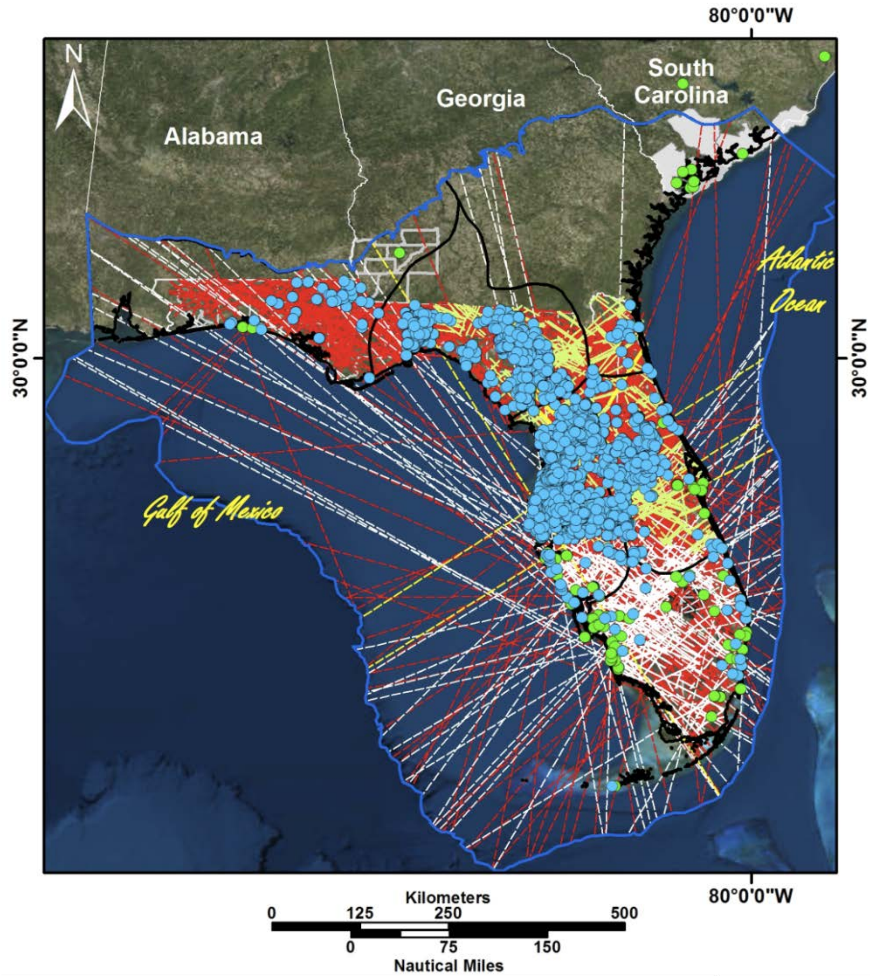


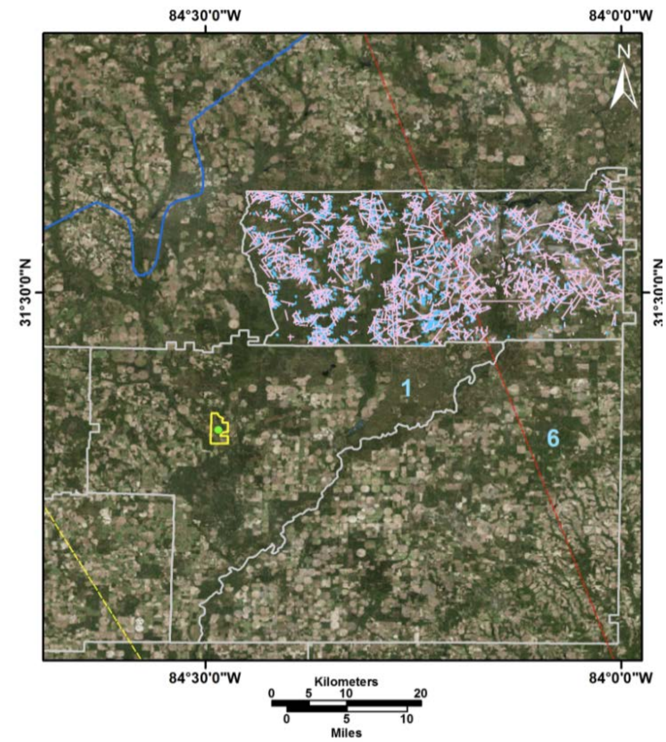
Figure 2. Proximity of modern sinkholes in Florida (blue circles) and permitted ASR wells in Florida, Georgia, and South Carolina (green circles) to:

A. fractures in Florida, as reported by the ACOE (2004, diagonal white lines) and mapped by FDOT (1973, diagonal red lines) and Vernon (1951, diagonal yellow-green lines), and

B. extensions of those fractures in proximity to ASR wells (dashed diagonal lines of same colors)

Enlarging the vicinity of the permitted Elmodel WMA ASR demonstration well in Baker County, Georgia (Figure 3A), shows the proximity to the dense network of fractures and sinkholes mapped by Brook and Allison (1986) in Dougherty County, north of Baker County (1). The dark green areas in Figure 3A for Dougherty County, where no fractures were mapped, are streams and riparian wetlands that obscure features indicative of fractures, similar to the Lake Okeechobee open-water area in south Florida. The extensive circular and rectangular light areas in Figure 3A for Baker County (1) and Mitchell County (6) are center-pivot irrigation areas and other agricultural fields that also are irrigated. The yellow and red diagonal dashed lines southwest and northeast of the Elmodel WMA ASR demonstration well in Figure 3A are extensions of fractures mapped in Florida in proximity to ASR wells in that state. Enlarging the vicinity of the ASR wells in South Carolina (Figure 3B) shows the proximity of the operational ASR wells in Hilton Head, Long Cove, and Palmetto Bay (Beaufort County) to the red diagonal dashed line extensions of fractures mapped in Florida, that are associated with ASR wells in that state. The additional ASR well and RO facility proposed for Edisto Beach (Colleton County) is not shown because it was not permitted at the time of acceptance of this paper for publication. That ASR well and facility would be located on the north shore of the mouth of the Edisto River, between the ASR wells in Beaufort County (southwest) and the ASR wells in Charleston County (north east), in proximity to the two intersecting fracture extensions also associated with ASR wells in Florida.

A



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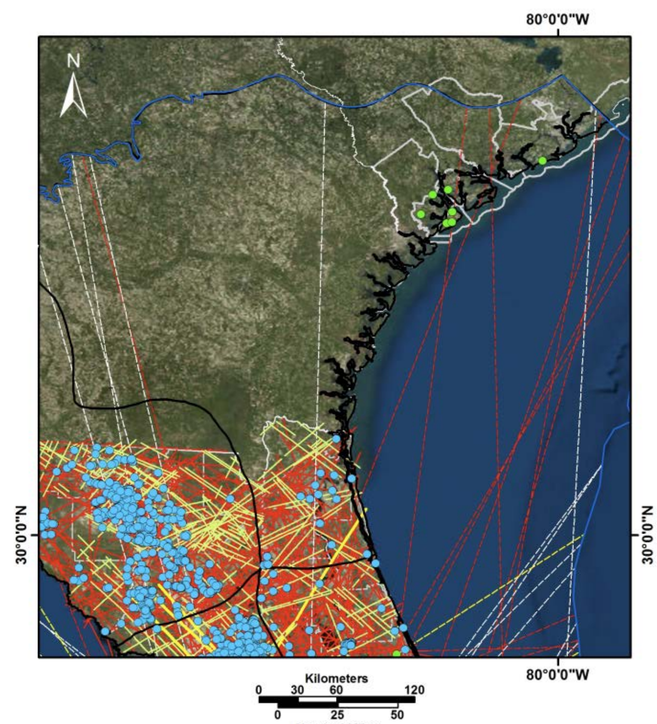


Figure 3. Enlargement of fracture extensions (dashed lines, as described in Figure 2), showing proximity to: A. fractures and relict sinkholes mapped in Dougherty County, Georgia by Brook and Allison (1986, pink lines and blue polygons, respectively) and the permitted Elmodel Wildlife Management Area ASR demonstration well in Baker County, Georgia and

B. permitted ASR wells in South Carolina within the FAS boundaries (in Beaufort, Charleston, Colleton, and Jasper Counties) and beyond the FAS boundaries (in Columbus, Georgetown, Horry, Marion, and Orangeburg Counties)

4.2 Length, Frequency, and Density of Fractures Mapped in Florida and Georgia

Table 2 summarizes the density of fractures, total number of fractures and the shortest, longest, and mean fracture lengths mapped in Dougherty County by Brook and Allison (1986) and mapped by Vernon (1951) and by FDOT (1973) in the 21 counties in north Florida selected for comparison in our study. Based on our georeferenced and digitized data 1,225 fractures were mapped in Dougherty County by Brook and Allison (1986). The lengths of the shortest and longest fractures were 0.1 km (0.1 mi) and 8.6 km (5.3 mi), respectively, and the mean fracture length was 1.2 km (0.8 mi). By comparison, the longest and most numerous fractures in the 21 north Florida counties in our study were mapped by FDOT (1973), with the shortest and longest fractures 17 km (10.6 mi) and 373 km (231.8 mi), respectively. Mean fracture lengths from the FDOT (1973) data set ranged from 68.4 km (42.5 mi) to 117.5 km (73 mi). The most numerous fractures mapped in those north Florida counties by FDOT (1973) occurred in Washington County, which included 60 fractures (Table 2). Only six of the 21 counties in north Florida included fractures mapped by Vernon (1951). The most numerous fractures mapped in north Florida counties for that data set occurred in Columbia County, which included 36 fractures. The length of the shortest and longest fractures in the Vernon (1951) data set was 5 km (3.1 mi) and 65 km (40.4 mi) and mean fracture lengths ranged from 25.6 km (15.9 mi) to 38.4 km (23.9 mi). The mapped fractures reported in Florida by the ACOE (2004) did not include north Florida counties (Table 2 and Figure 2). Total density of fractures and fracture density per 100 km^2 for all three data sets, by county, also is provided in Table 2.

Table 2. Density and frequency of fractures, lengths of shortest and longest fractures, and mean fracture lengths for Dougherty County, Georgia[1] and 21 counties in north Florida[2]

	Number of Fractures/ 100 km^2			Total Number of Fractures			Total Combined	Shortest-Longest Fractures (km)			Mean Fracture Length (km)		
County	B&A	FDOT	Vernon	B&A	FDOT	Vernon	Fractures	B&A	FDOT	Vernon	B&A	FDOT	Vernon
Dougherty	141.3	-	-	1,225	-	-	1,225	0.1-8.6	-	-	1.2	-	-
Bay	-	2.8	-	-	54	-	54	-	30-355	-	-	93.4	-
Calhoun	-	3.6	-	-	54	-	54	-	20-373	-	-	100.6	-
Columbia	-	2.7	1.7	-	55	36	91	-	32-373	5-65	-	111.5	28.0
Escambia	-	0.6	-	-	10	-	10	-	20-163	-	-	76.6	-
Franklin	-	1.3	-	-	19	-	19	-	36-222	-	-	100.8	-
Gadsden	-	2.6	-	-	36	-	36	-	26-373	-	-	113.8	-
Gulf	-	1.9	-	-	29	-	29	-	31-159	-	-	81.3	-
Hamilton	-	2.2	2.2	-	30	30	60	-	31-373	8-52	-	111.3	26.7
Holmes	-	2.6	-	-	32	-	32	-	35-236	-	-	79.4	-
Jackson	-	2.2	-	-	53	-	53	-	20-373	-	-	85.4	-
Jefferson	-	2.5	1.3	-	39	20	59	-	21-373	10-51	-	117.5	28.6
Leon	-	2.9	0.6	-	53	10	63	-	23-373	30-51	-	105.3	38.4
Liberty	-	2.6	-	-	57	-	57	-	26-373	-	-	106.2	-
Madison	-	2.0	-	-	37	-	37	-	31-373	-	-	103.3	-
Okaloosa	-	1.4	-	-	34	-	34	-	35-222	-	-	80.9	-
Santa Rosa	-	1.1	-	-	28	-	28	-	20-163	-	-	68.4	-
Suwannee	-	2.5	1.6	-	44	29	73	-	21-355	7-49	-	96.5	25.6
Taylor	-	1.4	0.1	-	37	4	41	-	27-182	14-48	-	87.1	32.0
Wakulla	-	2.7	-	-	43	-	43	-	32-163	-	-	91.1	-
Walton	-	1.8	-	-	50	-	50	-	17-355	-	-	92.3	-
Washington	-	3.8	-	-	60	-	60	-	30-373	-	-	96.7	-
								0.1-8.6	17-373	5-65			

[1] from Brook and Allison (1986), georeferenced/digitized for our study
[2] from FDOT (1973) and Vernon (1951)

Figure 4 provides a comparison of the length and frequency of fractures mapped in the 21 counties in north Florida (from FDOT, 1973 and Vernon, 1951), to length and frequency of fractures mapped in Dougherty County by Brook and Allison (1986). The scale of the X and Y axes for the north-Florida counties are the same, with a maximum of 60 fractures and 400 km, respectively. The scale of the X and Y axes for Dougherty County was adjusted for a maximum of 1,200 fractures and 10 km, respectively, because of the shorter, more numerous fractures mapped in that county.

