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Thermoelectric Power Plant Water Demands Using Alternative Water Supplies: Power Demand Options in Regions of Water Stress and Future Carbon Management

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Prepared By
Peter H. Kobos, Earth Systems; Jim L. Krumhansl, Geochemistry; Thomas A. Dewers, Geomechanics; Geoffrey T. Klise, Earth Systems; Brian P. Dwyer, Geotechnology and Engineering; Vincent C. Tidwell, Earth Systems; Richard Kottenstette, International Chemical Threat Reduction; and David J. Borns, Geotechnology and Engineering

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0735

Andrea McNemar
National Energy Technology Laboratory

NETL Contact:

Andrea McNemar
Project Manager

National Energy Technology Laboratory
www.netl.doe.gov

Abstract

Throughout the United States, many sizable saline formations may have the potential to hold carbon dioxide (CO_2), a capability that could be used to manage CO_2 emissions from power plants. This analysis examined the southeastern U.S. to determine where saline formations exist that could be used both to hold CO_2, as well as to provide saline waters for treatment to develop a coupled-use system to extract the water, treat it, and then use it to help with power plant cooling efforts. While this is a high-level study, the results indicate that limited saline formation/well data restricted the ability to adequately assess many regions of the southeastern U.S. In Texas, however, the Carrizo-Wilcox system met the size, location, depth, and other criteria to potentially host a coupled CO_2 sequestration system along with water extraction and treatment for use. Using the analytical framework applied in this analysis, other regions of the country and site-specific test cases may benefit from the insight provided by a coupled-use (or similar) system to increase the value of CO_2 storage to meet growing regional water stress on the surface.

Acknowledgements

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Acronyms and Abbreviations

$	dollars (United States)
°C	degrees Celsius
BWRO	brackish water reverse osmosis
CBM	coal bed methane
CCS	carbon capture and storage
CO_2	carbon dioxide
DOE	Department of Energy
eGRID	Emissions & Generation Resource Integrated Database
EPA	Environmental Protection Agency
Fm	formation
ft	feet
ft^3	cubic feet
g	grams
GAM	Groundwater Availability Model
g/cm^3	grams per cubic centimeter
gpm	gallons per minute
H_2O	water
GW	Groundwater
HERO™	high-efficiency reverse osmosis
IGCC	integrated gasification combined cycle
JTU	Jackson Turbidity Unit
kg/s	kilograms per second
km	kilometers
kWh	kilowatt-hours
m	meters
m^2	square meters
m^3	cubic meters
Mg	magnesium
MGD	millions of gallons per day
MGY	millions of gallons per year
mi	miles
MPa	megapascals
MW	megawatts
Na	sodium
NATCARB	Distributed National Carbon Sequestration Database and Geographical Information System
NETL	National Energy Technology Laboratory
O&M	Operational and maintenance
P	pressure
Pa	pascals
PC	pulverized coal
ppm	parts per million
RO	Reverse osmosis
s	seconds
SECARB	Southeast Regional Carbon Sequestration Partnership

SNL	Sandia National Laboratories
SDWA	Safe Drinking Water Act
s.u.	Standard Units
TCF	trillion cubic feet
TDS	total dissolved solids
TWDB	Texas Water Development Board
µS/cm	microSiemens per centimeter
U.S.	United States
USBR	United States Bureau of Reclamation
WECS	Water, Energy, and Carbon Sequestration
yr	years

1. Introduction

Expanding power demands across the country may face increasingly restrictive water supplies and environmental considerations in certain regions, including carbon management in the coming decades. Capitalizing on previously untapped sources of water, possibly unsuitable for potable demands may relieve growing concerns with water, environmental, and other constraints on power demand growth. Produced waters, nonpotable groundwater, and previously underutilized waters provided by local municipalities (already being used in some parts of the country) may prove an increasingly valuable resource. Regions of the country, especially in the west and southwestern United States, will likely see an increase in demand for lower-quality waters in an effort to save higher-quality waters for more valuable uses such as meeting agriculture, commercial, and residential demand. At the same time, other regions, such as the southeastern United States, may see increasing pressure to supply power for a growing regional economy.

A better regional understanding is needed of power plant water needs, suitability for existing and new water treatment and power plant cooling technologies, and regional power demand growth with an eye on a possible future with carbon dioxide constraints. With this better understanding, several technological, policy, and water resource management questions can be addressed when planning for sustained (or growing) power plant water demands. Of paramount importance within this project is to identify where potential value may be added to meet water stress issues and enhance the sustainability of economical power supplies. Figure 1-1 illustrates the overall concept of a coupled CO_2 sequestration system, with an extracted and treated water system as described in Kobos et al. (2009).

