What Georgia Can Learn from Aquifer Storage and Recovery (ASR) in Florida

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Abstract. Preferential groundwater flow through fractures has been documented in karst and non-karst aquifer systems, including regional aquifer systems of Florida and Georgia. This preferential flow is induced by groundwater withdrawals and aquifer injections of fluids. Most recently, evidence of preferential groundwater flow through fractures has been associated with aquifer injections of sewage effluent in south Florida and subsequent discharge of nitrogen contaminants in coastal waters associated with the Florida Keys, where harmful algal blooms and coral decline and death occurred. Large-scale aquifer injections and withdrawals as "aquifer storage and recovery" ("ASR") were proposed for south Florida by the U.S. Army Corps of Engineers' 2014 report. That report did not consider the dense network of fractures that were mapped by the Florida Department of Transportation's Remote Sensing office in 1971 or other mapped networks that have been published. A closer look at previously published ASR reports from Florida raises questions regarding claims of both "storage" and "recovery" and the role of fractures in these extremely low rates of actual recovery. The current work reports on our mapping and geospatial analysis of fracture distribution, extent and proximity to injection and withdrawal wells in southern Florida, including considerations regarding preferential flow of groundwater contaminants. The coastal plain of Georgia is underlain by the same regional karst Floridan aquifer system as Florida and could be expected to have similar ineffective ASR results as those documented in Florida. Mapped fracture networks in Georgia should be a prerequisite for consideration of ASR in Georgia.

BACKGROUND AND DISCUSSION

Regulation and Evaluation of ASR in Florida

The Safe Drinking Water Act (SDWA) regulates aquifer-injection wells in the United States (US), including "aquifer storage and recovery" (ASR) wells. Although the US Environmental Protection Agency (USEPA) implements the SDWA, this federal agency does not issue permits for ASR wells in Florida, but defers to the Florida Department of Environmental Protection (FDEP) to issue permits and regulate ASR wells in that state. Similarly, ASR wells in Georgia are regulated by the Georgia Department of Natural Resources (GDNR). Terminology related to ASR and used by regulatory agencies, municipalities and representatives of the ASR industry often does not conform with standard or scientific definitions of those terms, as described by Bacchus *et al.* (2015). (Refer to Table 1 of Bacchus *et al.* (2015) for definitions of terminology related to ASR.)

Based on the FDEP injection-well database, the first ASR wells permitted in Florida were the three South Cross Bayou ASR wells permitted in Pinellas County on 9/5/78, 10/30/78 and 12/16/78. More than two decades later, the US Geological Survey (USGS) appears to have published the first attempt at a synopsis of ASR wells in southern Florida (Reese, 2002), primarily based on data produced and provided by engineering consulting firms and municipal utilities. The report focuses on "ASR" sites in the Floridan aquifer system (FAS) and included 22 ASR and Comprehensive Everglades Restoration Plan (CERP) wells constructed in the brackish to saline Upper Floridan aquifer, for a total of 27 ASR sites, with one well under construction. Twenty of the ASR sites had been constructed in the 1990s, with 14 of those constructed since 1996. Ten of the 27 sites were under operational testing. Two case studies on each coast were included, but there were no monitoring wells in the ASR zone at the