4.3 Distances Between Previously Mapped Fractures and Sinkholes in Georgia and Florida

A histogram showing the distances between the 1,225 fractures and 934 relict sinkholes mapped in Dougherty County by Brook and Allison (1986) is provided in Figure 5A. All of those sinkholes were within 1.75 km (1.09 mi) of a fracture. Only six sinkholes occurred more than 0.75 km (0.47 mi) from the nearest fracture mapped by Brook and Allison (1986). The majority of those sinkholes, 627, were less than 0.25 km (0.78 mi) from a fracture, and 281 and 19 sinkholes were located between 0.25 and 0.75 km (0.16 mi and 0.47 mi), respectively, from the nearest fracture.

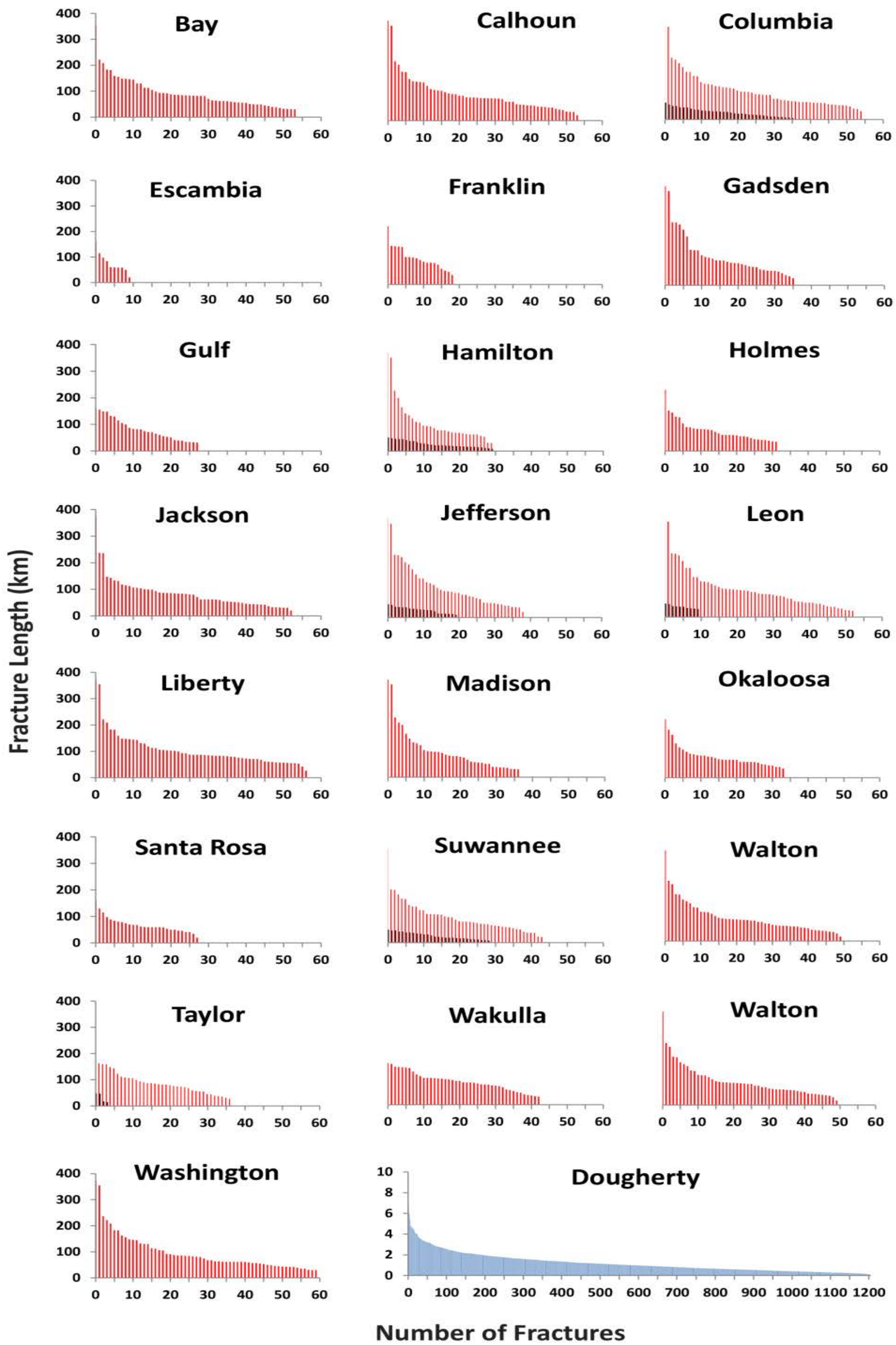


Figure 4. Length and frequency of fractures mapped in 21 counties in north Florida (red from FDOT (1973) and black from Vernon (1951)) and Dougherty County, Georgia (blue from Brook & Allison (1986))

A similar histogram is provided in Figure 5B, showing the distances of sinkholes within 5 km (3.11 mi) from each of the three sources of mapped fractures in Florida (ACOE, 2004; FDOT, 1973; and Vernon, 1951) and those combined fractures to the 2,814 modern sinkholes reported in Florida, based on the FDEP database. Only the FDOT (1973) fracture data set covered the entire state of Florida, while the ACOE (2004) data set was located in the southern part of Florida and the Vernon (1951) data set was located further north in the state. Half of the sinkholes reported in Florida (1,407) occurred within 1.25 km from the nearest mapped fracture and more than 75% of the sinkholes reported in Florida (2,115) occurred within 2.75 km (1.71 mi) from the nearest mapped fracture. All but 12 of the remaining sinkholes reported in Florida occurred between 2.75 km and 5 km.

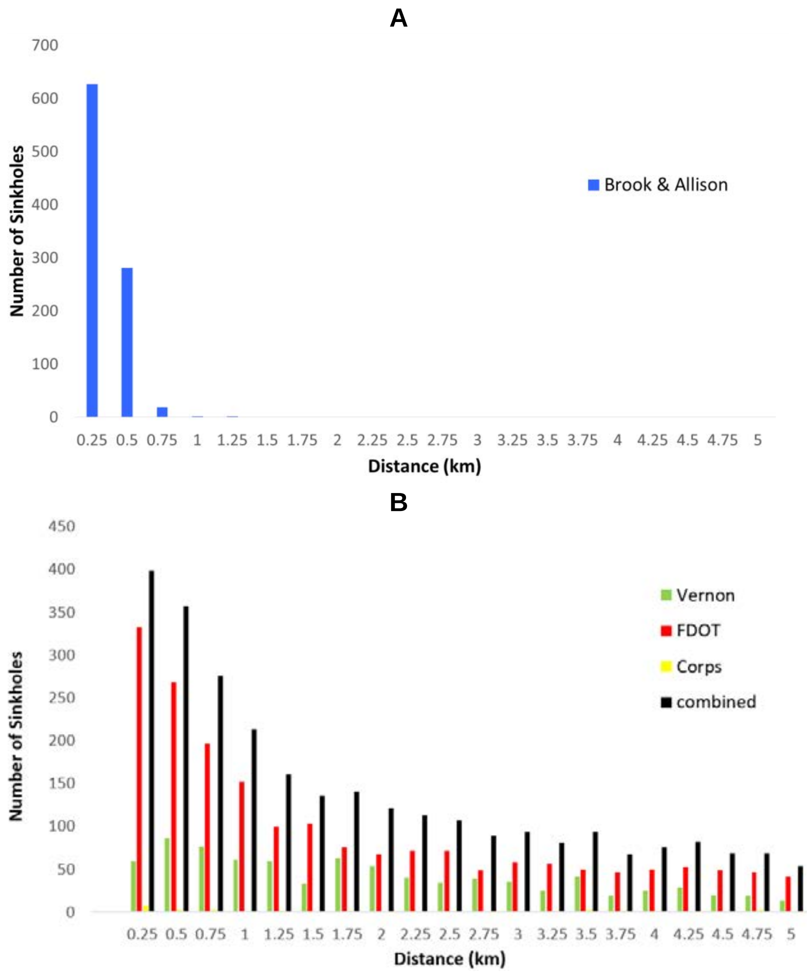


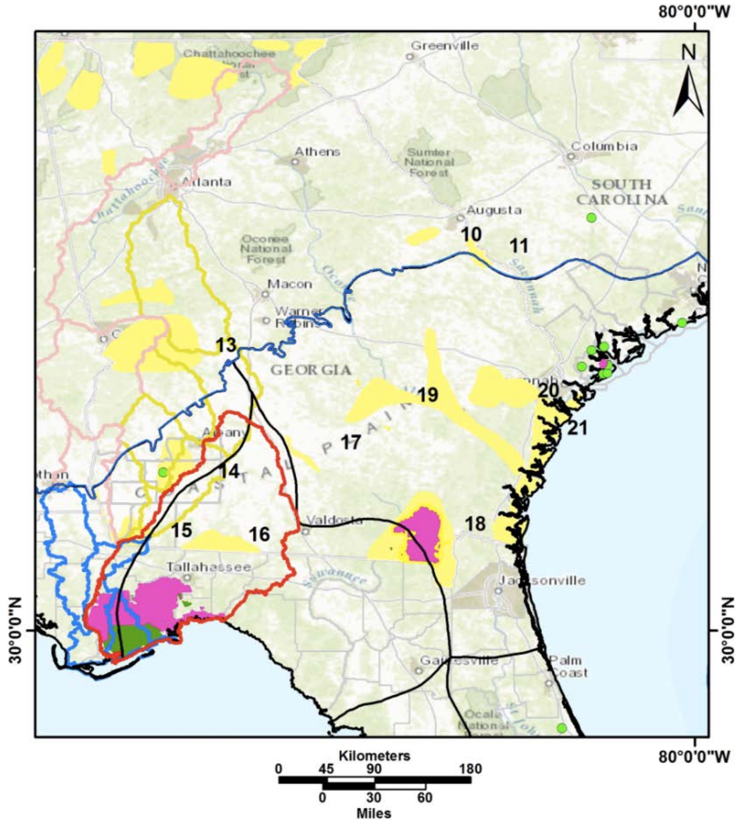
Figure 5. Distances from fractures mapped in: A. Dougherty County, Georgia to relict sinkholes in the same area (Brook & Allison, 1986) and B. Florida (ACOE, 2004; FDOT, 1973; and Vernon, 1951) to modern sinkholes in the state database

4.4 Proximity of Previously Mapped Fractures in Georgia and Florida and Extensions to ASR Wells, Sinkhole Clusters, and Federal, State, and Other Environmentally Sensitive Areas

Figure 6A illustrates the proximity of ASR wells (as described in Figure 2) and fractures mapped in Florida and Dougherty County (as described in Figure 5) to examples of federal lands (i.e., Apalachicola National Forest, Florida; Okefenokee National Wildlife Refuge, Georgia; Pinckney Island National Wildlife Refuge, South Carolina; and St. Marks National Wildlife Refuge, Florida). Figure 6A also shows proximity of those ASR wells and mapped fractures to examples of state lands (i.e., Elmodel Wildlife Management Area, Georgia; Okefenokee State Park, Georgia; Tate's Hell State Forest, Florida; and Wakulla Springs State Park, Florida); and Georgia's Priority Amphibian and Reptile Conservation Areas (PARCAs), in addition to the ACF River Basins (adapted from Seaber et al., 1987).