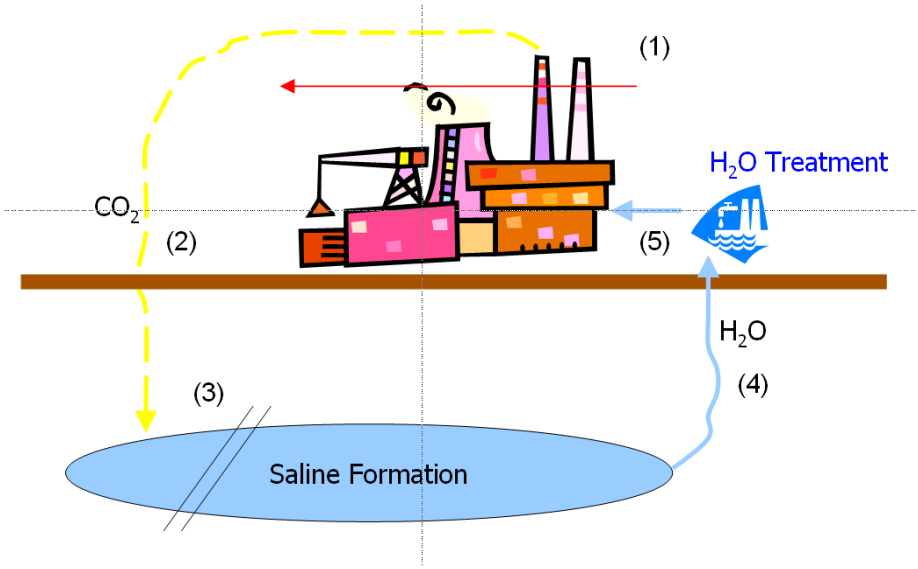

Figure 1-1: Coupled Carbon Dioxide Sequestration and Water Extraction and Treatment Conceptual Model Framework.

(1) Power Plant Metrics, (2) Carbon Sequestration System, (3) Saline Formation Geochemical and Geomodeling Assessment, (4) Water Extraction Analysis, (5) Water Treatment Analysis for Power Plant Cooling.

Several water treatment and desalination issues must be addressed to assess the scale of potential water supplies, their relative cost (e.g., if they require treatment for an appropriate use), and regional considerations. One is to address the scale of nontraditional water supply availability in different regions of the country relative to the power plant demands. Coal, nuclear, and other large-scale power plants require sustained, low-cost supplies of water for cooling. There may be, however, an equally high demand for additional water supplies from competing uses. Therefore, there may be a trend to site new (and replacement) power plants near sustainable water supplies that have less demand upon them such as existing, produced, or treated municipal water supplies. The economics of using these water resources for thermoelectric cooling potential in regions of the country with sizable supplies of otherwise underutilized waters should be assessed.

Additionally, several issues must be addressed regarding current and future power demand throughout the country. While there may be a regulatory drive to expand power supplies near existing power plants, some sites may be more suitable than others because of other factors. Of paramount importance will be the sustainability of water supplies, with consideration given to the full system's environmental issues. Water from geological saline formations, for example, will likely require some treatment prior to using it to cool power plants, but at an economic premium. Produced waters from fossil fuel production (e.g., coal-bed methane, mine pool waters, etc.) represent another source of potential cooling water. These sources, however, may prove challenging to fully characterize with respect to their overall size, uniformity of quality, potential environmental impacts, and thus long-term suitability as a sustainable resource for cooling water. Municipal waters previously underutilized, however, may also prove to be a unique source of cooling water.

This project systematically addresses each of these factors to determine (1) the applicability of the assessment framework to answer whether nontraditional water sources can be utilized for power plant cooling at the relative size and time scales necessary to provide an economical solution to constrained water supplies and (2) the identification of where market- and science-based solutions may offer relief to power plant demand that may be constrained by traditional water availability in certain regions of the U.S. by using water from geological saline formations. This will get to the very heart of the Energy-Water Nexus: how can power demand continue at current or increased levels while accounting for increasing water stress across many regions of the country?

The analysis addresses several central issues:

1. Down-select to areas within the southeastern U.S. to dovetail with potential pilot projects for carbon sequestration within National Energy Technology Laboratory's (NETL's) Southeast Regional Carbon Sequestration Partnership (SECARB) and additional regions of interest that are heavily reliant on coal-fired power plants to meet current and future demand loads;
2. Identify power plants in areas of interest to develop an analytical framework (e.g., a type of roadmap) to determine power demand solutions while accounting for potential increasing costs resulting from water demand stress for cooling options and potential carbon management issues;

3. Identify and characterize water treatment options for the regional ”story” of the potential water supplies while accounting for decreasing water quality (and hence increasing treatment cost) options in the face of sustained or growing demand for power plant cooling;
4. Consolidate the framework into a package of metrics, processes, and modeling aspects that may be applied to other regions of the United States to first identify the regional, and then more site-specific, aspects of water-for-energy planning.

2. Geoassessment of Saline Formations within the Southeastern United States

2.1 Geoassessment Introduction

The area of the southeastern United States considered within SECARB has recently experienced rapid growth that stressed regional resources, including assuring adequate supplies of electrical power and potable water. Increasingly, surface water resources are allocated to community water needs. Economic growth often comes with an increased demand for electricity that, in turn, may require additional water for power plants under specific growth scenarios (DOE, 2006a, b, c).

Sandia National Laboratories (SNL) and NETL have undertaken a program that addresses both carbon dioxide sequestration and water supply issues. The working premise is that capturing CO_2 from power plant stack gases may become necessary, and storing CO_2 underground may be one of many carbon management options. The analysis also accounts for the fact that injecting CO_2 into a porous underground formation will likely displace saline waters in some formations that could become a valuable resource with the application of specific water treatment technologies.

The Environmental Protection Agency (EPA) is proposing new federal requirements under the Safe Drinking Water Act (SDWA) to address underground injection of CO_2 (EPA, 2008). Under these requirements, saline formations containing waters with less than 10,000 parts per million (ppm) are not to be considered for projects involving geologic CO_2 sequestration. The analysis does not consider further study on saline formations under this proposed limit, although mildly salty "brackish" waters in geological formations may be a likely source of water for the utility industry. From a water desalination and economic standpoint, the general range of saline waters under consideration range from 10,000 ppm to 35,000 ppm. Additionally, the economics of transportation and injection of CO_2 dictate that formations receiving the gas must be at least 2,500 feet (800 meters) below the surface (Allis et al., 2003, NETL, 2008a).