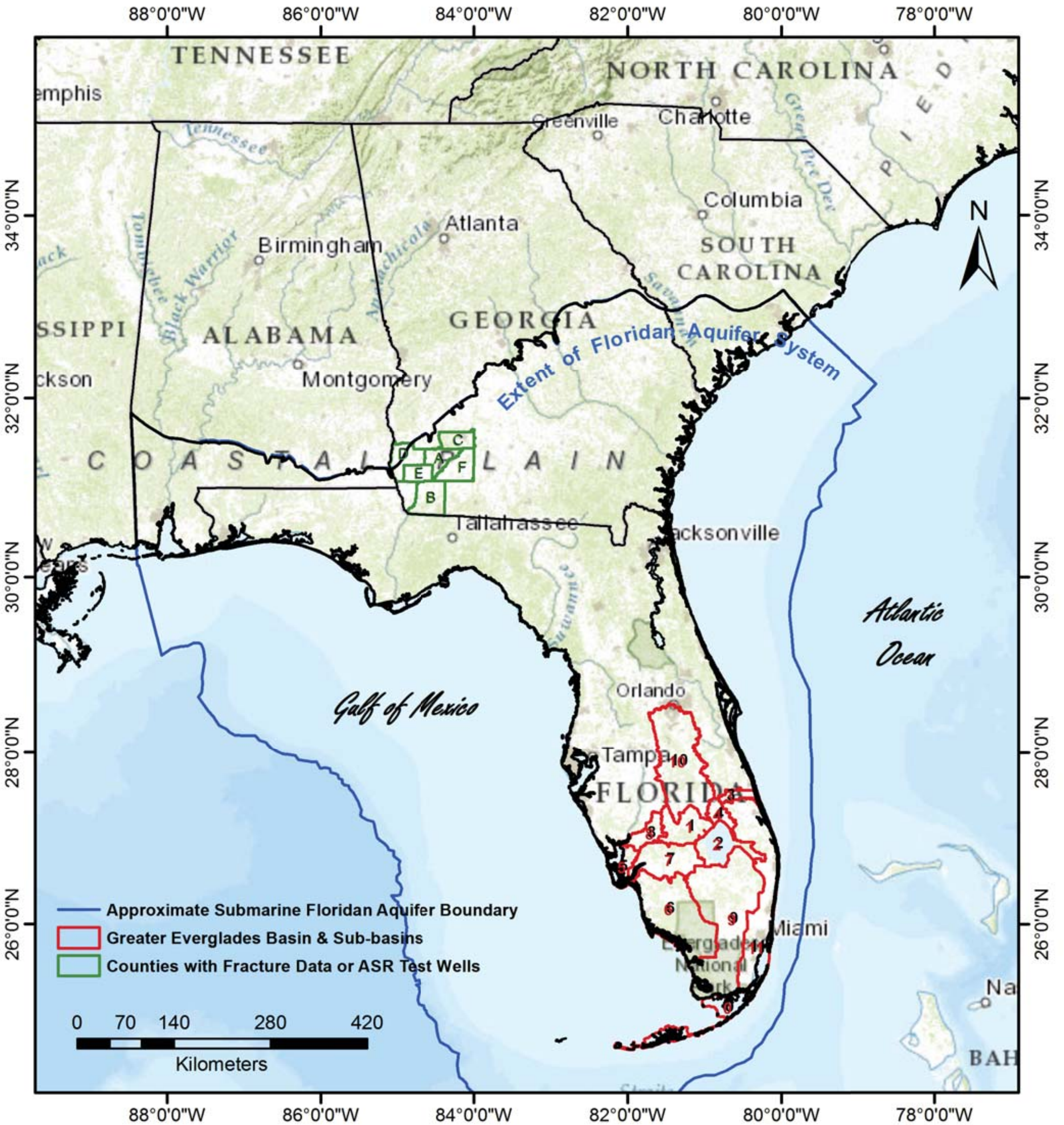

Figure 1: The northern extent of the Floridan aquifer system (FAS) in Alabama, Florida, Georgia and South Carolina; approximate submarine extent of the FAS in the Atlantic Ocean and Gulf of Mexico; boundaries of the Greater Everglades Basin and sub-basins in south Florida and boundaries of counties in Georgia with fracture data and ASR test wells.

east coast. Figure 1 illustrates the northern extent of the FAS in Alabama, Georgia and South Carolina (Bellino, 2011), in addition to the approximate submarine extent of the FAS in the Atlantic Ocean and Gulf of Mexico. The approximate submarine extent of the FAS was created by digitizing the margin of the continental shelf using ArcGIS Version 10.2 and a composite basemap including satellite imagery and bathymetric surfaces. The ASR well sites evaluated by Reese (2002) were associated with the boundaries of the Greater Everglades Basin, which are the outer boundaries in red in Figure 1.

The strategy of ASR, as described in that report, is to "store excess water" during the wet season and "recover" that water during the dry season, when it is needed as a supplemental supply for municipalities. There was no consideration for environmental needs during the wet and dry seasons in that evaluation. Withdrawal of water as "recovery" could occur immediately after injection and could continue until reaching a predetermined level of 250 mg/L chlorides, which is the limit for chlorides in potable water, established by USEPAs National Secondary Drinking Water Regulations, under the SDWA. There were no requirements for the quality of water "recharged" and "recovered" to be reported (Reese, 2002).