Figure 6B shows the proximity of modern sinkholes mapped in Florida (FDEP database) to the extensions (dashed white lines) of only fractures mapped in Dougherty County by Brook and Allison (1986) that are within the boundaries of the Chickasawhatchee Swamp/Ichauway Plantation PARCA (#13). Figure 6B also shows clusters of those fracture extensions that obscure PARCA 13, the Elmodel WMA/ASR demonstration well, and the Apalachicola and lower Flint River Basins identified in Figure 6A. Those clusters of fracture extensions also intersect PARCAs 15, 16, and 18; the Apalachicola National Forest and Tate's Hell State Forest; and they coincide with the clusters of Florida sinkholes in sub-regions H and U. An enlargement of Figure 6B, in the vicinity of the ACF River Basins, the six Georgia counties in our study (outlined in red), and the clusters of fracture extensions in sub-regions D, H, and U, is provided in Figure 6C.

A


80°0'0"W
N
Greenville
Chattahoochee
Athens
Sumter National Forest
Columbia
SOUTH CAROLINA
Atlanta
Augusta
Oconee National Forest
10
11
Macon
Warner Robins
13
GEORGIA
19
20
21
17
14
15
16
Valdosta
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Tallahassee
Jacksonville
Gainesville
Palm Coast
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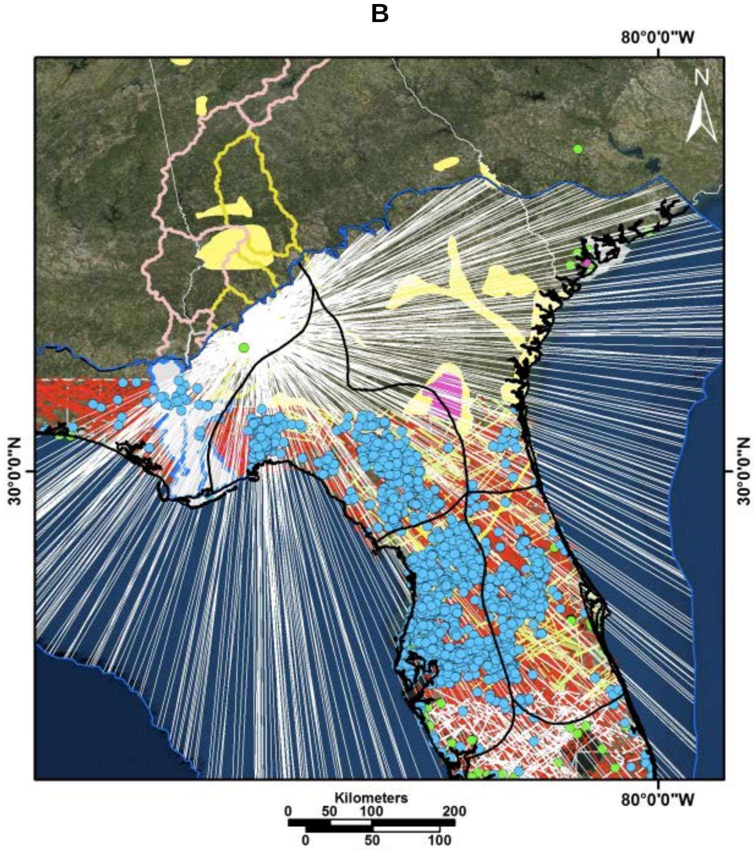
B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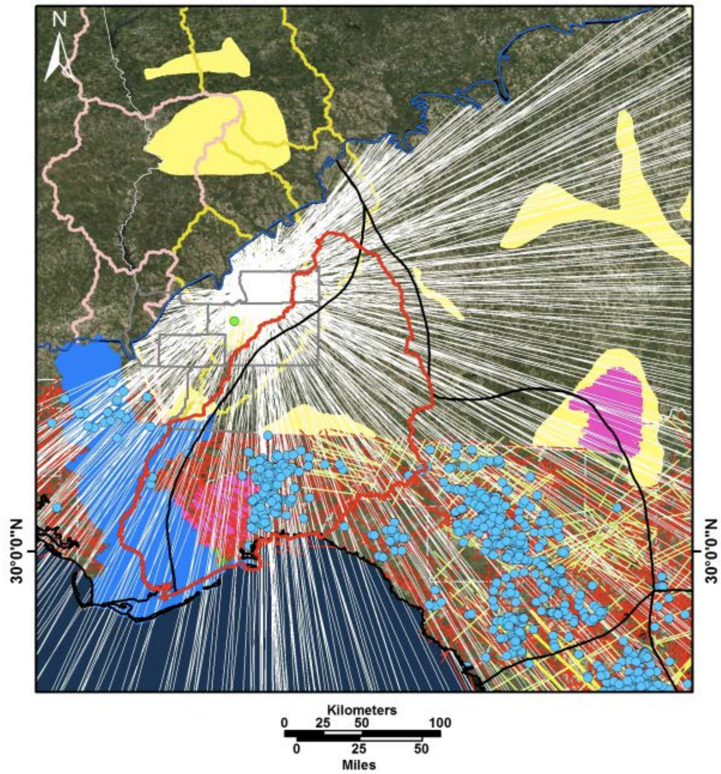

Figure 6. Fractures in Florida and Dougherty County, Georgia and ASR wells (as described in Figures 2 and 3) associated with the model boundaries for the Wakulla Springshed (from Kincaid et al., 2012 - outlined in red): A. federal lands (Apalachicola National Forest, Okefenokee National Wildlife Refuge, Pinckney Island National Wildlife Refuge, and St. Marks National Wildlife Refuge - fuchsia); state lands (Elmodel Wildlife Management Area, Okefenokee State Park, Tate's Hell State Forest, and Wakulla Springs State Park – dark green); Georgia's Priority Amphibian and Reptile Conservation Areas (yellow); the Apalachicola-Chattahoochee-Flint River Basins (as shown in Figure 1B);

B. extensions of fractures mapped in Dougherty County and within the boundaries of PARCA 13 (dashed white lines), modern sinkholes mapped in Florida, federal and state lands, and Georgia PARCAs;

C. Enlargement of clustered fracture extensions obscuring PARCA 13 and the Elmodel WMA/ASR demonstration well, and intersecting PARCAs 16 and 18, and sinkhole clusters (blue) in sub-regions H and U

The PARCAs addressed in our study are listed in Table 3, which identifies the sub-regions where the PARCAs occur. Those PARCAs are identified in Table 3 and Figure 6 by the numbers assigned to those PARCAs in Figure 1 of Jenson (2015). The Ft. Gordon PARCA (10) is north of the FAS boundary. All of the remaining PARCAs listed in Table 3 occur, at least in part, in Georgia's coastal plain, which coincides with the FAS in Georgia.

For the federal lands, the Apalachicola National Forest is split between sub-regions H and U; the Okefenokee Swamp Wilderness Area is split between sub-regions D and U; the St. Marks National Wildlife Refuge is in sub-region U; and the Pinckney Island National Wildlife Refuge is in the northeast portion of sub-region D. For the selected state lands, the Elmodel WMA occurs in sub-region H; Okefenokee State Park occurs in sub-region U; Tate's Hell State Forest occurs in sub-regions H and U; and Wakulla Springs State Park occurs in sub-region U. The lower extent of the ACF River Basins occurs within sub-region H, with the exception of a small portion of the southeastern Flint River Basin, which extends into sub-region U. The same environmentally sensitive areas included in Figure 6A are shown in Figure 6B, in proximity to sinkholes (as described in Figures 2 and 3A), mapped fractures and extensions of fractures mapped in Dougherty County that coincide with the Chickasawhatchee Swamp/Ichauway Plantation PARCA (13). Those fractures were extended to the FAS boundaries.

Table 3. Georgia's Priority Amphibian and Reptile Conservation Areas (PARCAs) and locations in FAS sub-regions.

ID	Name	FAS Sub-regions
10	Ft. Gordon[2]	-
11	Yuchi WMA/Plant Vogtle	D/-
13	Ft. Benning/Western Fall Line Hills[2]	-
14	Chickasawhatchee Swamp/Ichauway Plantation	H
15	Lake Seminole Region	H
16	Georgia Red Hills	U
17	Alapaha River and Sandhills	D
18	Okefenokee Swamp[3]	D/U
19	Altamaha-Ocmulgee-Ohoopee River Corridors	D
20	Ft. Stewart	D
21	Barrier Islands and Salt Marshes	D

[1] Priority Amphibian and Reptile Conservation Areas (PARCAs) from Jenson (2015).

[2] Located north of the FAS boundary.

[3] Located partially in sub-region D and partially in sub-region U.

5. Discussion and Conclusions About Influence of Fractures and Sinkholes on Hydrologic and Environmental Impacts

5.1 River Basins, Groundwater Basins, Breached Groundwater Divides, and Pirated Water

5.1.1 Pirated Water

Ground-surface elevations generally are used to determine the boundaries of river basins, such as the ACF River Basin. The boundaries of aquifers, also known as groundwater basins or groundwater reservoirs, rarely coincide with the boundaries of overlying river basins, as illustrated by the ACF River Basins (Figures 1B and 6A). The American Geological Institute's (AGI) Glossary of Geology (Neuendorf, 2005) defines groundwater basin and groundwater reservoir as follows:

Groundwater basin

(a) A subsurface structure having the character of a basin with respect to the collection, retention, and outflow of water.

(b) An aquifer or system of aquifers, whether basin-shaped or not, that has reasonably well defined boundaries and more or less definite areas of recharge and discharge.

Groundwater reservoir

(a) *Aquifer*.

(b) A term used to refer to all the rocks in the saturated zone, including those containing permanent or temporary bodies of groundwater

Krause and Randolph (1989) determined that breaches of the groundwater divides in the six sub-regions of the FAS had occurred in response to large withdrawals of ground water in the US southeastern coastal plain. The diversion of ground water also is known as captured or pirated water, as defined in the AGI Glossary of Geology (Neuendorf, 2005). The piracy can involve the capture of entire streams or portions of streams, including water from another valley, which is known as "beheading" when it involves the "cutting-off of the upper part of a stream and the diversion of its headwaters into another drainage system by capture." The terminology also is applied to the area within an aquifer in which ground water flows to a well under the influence of pumping conditions (Neuendorf, 2005). Although streamflow depletion from piracy can be determined by deducting the amount of water that flows out of an area from the amount of water that flows into the area (Neuendorf, 2005), a comparable determination cannot be made for water captured from depressional wetlands in a watershed or throughout a regional aquifer like the Floridan aquifer system. By the late 1980s in west-central Florida (sub-region F), pirated water from unsustainable FAS groundwater withdrawals, addressed as unintended subsurface interbasin flow, had resulted in environmental damage so severe that "Water Use Caution Areas" were established (Bacchus, 2000). Despite that designation, groundwater withdrawals in that area were estimated at approximately 246 MGD by 1993 and were causing both adverse economic and environmental impacts, including premature decline and death of longleaf pine in uplands and pond-cypress in wetlands, catastrophic destructive wildfires, and declines in native wildlife (Bacchus, 2000).