The first activity of the overarching analysis is to identify suitable geological formations deep enough to store CO_2 and contain saline waters for potential extraction, treatment, and use. Looking to the southeastern United States, the analysis begins by examining the area overseen by SECARB, one of NETL's partnership regions. This portion of the study reviewed these formations and determined whether potential coupled-use sites existed.

2.1.1 Geoassessment Introductory Summary

One of several aspects of the regional partnerships on carbon sequestration is to develop pilot tests of CO_2 injection processes. Thus, it was reasonable to ask if the projected pilot test sites within the SECARB region might also be amenable to analysis from the standpoint of coupled-

use applications. The initial assessment found that only one of the four sites (the Black Warrior Basin) looks promising for consideration as a coupled-use site.

A second approach towards the SECARB region was to survey the whole designated area based on data gleaned from various government publications. A compilation of potential CO_2 sequestration resources provided by the Texas Bureau of Economic Geology (Hovorka et al., 2000) was particularly helpful in this endeavor. Areas in south-central Florida (centered on Polk County; Sprinkle, 1989[1]; USGS, 1999[2]) and south-central Texas (inland ~100 miles from the Gulf coast; Texas Water Development Board, February, 2003) were identified as likely to meet the relevant water quality and depth criteria. A third promising area in southeast Georgia (Sprinkle, 1989[1]; USGS, 1999[2]) was also identified, but water quality data from this region are virtually nonexistent, which restricted further analysis.

The Black Warrior Basin, the Texas site, and the Florida site have storage capacities of 2.6×10^{11} kg of CO_2 (Pashin et al., 2003), 4.3×10^{11} m^3 and 2.6×10^{14} kg @ 100% CO_2 Occupancy(assuming that the CO_2 density is 0.6 g/cm^3), and 1.04×10^{12} m^3 and 6.2×10^{14} kg @ 100% CO_2 Occupancy (assuming that the CO_2 density is 0.6 g/cm^3), respectively. Sequestration at the Texas and Florida sites would involve the "standard" process of injecting CO_2 into a porous, brackish, water-filled sandstone. Hence, the initial storage capacity is simply based on a geometric estimate of the amounts of rock (and enclosed porosity) that meet coupled-use criteria. In the Black Warrior Basin, CO_2 is injected in conjunction with the recovery of coal bed methane. Since the methane is released as CO_2 and is absorbed (by coal), the sequestration mechanism is different from when pore waters are mechanically displaced by the CO_2. The Black Warrior Basin estimate was obtained from a study (Pashin et al., 2003) that considers such processes.

The initial findings suggest that only a small fraction of the total SECARB designated area is amenable to a coupled-use approach in the strictest sense of the concept. The study also revealed, however, that the potential coupled-use resource base would increase dramatically if a shallow (around 1,500 feet deep) formation provided the brackish water while the CO_2 was injected into a deeper (e.g., below 2,500 feet to keep the CO_2 in a supercritical state), high-salinity geological formation to extract saline waters. Technical questions still requiring resolution include the following:

1. Will CO_2 injected into a layered sequence of gently dipping rocks eventually migrate updip and reappear at the surface?
2. What fraction of the porosity of a brine-filled sandstone aquifer will the CO_2 actually displace?
3. What parameters are appropriate for evaluating the CO_2 sequestration capacity at coal bed methane sites, as compared to brine-filled sandstones. Modeling the impact of injecting CO_2 on local groundwater quality at these sites is an additional topic deserving of study.

2.2 Details of Regional Geoassessment Analysis

[1] Sprinkle (1989) illustrate this in Figure 27 of their work.
[2] USGS (1999) illustrates this in Figure 51 of their work.

The SECARB area comprises those states in the southeastern quadrant of the U.S. (Figure 2-1: lighter area—Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia plus counties in Kentucky, Texas, and West Virginia). This is a much larger area than the San Juan Basin (see Kobos et al., 2009) and contains a wider variety of geologic provinces to be evaluated. Along the western margin of the Appalachian Mountains are several basins that survived the mountain building and are filled with sediments (coal beds inter-layered with limestone, shale, and sandstone) and that are attractive CO_2 sequestration targets.