Comparison of Reported "Recovery" and Actual "Recovery"

Bacchus *et al.* (2015) compared chloride concentrations for water injected into ASR wells and for water reported as recovery by Reese (2002), then adjusted the chloride concentrations for water reported as recovery to match the chloride concentration of the injected water to determine actual recovery from those ASR wells. Table 1 includes 18 ASR sites, site names and numbers of the ASR sites evaluated by Reese (2002, Table 5), the range of percent recovery reported for multiple cycle tests, the number of days the injected water was stored and the range of actual recovery, by county. The reported recovery was based on the chloride concentration established under the SDWA for potable water (250 mg/L), rather than the chloride concentration of the water injected in to the ASR wells. Of those 18 ASR sites, 13 sites were reported as abandoned by Bloetscher *et al.* (2014), with an additional ASR well site evaluated by Reese (2002, San Carlos) reported in the Florida Department of Protection (FDEP) database as inactive. The names of those 14 ASR sites are shown in bold in Table 1, with examples of additional abandoned ASR sites in Collier County, Lee County, Miami-Dade County, Okeechobee County, from Bloetscher *et al.* (2014, Table 1) also in bold.

Table 1: Comparison of reported recovery and actual recovery ranges from cycle tests based on chloride concentration and "storage" periods for ASR wells inventoried by USGS in southern Florida, with abandoned ASR sites identified by site names in bold (actual recovery efficiency from Bacchus *et al.* (2015), rounded to nearest percent; all other data, except site names without site numbers, from Reese (2002, Table 5); all abandoned ASR wells identified by site names in bold are examples from Bloetscher *et al.* (2014) except for the abandoned San Carlos ASR site, which is based on the FDEP database). ¶

Site Name/ Site Number	Reported "Recovery" Efficiency (%)	Actual "Recovery" Efficiency (%)	"Storage" Period (days)
Broward County			
Broward/2	>20-26	3-4	0-9
Springtree/3*	>20-38	NC-10	0-1
Fiveash/4	>6-11	2-3	0-1
Charlotte County			
Shell Creek/5	9-37	5-12	0-1
Collier County			
Collier Co. N	-	-	-
Manatee Rd/7	NR-32	NR-6	6-20
Marco Lakes/8	NR-33	NR-12	2-109
Lee County			
Corkscrew/10	NR	NR	1-35
Lee County/9	10-39	9-10	0-98
N. Reservior/11	10	6	7
Olga WTP	-	-	-
San Carlos/13	2-3	0-1	0-6
Miami-Dade County			
Hialeah/15	33-48	9-12	2-181
Miami Beach	-	-	-
Miami-Dade NW	-	-	-
Well Field/17	NR-57‡	NR-14	0-123
Monroe County			
Marathon/19	28-72	0-12	0-81
Okeechobee County			
Tylor Cr/20	NR-7	NR-0	0-8
Lake Okeech.	-	-	-
Palm Beach County			
Jupiter/21	0-35	0-9	15-120
Boynton Bch/22	27-90	NR-17	0-174
W Palm Bch/24	NR	NR	0-3
St. Lucie County			
St. Lucie Co./27	3	NR	38

¶reported "recovery" adjusted to 250 mg/L chloride level for potable water by Reese, 2002; actual "recovery" adjusted to chloride concentration of injected fluids for each cycle test for our study (=reported/(recovered/injected))

* Cycle five had 52 Days of down time during the recharge period; **2 cycles "recovered" water with lower chloride conc.**

‡USGS report combined values for all three No. 3 ASR wells; **NR** Not Recorded; **NC** Not Calculated (chloride reduced)