An important contribution of the Woodville Karst Plain Hydrologic Research Program was the groundwater model created by Kincaid, Meyer, and Day (2012), which identified pirating of ground water from the Wakulla Springshed from agricultural and nonagricultural groundwater withdrawals in southwest Georgia. A springshed identifies the area that provides water to the spring system, similar to a watershed or river basin that identifies the surface area that contributes surface water to a river system. The northern extent of the groundwater basin for the Wakulla Springshed is located in southwest Georgia, with the southern extent at the Gulf Coast of Florida. The Wakulla Springshed is encompassed by the boundaries of the groundwater model (GWM) domain, which encompass a larger area for determining the boundaries of the Wakulla Springshed for the GWM (Figures 10 and 11 of Kincaid et al., 2012). Consolidated locations of agricultural and nonagricultural groundwater pumping were identified in their research in and surrounding the GWM domain. The distribution and magnitude of groundwater pumping for agricultural irrigation and municipal use in Florida and Georgia counties intersecting the GWM domain were provided in millions of gallons per day (MGD) in Tables 12 and 13, respectively, in Kincaid et al. (2012), based on 2005 data they obtained. Consistent with other groundwater models created for areas of the FAS, that GWM was not designed to include preferential flow through fractures, but we have incorporated those model boundaries into Figure 6A to show the proximity of this area of pirated ground water to mapped fractures and sinkholes included in our study.

The volume of groundwater extractions within that GWM domain (Kincaid et al., 2012) included the Florida and Georgia vicinities of our study. The total agricultural pumping for the 15 Georgia counties and eight Florida counties within that GWM domain was 182.88 MGD and 29.03 MGD, respectively. The largest groundwater withdrawals per county occurred in Baker, Decatur and Mitchell Counties, Georgia and were 30.75 MGD, 34.95 MGD, and 28.88 MGD, respectively. The number of extraction points (wells) for those three counties (Figure 1B and Table 1) were 373, 601, and 718, respectively. The withdrawals from each of those counties exceeded the total for all agricultural groundwater withdrawals in Florida counties within the GWM domain. The total municipal groundwater withdrawals from Georgia and Florida counties within the GWM domain were 53.92 MGD and 48.70 MGD, respectively. The largest volume of municipal groundwater withdrawals from the Georgia counties in the GWM domain was 13.35 MGD from the two suppliers in Dougherty County. The largest volume of municipal groundwater withdrawals from the Florida counties in the GWM domain was 39.10 MGD from the 11 suppliers in Leon County (Kincaid et al., 2012). The next step in GWM development for this area should be to incorporate preferential flow of these withdrawals through mapped fractures.

The results of the research and GWM by Kincaid et al. (2012) led to understanding the link between groundwater extractions in Georgia and the water budget of north Florida, without knowledge of the role fracture systems play in the pirating of ground water. The presumption prior to their study was that pumping in Florida represented the largest anthropogenic impact to the springs and coastal freshwater discharge. Based on the data compiled during that study, however, agricultural and municipal pumping in Georgia was identified as having a much larger magnitude than all groundwater pumping in the north-Florida model area. Therefore, it was clear that the data for Georgia groundwater withdrawals must be included in any modeling analysis designed to predict the impacts of pumping or sea-level rise on spring flows. Specifically, groundwater withdrawals in that area of Georgia have affected and will continue affecting the boundaries of the springsheds by reducing upland storage. Reduced storage, in turn, reduces hydrologic heads and flows, particularly in times of drought, rendering management actions that focus exclusively on Florida ineffectual. Additionally, arbitrary delineations of permeability designed to match heads (e.g., elevation, hydraulic, and pressure) are not likely to result in accurate or defensible delineations of springshed boundaries or groundwater travel-times (Kincaid et al., 2012).

The 182.88 MGD of groundwater withdrawals identified by Kincaid et al. (2012), in an area that includes southeastern portions of the ACF River Basins, are similar to the magnitude of groundwater withdrawals that resulted in interbasin transfer of ground water in west-central Florida (Bacchus, 2000). That strongly suggests ground water also is being pirated from the Flint and Apalachicola River Basins. One could conclude that the damming and surfacewater withdrawals of the ACF near the Florida/Georgia state line should not be the primary focus of the tri-state water wars that have existed between Alabama, Florida and Georgia for decades, but that preferential flow through fractures, in response to groundwater withdrawals should be of equal concern.

5.1.2 Geographically Isolated vs Hydrologically Connected Wetlands

Whether natural wetlands are geographically isolated, but hydrologically connected depends on characteristics of the underlying aquifer system. Research has shown that natural depressional wetlands that are characteristic of the FAS (e.g., pond-cypress wetlands and wet prairies) have historic surfacewater connections to navigable waters and occur in relict sinkholes that are aligned along fractures and connected to the underlying regional karst aquifer system, as summarized by Bacchus (1998; 2000; 2006; 2007) and Bacchus et al. (2003). Therefore, those wetlands are not hydrologically isolated from waters of the US or exempt from federal regulation under the Clean Water Act (CWA).

The 2001 US Supreme Court ruling in Solid Waste Agency of Northern Cook County (SWANCC) v. US Army Corps of Engineer (531 US 159) resulted in misconceptions about the application of that ruling by agencies charged with regulating wetlands and other waters of the US in the FAS, as well as with consultants and scientists who work with those wetlands. That Supreme Court case involved the ACOE's attempt to assert jurisdiction under the CWA over an abandoned sand and gravel pit in northern Illinois, a man-made wetland. The ruling simply clarified that CWA jurisdiction did not include that man-made mine pit, simply because the mine pit included wetlands and migratory birds were utilizing that area. That mine pit, with wetlands, had no scientific or legal relevance to the natural depressional wetlands characterizing the regional karst FAS and the southeastern coastal plain of the US.

For example, Wise, Annable, Walser, Switt, and Shaw (2000) acknowledged the hydraulic connectivity (also known as hydrologic connection) of the aquifer and natural depressional wetlands in Florida, but then referred to those wetlands as "isolated wetlands." The Georgia State Wildlife Action Plan (SWAP) is another example of the misapplication of the term "isolated wetlands" to natural depressional wetlands in the FAS (Albanese, Wiseniewskiki, & GaschoLandis, 2015; GDNR, 2015; Jenson, 2015; Schneider, & Keyes, 2015).

Recognizing the hydrological connection of natural depressional wetlands is important because those wetlands cannot be recreated at random locations. As emphasized by Wise et al. (2000), knowledge of the underlying groundwater interactions is required to assess the ecological impacts from anthropogenic changes in groundwater levels. More importantly, they described the misapplication of the federal "no net loss" policy adopted during the administration of former President George Bush (1989–1993) to depressional wetlands. That policy, largely in response to the National Wetlands Forum of 1988, presumed that those types of wetlands destroyed by developments or other means could be "replaced" elsewhere by man-made wetlands similar to the very wetlands that the SWANCC ruling concluded were not regulated. The reason those natural depressional wetlands cannot be replaced by man-made wetlands at random locations, such as excavated stormwater and mine pits, is because the natural depressional wetlands were established in relict sinkholes aligned along fractures, in response to groundwater conditions that cannot be recreated at random locations that are convenient for develop, industry and agriculture (Bacchus, 2007). Solutions to the incorrect application of terminology would be to reference natural depressional wetlands in the FAS that are hydrologically connected via ground water either as geographically isolated or simply as natural depressional wetlands.

The knowledge that natural depressional wetlands in the FAS are aligned along fractures also is an important consideration for interpreting the results of our study. For example, comparing the proximity of the relict sinkholes to fractures mapped in Dougherty County by Brook and Allison (1986) and shown in Figures 3A and 5A to the greater distances between sinkholes and the three sets of mapped fractures in Florida (Figure 5B) suggests that there are additional fractures in Florida that have not been mapped. Further support that additional, unmapped fractures occur in Florida is provided by the greater density of fractures mapped in the Dougherty County study area.

5.1.3 Adverse Environmental Impacts Associated with Pirated Water from ASR and Other Aquifer Withdrawals and Injections

Removing water from and injections into aquifers can create adverse environmental impacts. Examples of adverse environmental impacts throughout the extent of the FAS associated with pirated water from aquifer withdrawals (mechanical and nonmechanical) and injections, including ASR, have been described by Bacchus (1998; 2000; 2001; 2002; 2006; 2007); Bacchus and Barile (2005); Bacchus and Brook (1996); Bacchus et al. (2000; 2003; 2005; 2011; 2014; 2015a); Bernardes, He, Bacchus, Madden, and Jordan (2014); Cunningham, Renken, Wacker, and Zygnerski, (2003); Fitterman and Deszcz-Pan (1999); Hofstetter and Sonenshein (1990); Lines et al. (2012); Maslia and Prowell (1990); McNeill (2000); Price and Pichler (2004); Renken, Shapiro, Cunningham, Harvey, Zygnerski, Metge, and Wacker (2004); Sonenshein and Hofstetter (1990); and Wilcox, Solo-Gabriele, and Sternberg (2004). This large body of literature has identified many categories of adverse impacts. Examples include: (1) depletion of groundwater reserves; (2) intrusion of water of undesirable quality (e.g., lateral saltwater intrusion, upconing of brackish and saline water through fractures and other karst conduits, and contaminants such as arsenic and benzene); (3) contravention of existing water rights; (4) excessive depletion of streamflow by induced infiltration/recharge; (5) land subsidence (e.g., "reactivating" relict sinkholes by increasing flow through infilled sediments and debris); (6) reductions of levels and/or extent of lakes and wetlands, invasion of alien/nuisance species and premature decline and death of trees from insects and pathogens, with consequent loss of valued habitat; (7) reductions in extent of areas where water is available to plants that use the capillary fringe, followed by catastrophic destructive wildfires and loss of habitat; and (8) reductions of groundwater outflow to coastal waters, with consequent impacts to coastal wetlands and/or nearshore benthic marine habitats.

The co-location of groundwater-extraction wells at an area established as a wilderness park in west-central Florida, renamed the J.P. Starkey Wellfield and Wilderness Park (Starkey Wilderness Park), is similar to the co-location of the proposed ASR demonstration well for groundwater extraction in the Elmodel Wildlife Management Area (Elmodel WMA) and Chickasawhatchee Swamp/Ichauway Plantation PARCA (13) in Georgia. A permit authorized 15 MGD of groundwater withdrawals from Starkey Wilderness Park, but irreversible environmental damage occurred when pumping of only 12 MGD was reached. The environmental damage included catastrophic, destructive wildfires that spread during a routine prescribed burn, killing longleaf pines in the uplands and pond-cypress in the wetlands designated for protection in the Starkey Wilderness Park, and igniting and consuming the organic sediments in wetlands, destroying the roots. Similar catastrophic, destructive wildfires are typical throughout the FAS in other areas of unsustainable groundwater withdrawals, also known as groundwater mining (Bacchus, 2000). Photographs of the irreversible damage to depressional wetlands characteristic of wildfires caused by unsustainable groundwater withdrawals are included in Bacchus (2007).

Adverse environmental impacts associated with pirated water from ASR and other aquifer withdrawals and injections that are characteristic and diagnostic of unsustainable groundwater withdrawals in the FAS include the premature decline and death of native upland and wetland trees, particularly oaks, longleaf pine and pond-cypress, and accompanying infestations of insects (e.g., beetles) and pathogens. Such adverse environmental impacts routinely and erroneously are attributed to “drought” rather than chronic water stress from unsustainable groundwater withdrawals. Unsustainable groundwater withdrawals and pirated water are not restricted to mechanical dewatering (e.g., pumping from groundwater supply wells, including ASR wells), but also result from nonmechanical dewatering (e.g., evaporative loss from excavated pits). One approach for estimating the volume of water being diverted (pirated) from wetlands in the Everglades National Park (ENP) by municipal wellfields, directly and indirectly, used isotopic analysis of the water (Wilcox et al., 2004), but did not assess the damage to ENP wetlands from the pirated water. The irreversible degradation of habitat leads to declines in native wildlife (Bacchus, 2000). Examples of these and other adverse environmental impacts in the FAS are described in Bacchus (1998; 2000; 2001; 2006; 2007) and Bacchus et al. (2000; 2003; 2005; 2011; 2015a).