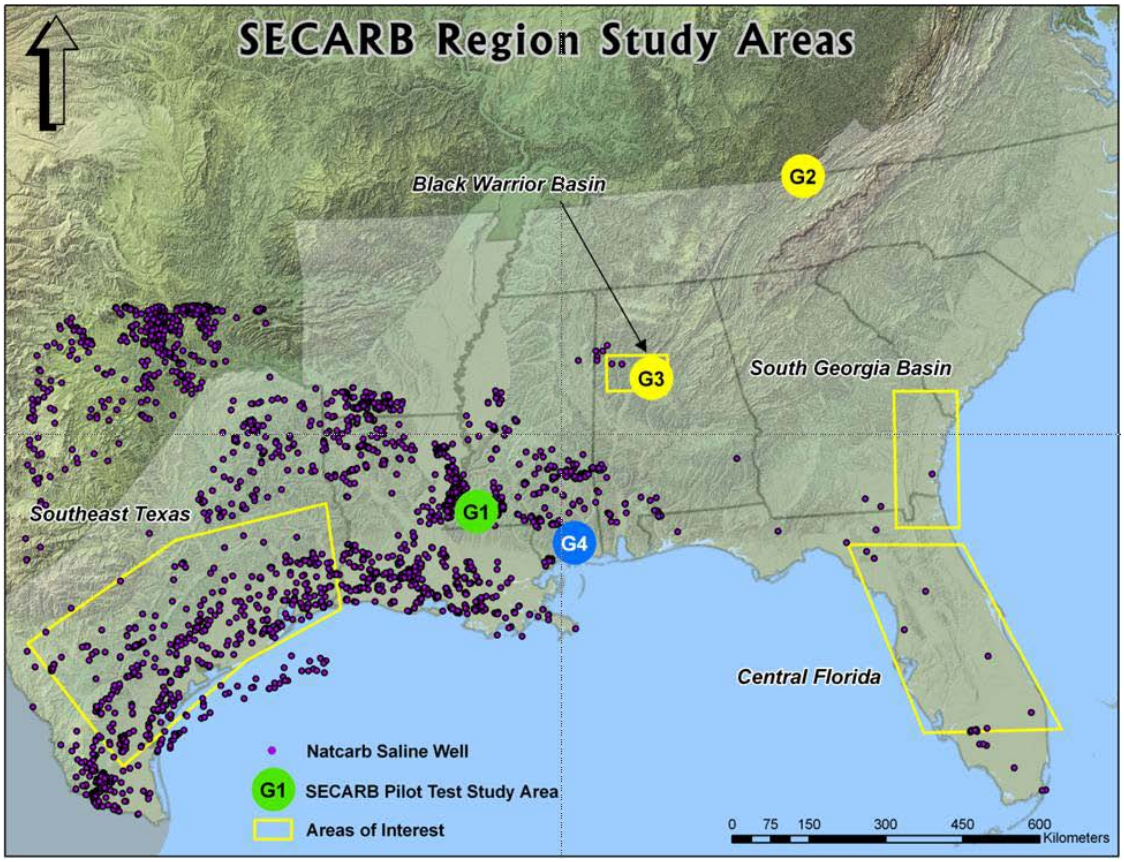

Figure 2-1: Location of Coupled-Use Formations in SECARB Region.
(Data Source: NATCARB, 2008; NETL, 2008a, 2008b. Note: Regional designation with four pilot test site locations (NETL, 2008b). Cranfield (G1, green), Central Appalachian Basin Coal Test (G2, yellow), Black Warrior Basin Coal Test (G3, yellow): Mississippi Saline Reservoir Field Test (G4, blue). Yellow Boxes locate potential coupled-use sites found during the regional survey.)

Further from the western margin of the Appalachian Mountains, a thick apron of younger sediments (principally shales, sandstones, and the occasional limestone of Cretaceous through Tertiary age) skirt the mountains from the Atlantic Coastal Plain of Virginia and the Carolinas through eastern Georgia and then extend westward into southern Alabama. Although widely distributed along the Atlantic seaboard, these sediments do not approach the thicknesses needed for our applications until one gets to southeastern Georgia. Westward (into Mississippi and eastern Louisiana), this apron merges into a massively thick wedge of sediments deposited in the Mississippi River embayment and along the margins of the Gulf Coast (Figure 2-2).

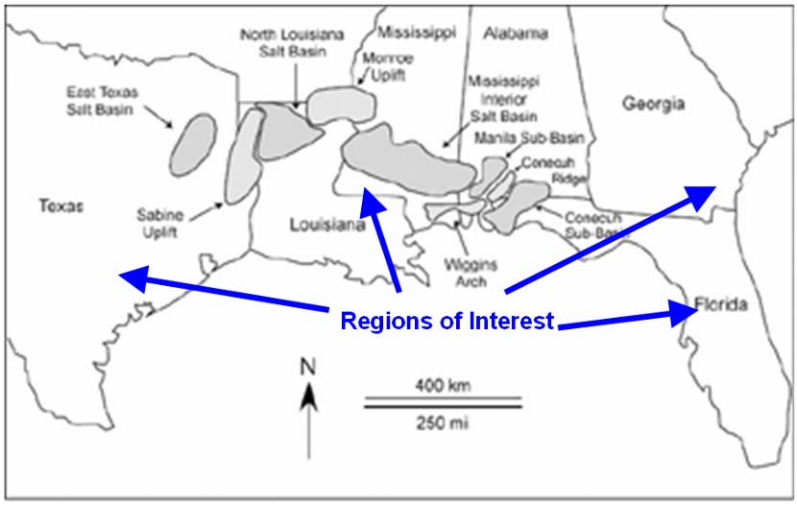

Figure 2-2: Distribution of Interior Salt Basins in Southeastern United States.
(Adapted from Mancini and Goddard 2007.)

In general, these sediments dip gently southward, and the individual units also usually thicken southward. Because of this southward dip, older rocks (of middle to late Cretaceous age) are exposed at the surface fifty or a hundred miles inland, but are deeply buried by Tertiary (and Recent) sediments along the current Gulf coastline. When the burial depth is great enough to be favorable, the shales (siltstones, mudstones, etc.) can act as migration barriers, while the more porous sandstone units become attractive reservoirs for CO_2 disposal. South of the sediment apron, in Florida, sediments washing down from the Appalachians and interior continent had less influence, and the sedimentary section contains several thousand feet of Cretaceous limestone, which may also act as sequestration reservoirs if there is an impermeable cap above them.