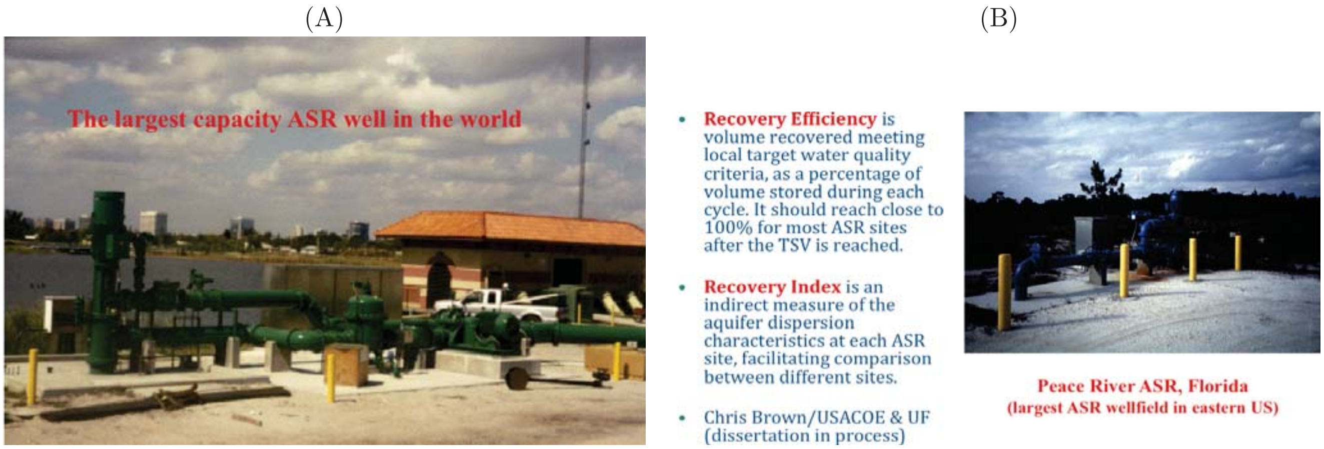

Figure 2: Photographs of: (A) West Palm Beach, Florida ASR well, described as the largest capacity ASR well in the world, equipped for 8 MGD capacity and abandoned because of recovery problems; and (B) Peace River, Florida ASR well, described as the largest ASR wellfield in the eastern US (from Pyne, 2004).

The survey by Bloetscher *et al.* (2014) identified 32 ASR well sites in Florida that were no longer active because of problems such as arsenic contamination, clogging, recovery problems or water quality deterioration, based on data collected through July 1, 2013. One of those well sites, Corkscrew in Lee County, included six ASR wells that had been abandoned due to recovery problems. Dissolved solids had been recorded instead of chloride concentration at that ASR site (Reese, 2002). The Punta Gorda-Hell Creek ASR well site was another ASR site that Bloetscher *et al.* (2014) surveyed and that site included four ASR wells abandoned because of arsenic contamination. Another of those well sites, Miami-Dade Water and Sewer Department NW, included three ASR wells abandoned because of recovery problems. The City of St. Petersburg included two ASR wells abandoned for unidentified problems. The rest of the 32 ASR sites in Florida with abandoned wells included only one well per site. 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. All but one of those ASR sites was reported as abandoned by Bloetscher *et al.* (2014).

The greatest actual recovery was 17% for one of the 17 cycle tests at the Boynton Beach ASR site (#22), the reported recovery for that cycle test is shown in Table 1 as 90% (Reese, 2002). Graphs for reported recovery and actual recovery at the Boynton Beach ASR site (east coast) and the Marco Lakes ASR site (#8, west coast) are included as Bacchus *et al.* (2015, Figure 4). Only four of the ASR wells summarized by Reese (2002) were still operational when Bloetscher, *et al.* (2014) conducted their survey of ASR wells in the US. The chloride concentration of the injected water was not reported (NR) for some of the well sites, such as the West Palm Beach ASR site (#24). That made it impossible to calculate the reported recovery and the actual recovery of those wells.

Photographs of West Palm Beach ASR site and the Peace River ASR site are provided in Figure 2A and B, respectively. These ASR sites are promoted as the largest ASR well in the world and the largest ASR wellfield in the eastern US respectively (Pyne, 2004). The West Palm Beach well site reportedly was equipped for "8 MGD" (millions of gallons per day) capacity and abandoned because of recovery problems.