Assessing impacts on wildlife, Georgia’s 2005 and 2115 State Wildlife Action Plans (SWAP) included a list of 25 Standardized Threat Descriptions for the state’s wildlife. Table 4 includes the headings of the original 2005 rankings and revised 2015 statewide, Atlantic and Gulf rankings of those threats. The headings, descriptions and rankings of 17 standardized threats from the 2005 SWAP that result from or result in pirated water from mechanical and nonmechanical aquifer withdrawals and injections, including ASR, are provided in Appendix A. Headings in red in Appendix A and Table 5 were identified in the 2015 SWAP as particularly relevant to aquatic species.

At least the following three threats (preceded by the original ranking number) included in Table 4 result from groundwater withdrawals and injections: 3. Altered Fire Regimes; 10. Disease; and 21. Invasive/Alien Species. Additionally, the following examples of standardized threats (preceded by the original ranking number) included in Table 4 result in alterations of hydrology and water quality: 2. Incompatible Agricultural Practices; 6. Commercial/Industrial Development; 7. Conversion to Agriculture; 8. Dam and Impoundment Construction; 9. Development of Roads or Utilities; 14. Incompatible Forestry Practices; and 15. Global Warming/Climate Change. It could be useful for public understanding to revise the standardized threats to include actions resulting from and in alterations of hydrology and water quality that can be intensified and spread far beyond the surface footprint of those threats by the presence of fractures.

The types of hydrologic impacts that can spread beyond the surface boundaries of projects, river basins, and groundwater basins via preferential flow through factures can result in irreversible degradation to habitat for high priority state and federally listed species. Tables 5A-C list examples of Georgia’s high priority state and federally listed species in the ACF River Basins and coastal plain with jeopardized survival and recovery by adverse direct, indirect, and cumulative impacts from the threats listed in Appendix A in Florida, Georgia, and South Carolina.

Table 4. Rankings of Standardized Threats to High Priority Fish and Aquatic Invertebrate Species in Georgia in 2005 and 2015.

Statewide Rankings[2]	Atlantic Rankings[2]	Gulf Rankings[2]
#1 – 5. Altered Water Quality	#1 – 4. Altered Hydrology	#1 – 4. Altered Hydrology
#2 – 2. Incompatible Agricultural Practices	#2 – 5. Altered Water Quality	**#2 –11. Ground/Surface Water Withdrawal**
#3 – 4. Altered Hydrology	#3 – 14. Incompatible Forestry Practices	#3 – 5. Altered Water Quality
#4 – 23. Residential Development	#4 - 8. Dam & Impoundment Construction	#4 – 2. Incompatible Agricultural Practices
#5 – 8. Dam & Impoundment Construction	#5 – 2. Incompatible Agricultural Practices	#5 - 8. Dam & Impoundment Construction
#6 – 11. Ground/Surface Water Withdrawal	#6 – 6. Commercial/Industrial Development	#6 – 21. Invasive/Alien Species
#7 – 6. Commercial/Industrial Development	#7 – 15. Climate Change	#7 - 23. Residential Development
#8 – 14. Incompatible Forestry Practices	#8 – 23. Residential Development	#8 - 9. Develop. of Roads/Utilities
#9 – 20. Industrial/Municipal Pollution	#9 – 21. Invasive/Alien Species	#9 - 14. Incompatible Forestry Practices
#10 – 21. Invasive/Alien Species	#10 – 18. Incompat. Mining/Mineral Extraction	**#10 - 19. Incompat. Road/Utilities Mgmt**
#11 – 9. Develop. of Roads/Utilities	**#11 – 7. Conversion to Agriculture**	#11 – 20. Industrial/Municipal Pollution
#12 – 15. Climate Change	**#12 – 11. Ground/Surface Water Withdrawal**	#12 - 6. Commercial/Industrial Development
#13 – 7. Conversion to Agriculture	**#13 –19. Incompatible Road/Utilities Mgmt**	#13 – 15. Climate Change
#14 – 19. Incompatible Road/Utilities Mgmt.	#14 – 20. Industrial/Municipal Pollution	
#15 – 18. Incompat. Mining/Mineral Extraction	**#15 –25.Vehicle-Induced Mortality**	
#16 – 24. Unmanaged Recreation		
#17 – 17. Incompatible Fisheries Practices		
#18 – 25. Vehicle-Induced Mortality		

from Albanese et al. (2015); threats particularly relevant to aquatic species in red font

2015 rankings Statewide and for Atlantic and Gulf areas (#) followed by 2005 rankings for each standardized threat

Table 5A. Examples of Georgia's high priority state and federally listed bird species in the ACF River Basins and coastal plain with jeopardized survival and recovery by adverse direct, indirect, and cumulative impacts from Floridan-aquifer injections and withdrawals in Florida, Georgia, and South Carolina.

Bird Species	Status	Examples of Habitat & Adverse Impacts
Little blue heron *Egretta caerulea*	Special Concern	Coastal plain– dewatering/altering natural hydroperiods & water quality of marshes, flood plains & swamps required for nesting/feeding
Tricolored heron *Egretta tricolor*	Special Concern	Coastal zone– dewatering/altering natural hydroperiods & water quality of wetlands required for nesting/feeding
Florida Sandhill Crane *Grus canadensis pratensis*	Special Concern	Coastal plain– dewatering/altering natural hydroperiods & water quality of depressional wetlands required for nesting/feeding; Okefenokee NWR is only breeding site in Georgia
Bald Eagle *Haliaeetus leucocephalus*	High Priority	Lower Chattahoochee River (CR) – edges of lakes & large rivers; seacoasts
Wood Stork *Mycteria americana*	Federally Threatened	Coastal plain– dewatering/altering natural hydroperiods & water quality of depressional wetlands required for nesting/feeding
Red-cockaded Woodpecker *Picoides borealis*	Federally Threatened	Pine savannas, 13,16,20– destruction of critical nest trees from chronic water stress related to dewatering/altering natural hydroperiods

[1]Information from Schneider and Keyes (2015) and two-digit numbers indicating Priority Amphibian and Reptile Conservation Areas (PARCAs) described in Jenson (2015)

Table 5B. Examples of Georgia's high priority state and federally listed amphibian and reptile species in the ACF River Basins and coastal plain with jeopardized survival and recovery by adverse direct, indirect, and cumulative impacts from Floridan-aquifer injections and withdrawals in Florida, Georgia, and South Carolina.

Species	Status	Examples of Habitat & Adverse Impacts
Amphibians		
Reticulated Flatwoods Salamander *Ambystoma bishopi*	High Priority	14–dewatering/altering hydroperiods & water quality of depressional wetlands required for reproduction
Eastern Tiger Salamander *Ambystoma tigrinum*	High Priority	13,14,16,17,19,20–dewatering/altering hydroperiods & water quality of depressional wetlands required for reproduction
Chamberlain's Dwarf Salamander *Eurycea chamberlaini*	Petitioned Species	Lower Chattahoochee River (CR) – elimination of seepage in ravines
Georgia Blind Salamander *Eurycea wallacei*	Petitioned Species	Floridan aquifer system – dewatering & water quality alterations
Gopher Frog *Lithobates capito*	Petitioned Species	13,14,16,17,19,20–dewatering/altering hydroperiods & water quality of depressional wetlands required for reproduction
Striped Newt *Notophthalmus perstriatus*	Federal Candidate	13,14,17-20 – dewatering/altering hydroperiods & water quality of depressional wetlands required for reproduction
Reptiles		
Eastern Indigo Snake *Drymarchon couperi*	Federally Threatened	15,17-19 – destruction of micro-climate conditions related to altered hydroperiods
Gopher Tortoise *Gopherus polyphemus*	Federal Candidate	10,11,13-20 - destruction of micro-climate conditions in burrows related to altered hydroperiods
Barbour's Map Turtle *Graptemys barbouri*	Federal Candidate	Lower CR, 12-14 – reduced flow of rivers & large creeks of Apalachicola River drainage
Alligator Snapping Turtle *Macrochelys temminckii*	Petitioned/ Threatened	Lower CR, 14 – reduced flow of large streams & rivers; impoundments; river swamps

[1]Information and two-digit numbers indicating Priority Amphibian and Reptile Conservation Areas (PARCAs) from Jenson (2015)

Table 5C. Examples of Georgia's high priority state and federally listed fish and invertebrate species in the ACF River Basins and coastal plain with jeopardized survival and recovery by adverse direct, indirect, and cumulative impacts from Floridan-aquifer injections and withdrawals in Florida, Georgia, and South Carolina.

Species	Status	Examples of Habitat & Adverse Impacts
Fish		
Gulf Sturgeon *Acipenser oxyrinchus desotoi*	Federally Threatened	Lower Chattahootchee River (CR) – reduced fresh water in estuaries; deep pools at lower end of large rivers
Spotted Bullhead *Ameiurus serracanthus*	Rare	Lower CR – reduction in moderate currents of large streams with rock-sand substrate
River Redhorse *Moxostoma carinatum*	Rare	Etowah River[2] – reduced flow in swift waters of medium to large rivers
Robust Redhorse *Moxostoma robustum*	Endangered	Broad, Ocmulgee, Oconee & Ogeechee Rivers – reduced flow in medium to large rivers, shallow riffles to deep flowing water with moderately swift current
Broadstripe Shiner *Pteronotropis euryzonus*	Rare	Lower CR – reduced flow of medium sized streams associated with sandy substrate and woody debris or vegetation
Invertebrates		
Southern Elktoe *Alasmidonta triangulata*	Endangered	Lower CR – reduced flow in large to small streams
Rayed Creekshell *Anodontoides radiatus*	Threatened	Lower CR – reduction in flow of large to small streams on Gulf Coastal Plain
Delicate Spike *Elliptio arctata*	Endangered	Lower CR – reduction in flow of large to medium-sized streams

[1]Information from Albanese, Wiseniewskiki & GaschoLandis (2015)

[2]Not in the ACF River Basin or coastal plain, but includes a proposed ASR "water bank"

5.2 Strategic Location of ASR and Other Injection and Withdrawal Wells in Florida, Georgia, and South Carolina

Years before ASR wells were permitted in Florida, under the guise of aquifer “storage” and “recovery,” aquifer injections were permitted and constructed at similar depths for “disposal” of agricultural, industrial and municipal wastes, such as minimally treated sewage effluent. Evidence that these injected wastes rapidly flow through preferential pathways in the karst aquifer system, then discharge into nearshore coastal water, was summarized by Bacchus et al. (2014). Bacchus et al. (2015a) illustrated the proximity and frequencies of permitted ASR wells, other injection and withdrawal wells, to reported modern sinkholes, mapped fractures and fracture intersections in Florida.

It has been documented at least since the 1990s that the upper Floridan aquifer is connected to underlying aquifer zones by fractures that resulted in upconing of saline water from those underlying zones in response to unsustainable pumping from the upper Floridan (Bacchus, 2000; Odum et al., 1998; Spechler, 1994; Spechler & Phelps, 1997). The logical presumption is that pumping from those underlying aquifer zones results in induced recharge from the Floridan and surficial aquifer zones through fracture networks, as shown in Figure 3 of Odum et al. (1998) and Figure 37 of Spechler (1994). Brook and Sun (1982) and Brook et al. (1986; 1988) also documented the dependence of well yield on proximity of wells to fractures.

We found no peer-reviewed publications with results from scientific investigations in the FAS using groundwater tracers to determine where the fluids injected into ASR wells and disposal wells are going or isotopic analysis to identify the “fingerprint” of the native ground water prior to any injections and withdrawals associated with a new ASR well, to compare to the “fingerprint” of water that is “recovered” from ASR wells, similar to the isotopic analysis of water by Wilcox et al. (2004). Without such evidence, no assumptions can be made that injections into and withdrawals from ASR wells in the FAS function differently than wells used solely for water supply or for aquifer “disposal.”

The published literature we have referenced suggests that the proximity to fractures of ASR wells and other injection and withdrawal wells throughout the FAS plays a significant role in the performance of those wells, including ASR wells functioning as typical water-supply wells and disposal wells. For example, the strategic location of ASR wells near inland rivers, lakes, and depressional wetlands associated with fractures could increase the productivity of those ASR wells considerably as withdrawals divert water from those natural features. Conversely, other ASR wells in proximity to fractures may increase the time of occurrence, magnitude and public costs of those wells from water-quality deterioration from lateral saltwater intrusion, upconing of brackish and saline water and contaminants, such as arsenic and benzene via fractures and other karst conduits. Because fractures in the FAS also have been shown to extend under coastal waters, coastal ASR wells may be more vulnerable than inland wells for saltwater contamination of the aquifer system.