Particularly relevant for this study are the numerous salt domes found in a pair of broad arcs extending west from the Florida Panhandle to the border between the U.S. and Mexico (Beckman and Williamson, 1990). This reflects that throughout the Mississippi embayment and Texas Gulf Coast, the Tertiary and Cretaceous rocks sit on salt beds. Locally, these formations achieve considerable thickness in a series of "basins" extending northwest from the Florida Panhandle to northeast Texas (Figure 2-2, Mancini and Goddard, 2007). The formation of salt domes localized the occurrence of natural resources (gas, oil, and sulfur), and they provided a source of salt that has increased the salinity levels of shallow (often at depths of less than 1,500 feet) groundwaters over much of the area being surveyed in this analysis.

Because of the high salinity of the water of these geological formations, they may not meet the selection criteria for coupled CO_2 sequestration and water extraction and treatment systems. The central criteria for this coupled use are (1) assessing saline formations at depths greater than about 2,500 feet (800 meters) so as to confine the CO_2 at a density (about 0.6 gram per cubic centimeter) and (2) determining a salinity range of approximately 10,000 to 35,000 parts per million total dissolved salts (ppm – the ratio of the weight of the salts in a brine to the weight of the brine initially) so that the displaced formation waters can be desalinated economically for industrial applications. In fact, the target groundwaters would more correctly be termed "brackish water," rather than actual "brines." A further constraint is that current regulation proposals protect brackish waters with less than 10,000 ppm total dissolved solids (TDS) as

potential drinking water sources, which renders formations containing such waters ineligible as sequestration targets.

There has been much careful work by Hovorka (Hovorka 1999, Hovorka et al. 2000) showing that if salinity were not an issue, the CO_2 sequestration resource base in the SECARB region would be substantially larger. Absent, however, are surveys that assess the potential benefits of coupling underground CO_2 sequestration with extraction of the displaced brine for additional uses. Underground CO_2 injection tests are planned for these locations, and thus the modeling activities in this analysis could benefit directly from the tests planned for these sites, or vice versa.

There has been much published information that relates to regional hydrologic and geologic trends that should be applicable to more broadly identifying areas where our coupled-use approach might be applied. These resources may not, however, provide answers regarding site-specific, local hydrologic conditions. There are several explanations for this situation. First, when the levels of TDS exceed several ppm, institutions looking for potable water sources may lose interest and stop drilling. Consequently, water chemistry profiles at the depths considered in this analysis may be difficult to locate. Second, the quality of the different geologic surveys differs from state to state, as does the availably of their information resources. A final point is that the upper depth limit (where salinity is likely to be lowest) is too shallow to benefit from the large amount of information generated during (deeper) petroleum or natural gas exploration activities. Additionally, if other projects do target the shallow depths of interest to this study, it may often be at the margins of a salt dome, which may preclude finding saline formation waters with the TDS range under consideration.

An assessment of this nature is actually a two-step process. The first step involves identifying locations where the local geology and hydrology appear to be permissive for a coupled-use project (e.g., formation depth and water salinity). It may prove beneficial to future work to verify that a potential host formation is overlain by at least one impermeable bed (preferably shale or mudstone, for example, for their ability to act as an effective sealing, caprock formation). Tertiary and Cretaceous stratigraphic units found in the Mississippi embayment illustrate the interlayering of porous groundwater containing units, largely sandstones, and essentially impermeable low-porosity mudstones and shales (SECARB, 2008). Demonstrating confinement in a former natural gas reservoir may be convincing because of the history of trapping natural gas over the years (barring impacts of the wells), but for oil and brine fields, the presence of an upper confining bed needs to be explicitly demonstrated.

The second, and more involved part of the assessment process, involves estimating the capacity of a potential reservoir such that the service life of the coupled-use installation can be established. This requires much site-specific information, which is often challenging to obtain, or the coverage is not sufficient to provide a complete analysis. Thus, the resource size estimates provided are at best a preliminary result, as are the generalized brine chemistries suggested as being appropriate for these sites. Finally, this study does not attempt to model the geochemical impacts of injecting CO_2 into the identified formations, but this would be an appropriate future development to more fully assess the formations' suitability for coupled use.

2.2.1 Assessment of SECARB Field Test Sites

The SECARB regional map (see Figure 2-1) shows four sites being evaluated for their CO_2 sequestration potential. The two yellow marks labeled G2 and G3 are coal bed methane production sites where CO_2 is already being introduced to facilitate methane gas production. The green mark (G1) is at a site where oil was produced. Existing wells are to be used at this site to access lower parts of an oil-containing dome-like structure where brine has already displaced the indigenous oil. The blue mark (G4) is at an area, actually several sites close to each other, where deep, porous sandstone is naturally filled with saline water. It is worth noting that both G1 and G4 sites actually target the same rock unit, the Tuscaloosa Formation, which is a substantial regional water-bearing formation. The key element for any of these sites is their porosity, and the porosity level drives the rate of brine displacement. For the coal bed methane sites (G2 and G3), the mechanism by which coal actually absorbs carbon dioxide (while releasing methane) also greatly drives the rate of potential CO_2 sequestration injection rates. This process displaces no pore fluids; however, a great deal of brine is typically brought to the surface under standard methane production activities. The following discussion summarizes the specific SECARB sites from the perspective of a potential coupled-use application.

2.2.1.1 Cranfield Site (G1)

The Cranfield Site is located in west-central Mississippi on a partly expended oil field where a closed dome-shaped structure in the Tuscaloosa sandstone localized a cap of oil floating on brine. Withdrawal of oil has allowed the brine to move upward in the formation toward the top of the dome. According to NETL (2008b), the field test in the lower Tuscaloosa Formation in the Cranfield unit will be at a depth of 10,300 feet, where the planned injection rates may be between 100,000 and 500,000 tons per year of CO_2. As expected for a site located in an oil field, the NATCARB database provided considerable perspective on local brine chemistry (Table 2-1). The initial assessment indicates that the waters there are too saline to be desalinized economically.