Preferential Flow

In 1989 the consulting engineering firm CH2M Hill reported aquifer flow characteristics, unexpected to them, during aquifer injections and withdrawals. Their findings resulted in further evaluation and collection of data by the USGS from April 1991 to September 1994 in cooperation with the South Florida Water Management District (SFWMD). The findings of the USGS evaluation and additional data collection suggested that the aquifer system responds as a conduit or cavernous-type flow system, rather than one of simple uniform-isotopic type flow (Quiñones-Aponte *et al.*, 1996), as had been assumed by agencies promoting aquifer injections and withdrawals in Florida. The conduit flow zones at that site (northern shore of Lake Okeechobee) were located at depths of 389-398 m (1,276-1,305 ft), 419-424 m (1,374-1,391 ft), 456-462 m (1,496-1,515 ft), and 472-476 m (1,548-1,561 ft) below sea level (Quiñones-Aponte *et al.*, 1996). The

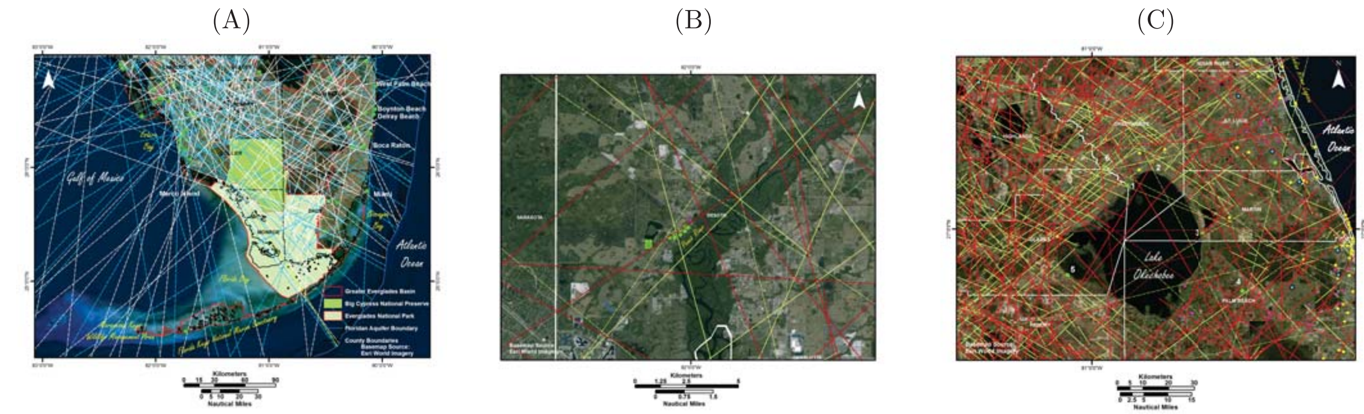

Figure 3: Proximity of fractures reported by US Army Corps of Engineers (ACOE, 2004, solid diagonal blue lines), and mapped by FDOT (1973, solid diagonal white lines) and Vernon (1951, solid diagonal yellow lines), extensions of fractures (dashed diagonal lines), other Class V injection wells (pink circles), Class I injection wells (yellow circles), and modern sinkholes (blue circles) in the southern extent of the Greater Everglades Basin to permitted ASR wells (green circles) including: (A) the West Palm Beach, Boynton Beach and Delray Beach ASR wells on the east coast; (B) the 22 Peace River ASR wells in westcentral Florida; and (C) ASR wells in the vicinity of Lake Okeechobee in southcentral Florida (from Bacchus *et al.*, 2015).

depths of the shallowest flow zones at that site are similar to depths of ~305-335 m (~1,000-1,100 feet) of the aquifer cavities intersecting the open borehole below the casing of the ASR well in the Pelican Bay wellfield on the west coast of Florida, in Collier County. The cavities at the Pelican Bay site were recorded on the borehole video produced by MV Geophysical Surveys, Inc./Diversified Drilling Corporation for Water Resources Utilities and Collier County Utilities.

Bacchus *et al.* (2015) summarized preferential flow in karst aquifer systems, including preferential flow through fractures and showed that many of the ASR wells in southern Florida are located in the vicinity of fractures and fracture networks. Examples of ASR wells in the vicinity of fractures include the West Palm Beach, Boynton Beach and Delray ASR wells on the east coast of Florida (Figure 3A), the 22 ASR wells at the Peace River ASR site in westcentral Florida (Figure 3B) and ASR wells in the vicinity of Lake Okeechobee in southcentral Florida (Figure 3C).