5.2.1 Abandoned, Inactive and Active ASR Wells in Florida

Bloetscher et al. (2014) identified 32 ASR well sites in Florida that were no longer active because of problems including arsenic contamination, clogging, “recovery” problems or water quality deterioration, with 13 ASR well sites in Florida reported as a abandoned in that study. Their study incorporated data from Herczeg, Rattray, Dillon, Pavelic, and Barry (2004), that previously described arsenic contamination as a common problem associated with ASR wells, and included data collected through July 1, 2013. Neither study evaluated the hydrological influence that fractures might have on the long-term operation of ASR wells in Florida and other areas with karst aquifer systems, such as the proximity of ASR wells to fractures. Bacchus et al. (2015b) described the 13 ASR well sites in Florida that were evaluated by Reese (2002), and later identified by Bloetscher et al. (2014) as abandoned. Some of those 13 abandoned ASR well sites had multiple ASR wells (Bacchus et al., 2015b). The consulting firm CH2M Hill was involved in the construction, operation, or testing associated with the ASR cycle-test data for the Boynton Beach, Broward County, City of Delray, Lake Okeechobee, Marathon, Miami-Dade W Well Field, San Carlos Estates, and West Palm Beach ASR wells. Ironically, all but one of those ASR sites, including the West Palm Beach ASR sites, was reported as abandoned by Bloetscher et al. (2014). The West Palm Beach, Florida ASR well was described as the largest capacity ASR well in the world (Pyne, 2004). That ASR well was located near the coast, but included no record of the chloride levels for injected or “recovered” water (Reese, 2002; Bacchus et al., 2015a). The proximity of those ASR wells to fractures and fracture extensions was shown in Bacchus et al. (2015a; 2015b). That suggests the proximity of abandoned and inactive ASR wells to fractures may have resulted in favorable “recovery” initially, followed by increasing chloride levels that resulted in comparable increases in operating costs.

Although our study did not attempt to determine if additional ASR wells in Florida had been abandoned after the 2013 data-collection date used for Bloetscher et al. (2014), Bacchus et al. (2015b) identified another ASR site evaluated in Florida by Reese (2002, San Carlos) that was listed by FDEP as inactive, but not identified as an abandoned or inactive ASR well by Bloetscher et al. (2014). It is unclear how many of those 33 ASR well sites in Florida were abandoned or were inactive because of preferential flow through fractures or other karst conduits of the aquifer injections and withdrawals associated with those ASR wells. Also unclear is if attempts are being made to strategically locate ASR wells in proximity to fractures in Florida, Georgia, and South Carolina to increase the productivity of those ASR wells, particularly in cases where the capacity of the aquifer has been depleted and new supply wells are receiving more scrutiny.

The ASR wells in the vicinity of Lake Okeechobee and the Peace River also are associated with fracture networks (Bacchus et al., 2015a; 2015b) and appear to be additional examples of strategically located ASR wells capable of tapping water from those natural resources. The Peace River ASR site, located along the west bank of the Peace River, reportedly is the oldest ASR project in Florida, with initial investigations beginning in 1983 and full-time operations initiated in 1988 (Brown, 2005). Pyne (2004) described the Peace River ASR site as the largest ASR wellfield in the eastern US. There are no investigations assessing the role of preferential flow through fractures and other karst conduits in response to ASR operations at the Peace River site in the formation of sinkholes described by Patten and Klein (1989). Aquifer injections into the 22 ASR wells associated with fracture networks at the Peace River ASR site are of particular concern, considering that the largest groundwater withdrawals in that area are from phosphate mining located in proximity to those ASR wells.

Mining is widespread in Florida and results in mechanical and nonmechanical extractions of large volumes of water from the FAS, depleting ground water from natural resources and availability for municipal use. For example, the 25th modification of the Water Use Permit (WUP) for current phosphate mining in south-central Florida allows groundwater pumping that ranges from “69,600,000 gpd” to “87,000,000 gpd” through 2032, in a five-county area (Southwest Florida Water Management District WUP 20011400.025 issued 2/1/12). That does not include the significant evaporative loss of water from the large open mine pits that remain in perpetuity after the mining is completed or additional ground water used for the mining, but permitted as separate agricultural permits. The cost to the mining industry for this water use is confined to the cost of the permits and fuel for the pumps to extract ground water from supply wells. Although this water use depletes ground water that is the primary source of municipal water supply, the mining industry does not pay the high costs of constructing ASR wells, treating the water that is injected into those wells, or treating the water that is withdrawn from ASR wells, such as the cost of constructing, operating and maintaining the 22 ASR wells at the Peace River site. Those costs are paid by the public for a “supplemental” source of municipal water perceived to be “recovery” rather than ground water. Yet no data have been produced to show that the water injected into those 22 ASR wells is not being withdrawn by the neighboring phosphate mining supply wells via the fracture network.

5.2.2 Recent ASR Wells in Georgia

Unlike Florida and South Carolina, Georgia only recently permitted and constructed the first ASR well in the state, following expiration of a state-imposed moratorium on ASR wells. This well was permitted by GDNR as an ASR “demonstration” well. On December 21, 2012, a statement of qualifications for the ASR “Demonstration Program” was submitted to the Southwest Georgia Regional Commission by David Pyne, President of ASR Systems, LLC. At that time, the moratorium on ASR wells was still in effect in Georgia. The location selected for the ASR “Demonstration Program” was the Elmodel WMA and the purpose was to augment the dry season flow of the Flint River and its tributaries. Pyne referenced 30 years of engineering services provided to CH2M Hill as evidence of his ASR expertise. His letter also referenced Ted Belser, another CH2M Hill employee (in the capacity of lead design engineer, department manager, and senior project manager), as an additional member of the “team” for the proposed Elmodel ASR “Demonstration Program.”

Belser’s expertise listed in the statement of qualifications, indicated “ASR systems for which he has provided design services in recent years include projects for: ... Orangeburg, SC; Hilton Head (North Island), SC; Hilton Head (South Island), SC; City of Bradenton, FL; Beaufort-Jasper Water Supply Authority, SC; Orange County, FL; ... the City of Rockledge, FL; and Charlotte County, FL.” The FDEP ASR database dated December 20, 2014: (1) does not include an ASR well identified as the Orange County ASR well(s); (2) indicates that the Rockledge, Florida ASR well is inactive; and (3) does not include an ASR well identified as the Charlotte County ASR well. Confirmation was obtained from FDEP staff that: (1) the Orange County ASR well has been cycle-tested from 2010 to the present, with “storage” ranging from 14 to 120 days; (2) neither the Rockledge ASR well nor the Rockledge ASR facility is active, although construction occurred between 2008 and 2010; and (3) there is no record of an ASR well referenced as the Charlotte County ASR well (Joe Haberfeld, FDEP

Geological Survey, UIC Program Geologist, pers. comm., 02/15/16).

The referenced statement of qualifications dated December 21, 2012, also stated that the Elmodel Project ASR Systems Team members have "represented Georgia in the joint studies and the negotiations with Alabama and Florida on the water resource conflicts in the Apalachicola-Chattahoochee-Flint (ACF) river Basin" and "secured an agreement with EPD that the agency will provide a copy of the State's numerical ground water flow model that will cover all of southwest Georgia including the relevant aquifers underlying the Elmodel Site."

That statement of qualifications also stated that a final report would be prepared, "including a recommended ASR wellfield expansion plan for the Claiborne and Clayton Aquifers of the lower Flint River Basin, with an ASR recovery capacity of up to 250 MGD. The wellfield expansion plan will consider alternate use of ground water during winter months as the source of supply for recharge, and also treated surface water during times when river and tributary flows are high." It is important to note that at the time ASR Systems, LLC was proposing to create a groundwater model for the vicinity of the Elmodel ASR demonstration well, "deemed most suitable to meet flow augmentation goals, utilizing approximately 30,000 acres of state-owned lands," a groundwater model for that area already had been created and released for that vicinity showing that groundwater withdrawals in that area were dewatering the Wakulla Springshed that occurs in southwest Georgia and northwest Florida (Kinkaid et al., 2012). That 250 MGD production capacity proposed by ASR Systems, LLC exceeds the 182.88 MGD total agricultural groundwater withdrawals for 15 Georgia counties in that vicinity that have contributed to the dewatering of the Wakulla Springshed (Kinkaid et al., 2012). The 250 MGD production capacity proposed by ASR Systems, LLC also exceeds the approximately 246 MGD occurring in the west-central Water Use Caution Area by 1993, that caused both adverse economic and wide-spread environmental impacts, including premature decline and death of longleaf pine in uplands and pond-cypress in wetlands, catastrophic destructive wildfires, and declines in native wildlife (Bacchus, 2000).

On July 8, 2015, the GEFA issued a media release announcing that dual-aquifer ASR well and two monitoring wells, that were designed, constructed, administered, and analyzed by CH2M Hill, had not performed as predicted. Specifically, the media release stated that the dual-aquifer ASR well at the Elmodel WMA is "unlikely to produce enough water for stream-flow augmentation in Chickasawhatchee Creek." That media release further announced that instead of moving forward with the dual-aquifer ASR well at the Elmodel WMA, GEFA and the Georgia EPD plan to have a Claiborne aquifer production well designed and installed next to the monitoring wells. The media release also stated "the information will support the state's evaluation and management of these aquifers as a potential alternative water source for the region."

The research by Brook and Sun (1982) and Brook et al. (1986; 1988) documented the dependence of well yield on proximity to fractures, specifically in the vicinity of the areas referenced in the GEFA press release. In fact, the following statement from the GEFA media release dated July 8, 2015 and the extensive research by USGS (Odum et al., 1998; Spechler, 1994; 1997) support the conclusion that the site-specific higher yields from the underlying Claiborne and Clayton aquifer zones result from induced recharge from the overlying Floridan and surficial aquifer zones:

The yield from the Claiborne and Clayton aquifers appears to be site-specific, which suggests more yield is possible at other locations in the basin. For example, a Claiborne production well drilled this spring to support irrigation-related research at the Stripling Irrigation Research Park, which is roughly 9 miles from the Elmodel WMA, showed significantly more yield.

The GEFA media release also indicated that a technical peer review of the Elmodel WMA ASR demonstration project was conducted by Cardno. Based on information on the Cardno website (12/09/15), the company is based in Australia, with US merger partners. The website stated that Cardno "provided groundwater modeling, well field design, construction oversight and water supply planning using our state-of-the-art aquifer storage and recovery (ASR) pretreatment system design" to "help supply fresh drinking water to Marco Island" (Florida). That ASR well was not included in the FDEP ASR database dated December 20, 2014. The FDEP staff confirmed that the Marco Island ASR well was not included in the FDEP database because that project was never constructed (Joe Haberfeld, FDEP Geological Survey, UIC Program Geologist, pers. comm., 12/14/15).

The process for the initial ASR demonstration well and program in Georgia suggests that the FDEP and GEFA are not aware of the body of peer-reviewed scientific publications related to adverse impacts associated with aquifer injections and withdrawals, including those associated with ASR wells. Rather, the consulting companies benefitting financially from designing, constructing, operating and monitoring/reviewing these types of wells appear to have been the sources of information for this ASR demonstration project. Additionally, the location of the Georgia ASR demonstration well in the Elmodel WMA to augment the dry season flow of the

Flint River and its tributaries in Georgia appears to be related to two water-depletion problems. The first and most widely known problem is the on-going “tri-state water wars” that began decades ago, based on allegations by Florida and Alabama that Georgia is depleting water in those downstream states because of excessive water withdrawals from and dams on the ACF. The second problem, most recently documented by Kincaid et al. (2012), is the depletion of ground water essential for maintaining Wakulla Springs in Florida that is resulting from the unsustainable groundwater withdrawals in the vicinity of the Elmodel WMA. Based on the body of scientific literature we have described, the continued and proposed increases in groundwater withdrawals in the Elmodel WMA area will increase the diversion of ground water from Florida and result in irreversible adverse environmental impacts to Georgia’s PARCAs within the FAS, particularly those associated with the fractures and fracture extensions shown in Figure 6.