Table 2-1: TDS Levels for Tuscaloosa Formation Brines Close to the G1 Site.
(Data adapted from the NATCARB (2008)).

Depth Base, feet	Depth Top, feet	Latitude, decimal degrees	Longitude, decimal degrees	Total Dissolved Solids (TDS), ppm
10286	10273	31.49	-91.45	162599
10257	10249	31.49	-91.45	147035
10705	10623	31.49	-91.03	195558
10705	10703	31.49	-91.03	206650
10258	10230	31.5	-91.49	142553
10320	10312	31.53	-91.19	153939
10362	10330	31.53	-91.18	150995
10319	10284	31.53	-91.17	171666
10366	10330	31.53	-91.16	157025
10364	10294	31.55	-91.17	159725
10552	10550	31.56	-91.01	211066

2.2.1.2 Central Appalachian Basin Coal Test (G2)

The Central Appalachian Basin Coal Test project will look to inject 1,000 tons of CO_2 into four coal seams in the Pocahontas Formation and four coal seams in the Lee Formation ranging in depth from 1,600 to 2,200 feet. The project will also include coal bed methane (CBM) recovery, whereas the main objective is to demonstrate the application of unminable coal seams to act as a safe method to store CO_2 (NETL, 2008b). For additional perspective, Nemeth (2005) provides an insightful regional overview.

A compendium provided by the EPA regarding environmental impacts of CBM production in this region is available in EPA (2003a), and a comprehensive discussion of the regional geologic setting and water quality issues can be found in EPA (2003b). Unfortunately, much of the reported water-quality information does not include well depths and offers limited insight in the assessment of water-quality information below the 2,500 foot deep criterion. Milici (2004) provides a good discussion of CBM in the Central Appalachian Basin and some general depth information on coal beds of interest to this analysis (Table 2-2) (the Pocahontas coal seam entries are of particular interest). Note that, as indicated in the SECARB site description (NETL, 2008b), the target formation appears to be present at depths too shallow to meet our minimum 2,500 foot depth criterion.

Table 2-2: Methane in Coal.
Depth of Methane Containing Coals in Virginia and West Virginia
(Source: DOE, 2003).

Coal Bed	County	Depth (feet)	CH_4 (SCF/ton)
Jawbone	Dickenson	678	278.3
Jawbone	Dickenson	680	278.3
Jawbone	Dickenson	431	281.5
Jawbone	Dickenson	431	156.8
Pocahontas	Buchanan	1,430	435.1
Pocahontas	Buchanan	1,518	463.9
Pocahontas	Buchanan	2,143	339.1
Pocahontas	Buchanan	1,737	348.7
Pocahontas	Buchanan	1,845	351.9

This location is the one of the four initially listed in the SECARB region with the least information on local groundwater chemistry. However, the NATCARB database offers well location information relating to the Pocahontas formation in West Virginia (with two entries for Kentucky). Figure 2-3 represents water quality in the Pocahontas Formation over much of southwestern West Virginia, while Figure 2-4 abstracts the data for just the counties specifically selected for Phase II SECARB study sites. Two conclusions can be reached from this evaluation: (1) from a *data analysis perspective*, based on the West Virginia data, the water quality (at relevant depths) in these formations will likely be too saline for the purposes of the coupled-use treatment and (2) the *modeling approach* in this analysis will not be able to be effectively applied because it was unable to quantify the *size of the resource*.

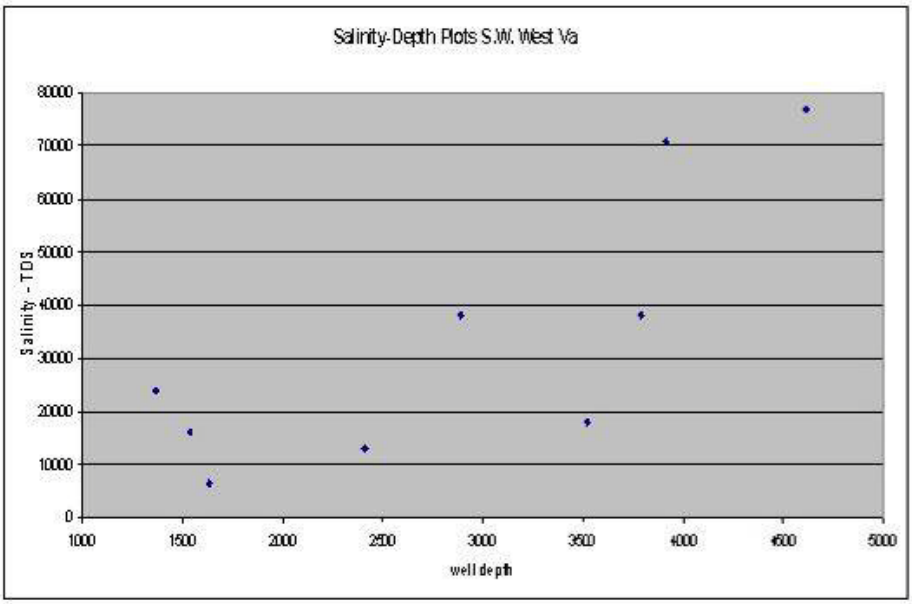

Figure 2-3: Water Chemistry in Wells in SECARB G2 Area of West Virginia.
(Note: Data from the NATCARB (2008) database, which had no well listings in the designated parts of either Kentucky or Virginia, well depth in feet).