This suggests that water injected into ASR wells will move rapidly through these fractures as preferential flow and discharge into surface waters, including coastal waters similar to sewage effluent injected into disposal wells in south Florida at comparable depths and aquifer zones to those used for ASR wells (Bacchus *et al.*, 2014). Thirty years earlier, Popenoe *et al.* (1984) confirmed the fractures extended into the submarine extent of the FAS. This may be a contributing factor in the abandonment of at least 32 ASR wells in Florida, particularly considering that during "recovery" pumping ASR wells can pull saline water laterally, from the coast through those fractures, as well as result in up-coning of saline water from lower zones of the aquifer system, as described by Spechler (1994), Spechler and Phelps (1997) and Odum *et al.* (1998). This also suggests that contaminants such as arsenic that is mobilized by ASR injections also will flow through those fractures for considerable distances from the ASR wells and that those ASR wells also can be dewatering other areas located along the same fracture or fracture network as those ASR wells. For example, the ASR well evaluated by Mirecki *et al.* (2013) was located in proximity to a fracture and fracture network as shown in Figure 3C and described in Bacchus *et al.* (2015).

Extensive phosphate mining occurs in the west-central Florida portion of the FAS, associated with the Peace River basin and the Peace River ASR site. A remote sensing evaluation of 567 depressional wetlands in that mining area where maximum aquifer withdrawals of 76,457 m^3/d (~20.2 MGD) were permitted in November 1977 suggested that spatial distribution of wetlands with high near infrared digital numbers (NIR DNs) indicative of invasive species and hydroperiod alterations was inconsistent with conical groundwater drawdown predicted by groundwater models but suggests more linear fluid movement via subsurface preferential NW-SE flow paths consistent with fracture flow (Bacchus *et al.*, 2011). The lack of abandonment of sites such as the Peace River ASR site and the Pelican Bay ASR site, may be due to the proximity of those ASR wells to fractures with preferential flow (Bacchus *et al.* 2015, Figure 13).

Natural vs. Artificial Recharge

The Water Resources Atlas of Florida by Fernald *et al.* (1998), illustrates how natural recharge (infiltration) decreases as areas with natural ground cover are replaced with increasing areas of impervious (nonporous) surfaces such as buildings and paved streets and roads. Combined shallow and deep infiltration is 50% with natural groundcover conditions. This natural recharge is reduced to only 15% (combined shallow and deep infiltration) when natural groundcover is converted to 75-100% impervious surface. Artificial recharge of the FAS using ASR wells resulted in actual recovery ranging from 0-17%, based on reported recovery efficiency adjusted to the chloride concentrations of water injected in ASR wells in Florida. The greatest actual recovery was less than half of the total natural recharge of the aquifer system that occurs as infiltration in areas with natural ground cover and less that deep infiltration to the aquifer in those natural areas. In fact, the actual recovery from ASR wells is comparable to or less than natural recharge that occurs in areas with 75-100% impervious (nonporous) surfaces. That natural recharge occurs at no cost to the public, including no cost for electricity to pump and pipe water from the source to the ASR injection wells for artificial recharge, then to the area of water use.

Costs of ASR

In south Florida, $45 million was proposed for the ASR pilot projects, with $1.7 billion for more than 330 ASR wells originally proposed for construction throughout the Everglades. From 2001-2006, the St. John's River Water Management District (SJRWMD) designated $47 million for ASR systems in its district. The feasibility studies for the two ASR sites proposed in Georgia would cost ~$5 million of state funds each, if they are completed (Jim Kennedy, GDNR, pers. comm. 5/7/15). The ACOE's Final ASR Report and groundwater model (ACOE, 2014) revised the recommendation to 232 ASR wells for the Greater Everglades Basin. Using the recent funding figure of ~$5 million per ASR well from Georgia, that would result in a cost of approximately $1.1 billion tax dollars. Those 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, such as hydroperiod alterations and contamination of surface waters with arsenic and the reversal of those impacts. Natural recharge in Florida requires no operation or maintenance and has none of the harmful consequences of ASR injection and withdrawal wells.

Table 2: Examples of counties and vicinities of ASR test wells and fracture studies in Georgia.