5.2.3 ASR Wells in South Carolina

The SCDEHC has issued permits to 11 water supply facilities for a total of 68 UIC ASR wells in South Carolina. No UIC “disposal” wells have been permitted in South Carolina. Facilities in Columbus, Georgetown, Horry, Marion, and Orangeburg Counties are beyond the FAS boundaries and account for 54 of the permitted ASR wells in South Carolina. A total of 34 of those 54 wells originally were conventional municipal supply wells operated by the Grand Strand Water and Sewer Authority, but resulted in a large cone of depression from extensive withdrawals and have been converted to ASR wells. Permit dates for those ASR wells range from April 15, 1994 to May 15, 2015. Nine of those ASR wells are operated by the Georgetown County Water and Sewer District, five are operated by Mount Pleasant Water Works (permitted from May 28, 2003 to November 27, 2012), four are operated by the Orangeburg Department of Public Utilities (permitted from January 10, 2008 to March 24, 2011), and one is operated by the Little River Water and Sewerage Company, Inc. (permitted on May 20, 2015). One of the ASR wells in Mount Pleasant and the only ASR well permitted in Myrtle Beach on May 16, 1995 and September 14, 1990, respectively, are reported as permanently abandoned. No reason was included in the SCDEHC data for either abandonment (SCDEHC, Christopher Wargo, pers. comm., 3/16). The figures showing locations for the South Carolina ASR wells include only one location dot for each facility rather than for each well.

The ASR wells permitted or pending in South Carolina within the FAS boundaries are located along the coast in Beaufort, Charleston, Colleton, and Jasper Counties. The pending ASR well and RO facility in Colleton County would be located in Edisto Beach, south of the ACE Basin National Wildlife Refuge. Neither the proposed well nor the ACE Basin NWR are shown in Figures 2 or 3, but the intersecting fracture extensions shown in Figures 2B and 3B are in the vicinity of the proposed Edisto Beach ASR well and RO facility. Permit dates for the four ASR wells operated by the Beaufort Jasper Water and Sewer Authority range from June 1, 1999 to January 7, 2011. The two ASR wells operated by the Charleston Water System were permitted on May 24, 1994 and May 26, 1999. The two ASR wells operated by the Hilton Head Public Service District (HHPSD) were permitted on November 8, 2010 and December 20, 2010 and both of those ASR wells are associated with a fracture extension (Figures 2B and 3B). Both of the ASR wells operated by the Kiawah Island Utility, Inc. were permitted on May 30, 2001. The four remaining ASR wells in South Carolina’s coastal counties of the FAS are operated by South Island Public Service District and were permitted from July 11, 2012 to October 16, 2013. They include the Long Cove and Palmetto Bay ASR wells that are associated with the same fracture extension as the two ASR wells operated by the HHPSD. The only one of those wells reported as “permanently abandoned” was the ASR well permitted for the Charleston Water System on May 26, 1999.

Extensive mapping of fracture networks, similar to the mapping conducted throughout Florida and Dougherty County, Georgia, was not available for South Carolina. Therefore, the inferences in our study about fractures in the portion of the FAS that extends into South Carolina were confined to extensions of fractures mapped in Florida and Georgia’s coastal plain.

Although South Carolina’s total number of ASR wells is sizeable, the paucity of information available about those wells is similar to the paucity of information about the sole ASR demonstration well constructed in Georgia. We found no publications for South Carolina comparable to the USGS review of ASR wells and well data in Florida (Reese, 2002). The most extensive information available about the ASR wells in South Carolina was included in the statement of qualifications by ASR Systems, LLC to secure the contract for Georgia’s Elmodel WMA ASR demonstration well that failed. That statement of qualifications indicated “[P]rior to five years ago ASR Systems staff provided ASR consultant services to ... the Kiawah Island Utility, SC.” The following quotes from that statement of qualifications regarding ASR wells in South Carolina have been included because similar information isn't available from sources such as peer-reviewed journal publications:

Hilton Head Public Service District, SC (HHPSD)

ASR feasibility assessment report, design, permitting, construction management, cycle testing and placing an ASR well in operation with a recovery capacity of 2.5 MGD. Facilities included one ASR well, two monitor wells, pump, motor, wellhead piping, wellhouse and telemetry. Freshwater wells on Hilton Head Island are being lost to saltwater intrusion in the Upper Floridan aquifer. Imported water from Beaufort Jasper Water and Sewer Authority is available at half cost during winter months. This water is blended with offpeak water produced from the HHPSD Reverse Osmosis (RO) plant, and also water from remaining fresh waterwells. The blended water is used for ASR recharge. The storage zone is the Middle Floridan aquifer, which is brackish. Water is recovered during summer months to help meet peak demands. The project was completed in a record short time of 23 months and came in under budget. Work was completed during 2012.

South Island Public Service District, SC (SIPSD)

Following the loss during 2010 of one of their ten production wells in the Upper Floridan Aquifer due to salt water intrusion, SIPSD embarked on a comprehensive water facilities upgrade and expansion program, based upon the expectation that all of their freshwater supply wells will be lost during the next 40 years. ASR Systems completed an ASR feasibility study, then proceeded with design of two ASR wells in the Middle Floridan Aquifer; five monitor wells in the Upper, Middle and Lower Floridan aquifers; and one Lower Floridan Aquifer production well to provide a backup water supply source in the event that the SIPSD Cretaceous Aquifer water supply well fails. This well is 3,800 ft deep and supplies 3.5 MGD to a reverse osmosis (RO) Water Treatment Plant (WTP) during peak demand periods and is the backbone of the SIPSD water supply system. Wellhead facilities design was completed and all facilities were permitted for construction, which is currently underway. Well construction is expected to be completed by April 2013, to be followed by interim recharge into each ASR well. Wellhead facilities construction will then begin and should be completed by the end of 2013. This will be followed by cycle testing. The source of water supply for recharge is fresh water from the remaining SIPSD wells in the Upper Floridan aquifer, supplemented by water available from the RO WTP.

Town of Edisto Beach, Edisto Island, SC

ASR Systems was part of a URS Team that prepared a water supply master plan for the Town, completed during 2012. Salt water intrusion is causing a deterioration of drinking water quality, shortened life of household appliances, and an increase in the salt concentration of reclaimed water that is utilized for golf course irrigation. The final plan included recommended construction of a reverse osmosis (RO) water treatment plant and brine disposal outfall structure. It also included an ASR wellfield to store drinking water during winter months when water demand is very low, for recovery during summer months with peak demands. ASR wells will provide water supply reliability since ground elevations are quite low, well below the hurricane surge elevation. Drinking water stored underground can provide a water supply after a major hurricane until such time as other infrastructure has been repaired and placed back into service.

5.3 Laws, Regulations and Costs without Scientific Basis

5.3.1 Construction Costs of ASR without Scientifically Designed and Executed Studies, Monitoring and Modeling

Considerable public funds are being spent for ASR wells in the FAS without any scientific basis to support the claims that injected water can be "stored" and "recovered" or to evaluate the role of hydrological connections between ASR wells and environmentally sensitive areas via fractures. For example, the cost of the unsuccessful Elmodel WMA ASR demonstration well in Georgia was $1,395,712.16. That cost included: (1) $625,455.26 for construction of the Claiborne and Clayton monitoring wells and the Floridan supply well; (2) $133,150 for data analysis and groundwater modeling related to the Claiborne and Clayton monitoring wells, which included analysis of the geophysical logging, performance of a geochemical assessment, and geologic core sample analysis; and (3) $637,106.90 for planning, surveying, designing, permitting, and other administrative and legal expenses (GEFA media statement, 07/08/15). There was no documentation or explanation why or how that ASR well failed.

The cost of the Hilton Head North Island ASR well, that was operational under HHPSD #1 in South Carolina at the time of our study, was \$3.9 million and was funded by general obligation (GO) bonds. Construction of this ASR well and associated equipment began in approximately 2010. Aquifer injections of "240 million gallons" began in October 2012 and continued to February 2013. Those aquifer injections were known as "building the bubble" for a "buffer" that was not to be withdrawn. The second series of aquifer injections began in October 2013, continued until February 2014 and totaled "241.631 Million Gallons." Withdrawals from that ASR well totaling "242.951 Million Gallons" and "237.761" began in May 2014 and continued through September 2014 and May 2015 through September 2015, respectively. The approximate chloride content of the injected water was 30 mg/L and increased to 164 mg/L in water withdrawn in September. The fact that "recovered" water has a chloride content that is 5.5 to 8 times (or more) greater than the chloride content of injected water is proof that the injected water is not remaining at the end of the ASR well as a "bubble" and may be increasing chloride contamination of the aquifer system rapidly via fractures. The HHPSD #1 reverse osmosis (RO) plant only produces "3 MGD," but it also buys water from the Beaufort Jasper Water and Sewer Authority (BJWSA), on the mainland. The Savannah River is the source of water for the BJWSA. This ASR well is dependent on the treated river water from BJWSA, sold to HHPSD #1 at off-peak rates in the winter months (Bill Davis, HHPSD #1, pers. comm., 12/22/15). Daily "recovery" from this ASR well for 2014 and 2015 was approximately 1.59 MGD and 1.55 MGD, respectively, based solely on the initial volumes withdrawn from this ASR well during these first two years and disregarding increases in chloride content to approximately 5.5 times the chloride content of the injected water.

An example of another costly ASR venture occurred in north and central Florida when the St. John's River Water Management District (SJRWMD) designated \$47 million for ASR systems in its district from 2001-2006. In south Florida, \$45 million originally was proposed for the ASR pilot projects, with \$1.7 billion for more than 330 ASR wells originally proposed for construction throughout the Everglades. The ACOE's Final ASR Report and groundwater model (ACOE, 2014) revised the recommendation to 232 ASR wells for the Greater Everglades Basin (Bacchus et al., 2015b). Using the recent funding figure of approximately \$1.4 million for the ASR well from the unsuccessful Elmodel ASR demonstration project in Georgia, that would result in a cost of approximately \$324.8 million tax dollars for the proposed Everglades ASR wells. Based on the funding figure of \$3.9 million for the Hilton Head North Island ASR well, those 232 proposed ASR wells would cost approximately \$904.8 million tax dollars.

All of these publically funded ASR wells have the potential to fail, due to lateral saltwater intrusion, upconing of brackish and saline water and contaminants (e.g., arsenic and benzene) via preferential flow through fractures and other karst conduits. The injections and withdrawals associated with these ASR wells also have the ability to result in adverse impacts to environmentally sensitive state and federal lands. Additionally, the costs for ASR projects exclude long-term operation and maintenance costs, which are energy intensive and also exclude the costs of extensive evaluations of adverse environmental impacts (e.g., hydroperiod alterations and contamination of surface waters with arsenic) and the reversal of those impacts. Natural recharge in the FAS requires no operation or maintenance and has none of the harmful consequences of ASR injection and withdrawal wells (Bacchus et al., 2015b; Fernald, Purdum, Anderson, & Krafft, 1998). Our study supports the conclusion that mapped fracture networks are so extensive in the FAS that it would be difficult to find any sites in the carbonate platform of Florida, Georgia, and South Carolina that would not be influenced by the fracture network and associated sinkholes.

On October 7, 2015, the US Office of Management and Budget, Council on Environmental Quality, and Office of Science and Technology Policy within the Executive Office of the President directed federal agencies to incorporate ecosystems services into the planning and decision making for those agencies. Clearly ASR wells permitted as UICs under the federal Safe Drinking Water Act, without consideration of adverse impacts to the federal Endangered Species Act and the Clean Water Act meets the intent of this federal directive. A minimum requirement for future reporting and permitting for all states with fractured aquifers should be the identification of fractures in the vicinity of permitted or proposed UIC wells and testing that involves tracer and isotopic analyses.