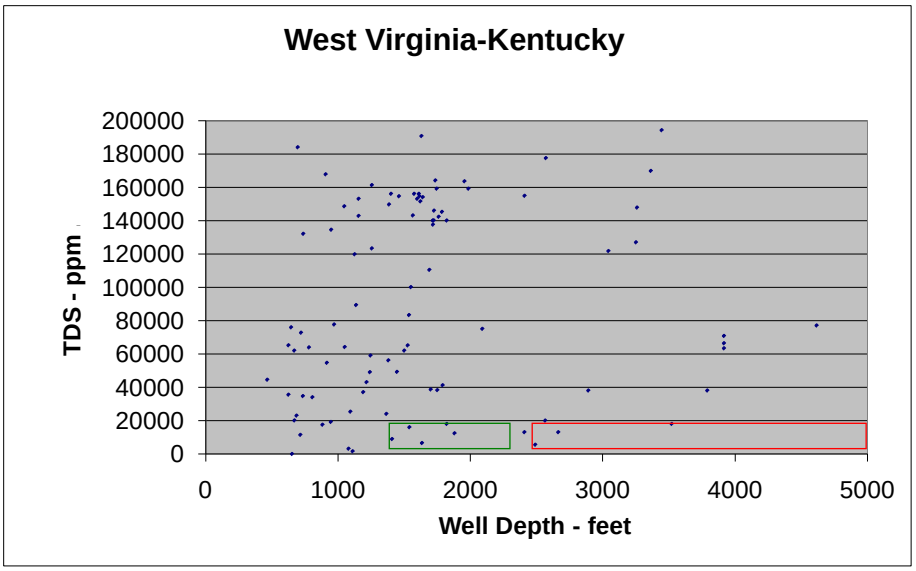

Figure 2-4: Broad Survey of Well Water Chemistry from Southwestern West Virginia and Eastern Kentucky.

(Note: There were only two wells in eastern Kentucky; data from the NATCARB (2008) database. Red box outlines conditions defined in our search for coupled-use sites; green box shows CO_2 injection parameters for coal bed methane sites as presented in NETL, 2008b.)

2.2.1.3 Black Warrior Basin Coal Test (G3)

The core objectives of the Black Warrior test are to assess CBM reservoirs for their ability to sequester CO_2, while at the same time looking to determine the injectivity rates possible within this region. The test will take place in three coal seams with an injection of 1,000 tons of CO_2 at a depth of approximately 1,500 to 2,500 feet below the surface (NETL, 2008b).

For this analysis, the Black Warrior Basin is a much more attractive candidate than the G2 site because of the substantial database already developed, which includes local groundwater chemistry and the CO_2 sequestration potential of the basin. Additionally, it is also a much larger feature than the G2 site (formally, the basin extends westward from central Alabama into eastern Mississippi). Murrie et al. (1976) provides a good regional overview of the regional geology, and Ortiz et al. (1993), Pashin et al. (1991), Pashin and Hinkle (1997), Pashin and Payton (2005), and EPA (2004) also provide additional context to the regional issues. The basin has a complex structure, and not all the coal seams are at sufficient depth to make them attractive CO_2 sequestration targets. However, there are many coal seams, and it is often reported that good quality water may be encountered while producing methane (EPA, 2004).

There are regional differences in water quality in the basin that can be explained by the fact that in the southwest the coal lies beneath a cover of Cretaceous sands and shales, while in the northeast, the aquifer is “unconfined” (e.g., communicates readily with the surface). In the unconfined portion of the formation, fresh surface waters discharge into the aquifer where the up-turned edges of the coal beds reach the surface. This hydrologic head, in turn, forces relatively low TDS ($NaHCO_3$-rich) waters to considerable depths (Pashin, 2007; EPA, 2004). In this setting, CO_2 sequestration might be somewhat problematic as the system would have to rely

on the chemical affinity between coal and carbon dioxide to trap injected gas because there is no overlying impermeable barrier to confine the CO_2.

An additional complication is that the overall TDS level may actually be so low, even below 2,500 feet, that groundwater could be considered as a potential drinking water source (less than 10,000 mg/kg TDS), and by the constraints on this analysis proposed by the EPA (2008), is potentially unavailable for CO_2 storage. In the southwestern part of the Black Warrior Basin, however, the older coal beds (Upper Pottsville Formation of Pennsylvanian age at around 300 million years old) are covered by a cap of younger Cretaceous sands and clays. Predictably, the salinity of the groundwaters rises to levels apparently in excess of 30,000 ppm in places, and NaCl becomes the dominant solute (Table 2-3) (Pashin, 2007; O'Neil et al., 1992).

To summarize, considering both depth and TDS constraints leads to the conclusion that the Black Warrior Basin would be a viable site to explore coupled-use models, but only in the southwest (and deepest) part of the basin. This area is only a small fraction of the whole basin, roughly an area 25 miles long by 10 miles wide, and it may also have the highest-salinity waters. It is also noteworthy that this part of the basin has seen little development activity, which may either mean that it is a resource waiting to be exploited or that access would be more difficult or expensive than for the shallower potential CBM locations in other parts of the basin. Finally, as with the G2 site, there is a clear need to clarify some of the criteria for site selection when CBM properties are the target, since much useful ground might otherwise be excluded based on an inappropriate depth criterion (compare red and green boxes in Figure 2-4).