ID	Georgia Counties	Vicinities
A	Baker County	Elmodel Wildlife Management Area ASR
B	Decatur County	Bainbridge
C	Dougherty County	Albany, Pretoria, Putney
D	Early County	Damascus
E	Miller County	Cooktown
F	Mitchell County	Camilla

Fractures in Georgia

Table 2 lists examples of counties and vicinities of fracture studies and ASR test wells in Georgia, as shown in Figure 1. Figure 4A illustrates the myriad fractures mapped by the Remote Sensing staff of the Florida Department of Transportation (FDOT, 1973), as solid red diagonal lines. Although those mapped fractures stop at the state boundaries, the fractures extend into the submarine portion (Popenoe *et al.*, 1984) and the Georgia portion of the FAS, particularly throughout the Dougherty Plain of Georgia (Brook and Sun, 1982; B. Brook *et al.*, 1986; C. Brook *et al.*, 1988), where the ASR feasibility studies are being conducted and fractures are known to influence well productivity (Brook, 1985). The fractures associated with ASR wells in northern Florida have been extended in Figure 4A (red dashed lines) to show areas of potential fractures in the FAS in Georgia, the Atlantic Ocean and Gulf of Mexico. One of those ASR fracture extensions from Florida dissects the clusters of supply wells evaluated by Brook *et al.* (1986; 1988). Figure 4B is an enlargement of that fracture extension in the area, overlying the fracture traces mapped in Dougherty County, Georgia by Brook and Allison (1986). That fracture extension coincides with some of those fracture traces mapped by Brook and Allison (1986).

Groundwater Models for the Floridan Aquifer System

Analysis by USGS of chloride concentrations in water at the injection-withdrawal well and at the deep monitor well at the northern shore of Lake Okeechobee described above, indicated that flow through the Floridan aquifer is not representative of a simple uniform outflow of freshwater in a confined aquifer during injection followed by a similar type of backflow during recovery withdrawals. The failure of simulated (modeled) chloride concentrations to match actual field (observed) chloride concentration results at this site was attributed to the conduit flow of the lower Floridan aquifer system. Those results suggested that a free-flow (conduit-flow or fracture-flow) model would produce a more realistic representation of the actual flow of fluids (Quiñones-Aponte *et al.*, 1996).