5.3.2 Ground Water Is Not an "Alternative" Source for Ground Water

As described above, decades of research results and other evidence have documented preferential flow laterally and vertically between every zone of the FAS induced in response to groundwater withdrawals from every FAS zone, beginning with the surficial aquifer and extending to the deepest zone, although the permitting of ASR wells presumes no hydrologic connections between the lower, middle, and upper Floridan and the surficial aquifer. Therefore, it is difficult to understand why millions of tax dollars currently are being proposed for theoretical artificial aquifer "storage" and "recovery" using ASR wells in Florida and Georgia. In fact, the following excerpt from the Florida Statutes implies that ground water can be used as an “alternative” source of for ground water, which the scientific data clearly shows is not possible for the FAS:

> Alternative water supply (AWS) “Salt water; brackish surface water and groundwater; surface water captured predominately during wet-weather flows; sources made available through the addition of new storage capacity for surface water or groundwater, water that has been reclaimed after one or more public supply, municipal, industrial, commercial, or agricultural uses; the downstream augmentation of water bodies with reclaimed water; stormwater; and, any other water supply source that is designated as nontraditional for a water supply planning region in the applicable regional water supply plan” (Section 373.019, Florida Statutes).

This example of state law reflects the apparent lack of lawmakers’ scientific understanding of groundwater responses in a regional karst aquifer system and the interconnections between all zones of the aquifer system and surface waters. This lack of understanding also appears to extend to the attorneys with practices that involve environmental litigation, based on the recent legal analysis of Florida’s new water law termed a “marvel of compromise,” that will take effect July 1, 2016 (if signed into law by the governor), and which acknowledges the following (Alderman, 2016):

> ...significant portions of Florida do not have enough water reserves from traditional groundwater sources to sustain continued growth. This dilemma has sparked the need to promote or even require development of alternative water supplies and to adopt additional limitations on withdrawals from traditional groundwater sources.
>
> Finally, the Bill addresses the multiple existing programs for protection of the South Florida natural environment...
>
> In addition to the threat of diminishing water supplies, continued concern for Florida's premier springs brought about the creation of a new regulatory category to afford them special protection, together with associated development limitations and remediation plans. Additional protections have also been afforded to help remediate impaired water bodies throughout the state, but particularly the ecosystems in south Florida.
>
> A new protected class of waters is created: the Outstanding Florida Spring (OFS) OFSs include all historic first magnitude springs and their associated spring runs and the following: De Leon, Peacock, Poe, Rock, Wekiwa and Gemini Springs, and their spring runs.
>
> Development of alternative water supplies for water-starved areas is encouraged through provision for pilot projects to be undertaken by the three largest water management districts: St. Johns, South Florida (SFWMD) and Southwest Florida.
>
> The decades of scientific research and data addressed in our study clearly show that the state’s environmentally sensitive lands and waters, particularly the springs, cannot be protected under this proposed new law with the proposed continuation of groundwater withdrawals, injections, and depletions from large excavations referenced as “reservoirs” and “water farming.” Therefore, the environment has gained nothing, but lost additional protection under this law. Hopefully those economically and environmentally costly proposed approaches will be replaced with closed loop systems that are capable of minimizing adverse environmental impacts, to earn the claim of true compromise.

6. Summary and Conclusions

Fractures and sinkholes in the FAS have been mapped throughout Florida and at least one coastal-plain county of Georgia, although this regional karst aquifer also extends throughout the coastal plain of Alabama and South Carolina, from the submerged carbonate platform of the Atlantic Ocean, Gulf of Mexico, and Straits of Florida. This carbonate aquifer system is characterized by bedding planes, fractures, dissolution cavities, and other karst features that result in preferential flow of ground water, particularly in response to anthropogenic perturbations such as groundwater withdrawals and aquifer injections. Extensive networks of fractures have been reported by the US Army Corps of Engineers (ACOE, 2004), and mapped by Florida Department of Transportation (FDOT, 1973), and Vernon (1951) throughout Florida and mapped in Dougherty County by Brook and Allison (1986). Krause and Randolph (1989) divided the FAS into six sub-regions for groundwater modeling and concluded breaches of those groundwater divides had occurred, attributing those breaches to large withdrawals of groundwater in the US southeastern coastal plain. Some of those mapped fractures extended from one sub-region into an adjacent sub-region in the FAS and may be facilitating the breaching of groundwater divides described by Krause and Randolph (1989) in that regional aquifer system.

The greater total fractures and fracture density in Dougherty County (1,225 and 141.3/100 km^2, respectively) compared to 21 north-Florida counties (10-91 fractures per county and 0.6-3.8/100 km^2, respectively) presumably is due to the scale of fracture mapping and shorter mean lengths of mapped fractures in Dougherty County (1.2 km), compared to north Florida counties (26-118 km), rather than to orders of magnitude increases in fracture densities in that part of the FAS. Extensions of the Dougherty County fractures, however, did not suggest that those short fractures were fragmented segments of longer fractures. The number of sinkholes (934) mapped in Dougherty County by Brook and Allison (1986) in analog form and converted to georeferenced digital format in our study increased by more than an order of magnitude, based on the number of sinkholes identified in a NASA DEVELOP project (18,557), using 2011 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images. When we extended the dense network of those fractures that occurred within the boundaries of Chickasawhatchee Swamp/Ichauway Plantation PARCA, that encompassed Dougherty County, those extensions covered the Elmodel WMA and ASR demonstration well in Baker County, Georgia. Those extensions also passed through numerous agricultural areas with center-pivot irrigation wells in southwest Georgia; intersected other Georgia PARCAs near the Florida/Georgia state line; and clumped in two areas of dense sinkhole clusters in northwest Florida (sub-regions H and U). The magnitude and extent of agricultural, municipal, and industrial groundwater withdrawals in Georgia’s coastal plain exceed groundwater withdrawals in Florida for that area of the FAS. No determination has been made regarding the contributions of those groundwater withdrawals in Georgia to water pirated, via preferential flow through fractures, from the Apalachicola-Chattahoochee-Flint (ACF) River Basins and Wakulla Springshed or to the increase in sinkholes in Dougherty County and the dense clusters of sinkholes in northwest Florida. Similarly, the survival and recovery of at least 24 animal species in Georgia that are either federally listed or high-priority state species may be jeopardized by adverse direct, indirect, and cumulative impacts from preferential flow through fractures, sinkholes, and other karst conduits in response to aquifer injections and withdrawals that have not been evaluated. Currently no regional groundwater model has been constructed to evaluate preferential groundwater flow through the mapped fractures, sinkholes, and other karst conduits in the FAS. Such a model is essential to determine the magnitude and extent of environmental impacts from ASR wells and other supply and disposal wells in this regional aquifer system, such as pirated water from the ACF and other river basins, alterations in submarine groundwater discharge to Apalachicola Bay and other coastal areas, saltwater intrusion, upconing of saline ground water, and resulting impacts to federally listed and high-priority state species.

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Appendix A.

2005 Rankings/Descriptions of Standardized Threats to High Priority Fish and Aquatic Invertebrate Species in Georgia related to Groundwater Withdrawals and Injections in the FAS. (* from Albanese et al. (2015); threats from 2005 SWAP Plan particularly relevant to aquatic species in bold red font.)

2. Incompatible Agricultural Practices

Includes agricultural practices that impact the environment well outside the actual agricultural operation through releases of excess nutrients, toxins, or sediments. Includes practices that degrade stream or wetland habitat quality.

3. Altered Fire Regimes:

Includes fire exclusion, fire suppression, alteration of habitats through unnatural timing, Frequency, or intensity of prescribed burns, and other incompatible fire management practices. Fire regimes are affected by altered community composition (e.g., increase of non-pyric species such as oak) and habitat fragmentation. Fire is an important ecological process that drives many of the terrestrial habitats in Georgia.

4. Altered Hydrology

Includes construction and use of ditches, levees, dikes, and drainage tiles, flow diversion,

dredging, channelization, filling of wetlands and headwater streams, destabilization of stream banks or channels, head-cutting, and other alterations to stream morphology or hydrologic regimes. Results in degradation or destruction of aquatic and wetland habitats.

5. Altered Water Quality

Includes various forms of point and non-point source pollution, such as herbicides, pesticides, sediments, nutrient loading, and thermal modifications that directly impact water quality. Sources are quite varied and include waste water discharges, excessive soil disturbance near streams, increased impermeable surface area resulting from development, and loss of vegetation in riparian buffers.

6. Commercial/Industrial Development

Includes development of structures and infrastructure (buildings, utilities, driveways and roads) for commercial or industrial purposes, usually in an urban setting. Impacts may include direct habitat destruction, fragmentation, altered thermal regimes, and indirect pollution sources that alter water quality.

7. Conversion to Agriculture

Includes the conversion of natural habitats to anthropogenic habitats managed for agricultural crops, pasture, horticulture, or silviculture. Usually involves removal of native vegetation, site preparation, and planting of off-site or non-native species. Results in habitat destruction or fragmentation and may impact water quality.

8. Dam and Impoundment Construction

Includes the construction of dams and impoundments (from agricultural ponds to large reservoirs) that directly affect stream flows and fragment aquatic habitat. Results in impacts to the impounded portion of the stream as well as habitats above and below the dam.

9. Development of Roads or Utilities

Includes construction of new roads (interstate highways, state highways, and county roads) and utility right-of-ways (e.g., electrical transmission lines, water/sewer, gas pipelines) that result in habitat destruction or fragmentation and creation of new avenues for invasion by exotic species.

10. Disease

Includes fatal or debilitating disorders resulting from infections, poisons, pathogenic microorganisms, or parasites. The most serious impacts generally result from introduced vectors or pathogens (e.g., sudden oak death, hemlock wooly adelgid, chestnut blight). Impacts can be devastating to the species directly attacked as well as natural communities.

11. Excessive Groundwater and Surface Water Withdrawal

Includes direct groundwater and surface water withdrawals for agricultural, industrial, and municipal water supplies. Excessive withdrawal can result in lowered water tables, diminished local aquifer discharges, and reductions in water available to sustain stream base flows, spring discharges, isolated wetlands, karst environments, and seepage communities.

14. Incompatible Forestry Practices

Involves poor forestry practices that impact species of concern. This includes failure to follow BMPs and site management activities that result in altered structure and composition of adjacent natural habitats or degraded stream or wetland habitats.

15. Global Warming/Climate Change

Defined as consistent, directed change in climatic conditions at regional scales. Such changes may include increases or decreases in average temperatures, changes in the rates, distribution, frequency, or timing of precipitation, and frequency and intensity of storm events. Local effects are often difficult to quantify.

18. Incompatible Mining/Mineral Extraction

Includes extraction of minerals, oil, or gas or similar activities that result in the disturbance or destruction of natural habitats as well as secondary impacts such as sedimentation or releases of toxins. Impacts may include increased sediment loads, downstream scouring, habitat destruction and disturbance, fragmentation, and creation of migration routes for invasive exotic species.

19. Incompatible Road/Utility Management

Includes management of roads or utility corridors that results in excessive releases of sediment or provides access for non-native species, as well as vegetation management practices that are environmentally “unfriendly” (e.g. indiscriminant use of herbicides).

20. Industrial/Municipal Pollution

Includes toxins and air-borne pollutants, thermally altered effluent, and other point source pollutants derived from industrial/commercial land uses in an urban or suburban setting. Involves direct impacts in the form of chemical or thermal stresses to species or natural communities.

21. Invasive/Alien Species

Includes exotic species as well as native species that have become invasive due to past habitat alterations (e.g. hardwood encroachment of long leaf pine habitats following fire suppression). Impacts include competition, hybridization, and predation as well as long-term alterations of ecological systems and processes (e.g. hydrologic changes, changes in soil attributes, altered fire regimes).

23. Residential Development

Includes primary and secondary home construction as well as development of associated infrastructure (e.g. subdivision roads and driveways, sewer and stormwater utilities). Impacts may include habitat destruction, disturbance, fragmentation, and introduction of invasive species.”