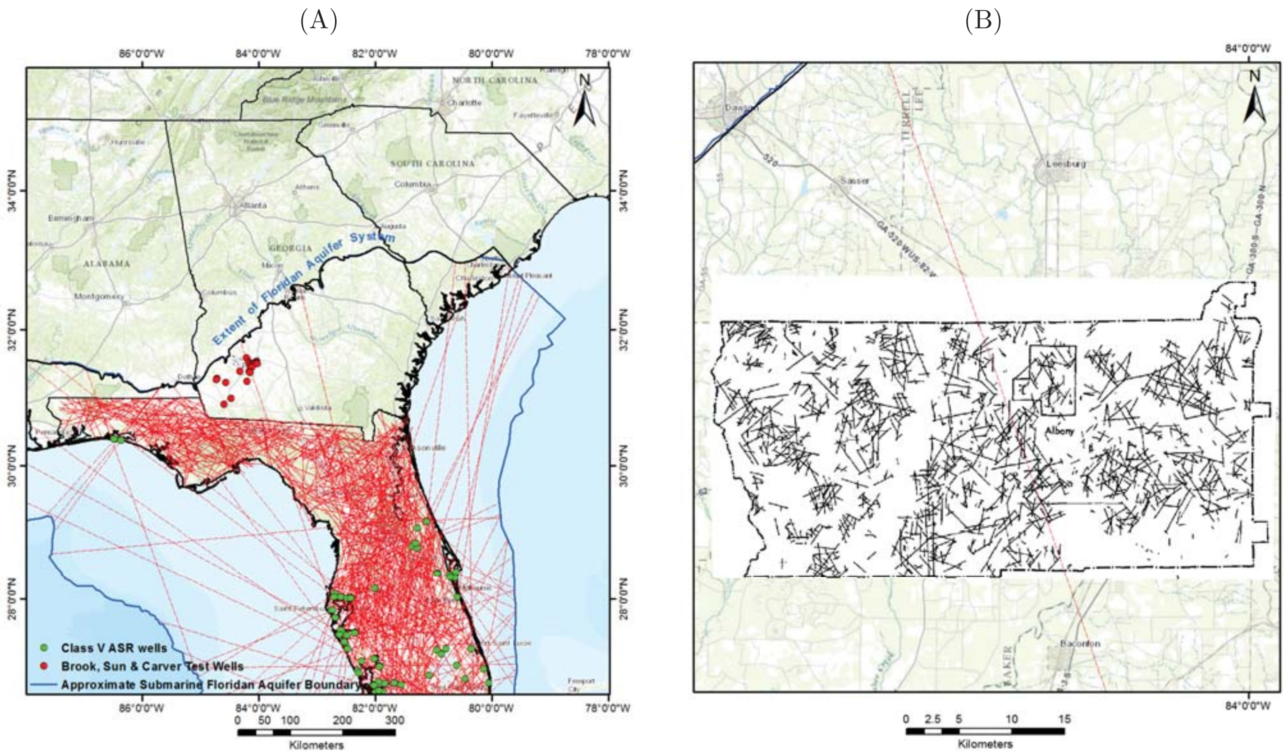

Figure 4: Locations of fractures mapped in Florida by FDOT (1973, solid red diagonal lines) and extensions of those fractures (dashed red diagonal lines) in proximity to: (A) the Class V ASR wells in Florida into the Atlantic Ocean and the Gulf of Mexico and the vicinity of the supply wells evaluated in southwest Georgia by Brook *et al.* (1986; 1988); and (B) fracture traces mapped by Brook and Allison (1986, bold black diagonal lines) in Dougherty County, southwest Georgia.

Additionally, expensive field analyses, such as tracer and isotopic analyses, is required to determine what percent, if any, of the water withdrawn from ASR wells is the same water that was injected into the ASR wells to calibrate the groundwater models. Groundwater models with fracture-flow calibrated for actual field conditions currently are not available.

CONCLUSIONS

Artificial recharge of the Floridan aquifer system (FAS) using ASR wells resulted in actual recovery ranging from 0-17%, based on reported recovery efficiency adjusted to the chloride concentrations of water injected in ASR wells in Florida. The greatest actual recovery was less than half of the total natural recharge of the aquifer system that occurs as infiltration in areas with natural ground cover and less that deep infiltration to the aquifer in those natural areas. In fact, the actual recovery from ASR wells is comparable to or less than natural recharge that occurs in areas with 75-100% impervious (nonporous) surfaces. That natural recharge occurs at no cost to the public, including not cost for electricity to pump and pipe water from the source to the ASR injection wells, then to the area of water use. The feasibility studies alone for the two ASR well sites proposed in the southwest Georgia vicinity of the FAS would cost approximately $5 million each, if completed. Actual recovery based on adjusted chloride levels is not sufficient to conclude that the water recovered from an ASR well is the same water that was injected. Much more detailed and expensive analyses, such as tracer and isotopic analyses, is required to determine what percent, if any, of the water withdrawn from ASR wells is the same water that was injected into the ASR wells. Many of the ASR wells in Florida are in the vicinity of fractures and fracture networks. This suggests that water injected into ASR wells will move rapidly through these fractures as preferential flow and discharge into surface waters similar to sewage effluent injected into disposal wells in south Florida at comparable depths and aquifer zones to those used for ASR wells. This may be a contributing factor in the abandonment of at least 32 ASR wells in Florida, particularly considering that during recovery pumping ASR wells can pull saline water laterally, from the coast through those fractures, as well as result in up-coning of saline water from lower zones of the aquifer system. This also suggests that contaminants such as arsenic that is mobilized by ASR injections also will flow through those fractures for considerable distances from the ASR wells. Although fractures have been mapped extensively throughout the state of Florida and fractures are known to occur in the Georgia portion of the FAS, similar fracture mapping has not occurred in that portion of the FAS. If ASR wells are going to proceed in Georgia, mapped fracture networks throughout the extent of the FAS in Georgia should be a prerequisite, with tracer test and isotopic analysis of native groundwater in the injection zone and water injected into and withdrawn from the ASR wells and groundwater models need to incorporate the locations of those fractures to evaluate preferential flow.

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