Table 2-3: Comparison of Water Quality in the Two Parts of Black Warrior Basin.
(Adapted from: O'Neil et al., 1992)

Parameter	Units	Produced Water-Southwest	Produced Water-Northeast
Specific Conductance	µS/cm	27,600–33,800	3,000–6,900
Turbidity	JTU	2–10	0–20
Dissolved Oxygen	ppm	4.2–9.8	1.4–8.2
Hardness	ppm	1,700–2,700	35–130
Nitrate as N	ppm	0–8.6	0–1.2
Ammonia as N	ppm	4.4–7.4	0–0.61
Phosphate as PO_4	ppm	0–4.6	–
TDS	ppm	16,700–21,200	1,900–4,300
BOD	ppm	<1.0–61	–
pH	s.u.	7.7–8.0	7.3–8.5
Bicarbonate	ppm	170–380	670–810
Carbonate	ppm	0	0–74
Calcium	ppm	460–740	7.8–41
Magnesium,	ppm	130–200	3.4–15
Sodium	ppm	5,900–7,200	540–1,800
Potassium	ppm	6.3–20	1.9–3.3
Sulfate	ppm	ND	0–110
Chloride	ppm	9,900–13,000	480–2,000
Silica	ppm	1.9–7.2	–
Iron	µg/L	0–30	10–410
Manganese	µg/L	160–440	0–130

2.2.1.4 Saline Reservoir Field Test: Mississippi Test Site (G4)

The Mississippi test site will involve injection of 3,000 tons of CO_2 at a depth of approximately 8,600 feet into the Lower Tuscaloosa Massive Sand Unit (NETL, 2008b). This test site differs from the others in that three potential locations are being considered, spanning a length of the Gulf Coast from the Florida Panhandle west to south-central Mississippi. To cover this region, a NATCARB search (Figure 2-5) was made for wells into the Tuscaloosa Formation inside a region extending from 30.7 to 31.2 E. latitude and -87.0 to -89.0 longitude. In this region, well depth may apparently have little systematic impact on salinity, and typical brines have around 150,000 ppm TDS. This is much greater than an initial 20,000 ppm TDS upper cutoff limit that is appropriate for our coupled-use modeling approach.

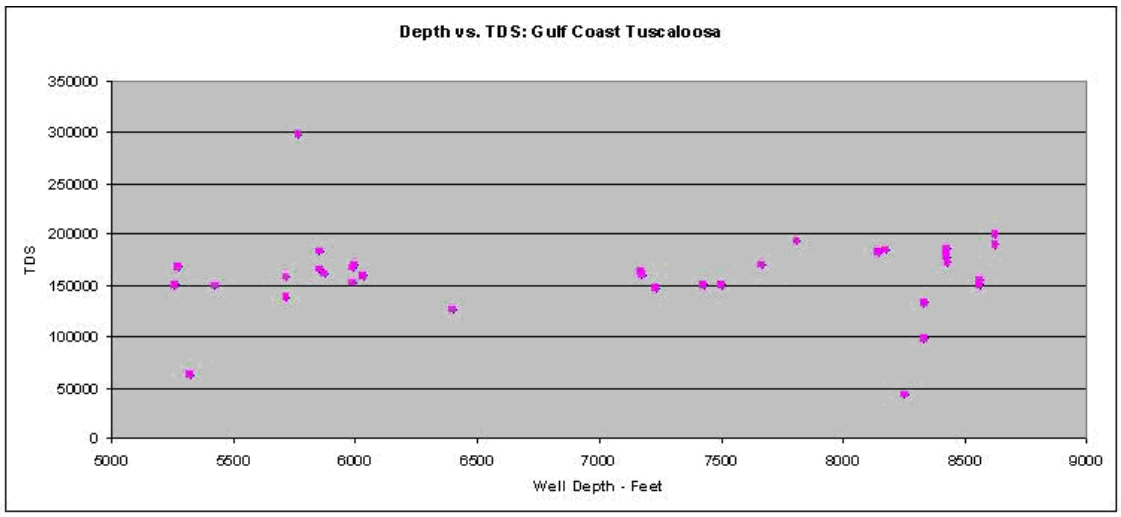

Figure 2-5: Distribution of Well Water Salinity (ppm TDS) from Tuscaloosa Formation along the Gulf Coast from Florida to Mississippi.
(Data Source: NATCARB (2008) brine chemistry database).

2.3. Regional Assessment of SECARB Brackish Water Resources

The previous section evaluated the four SECARB pilot test sites for coupled-use applications because of their potential for establishing informative interfaces with other CO_2 sequestration programs. The initial evaluation only targeted four relatively small plots in an area that comprises only a portion of the entire U.S. These considerations suggested that a reasonable approach would be to broaden our search objectives. Although much of the SECARB-designated area was subsequently ruled out based on regional geologic conditions, two potential coupled-use sites were identified with relative confidence, and a third possibility was noted. The following discussion focuses on characterizing regions with positive attributes, rather than describing in detail why various areas were not chosen.

The criteria used to select (or discard) various areas were the same as those used in evaluating the four SECARB pilot sites, though a wider variety of information resources had to be accessed. In East Texas, the NatCarb (2008) database and United State Geological Survey's (USGS, 2002) produced-water databases provided the basis site evaluation. Figure 2-1 indicates that there are

other potentially interesting areas for which the NATCARB database contains no data. A second source of regional groundwater information was the USGS water resources atlas, from which many of the figures in the following discussion were taken (USGS, 1999). However, the intent of the USGS effort was to define potential drinking water resources, so the water quality cut-off limit was often just a few parts per million TDS. For this study, it was assumed that if a water source of a few ppm TDS was documented at depths near the 2,500 foot depth, then a coupled-use resource would likely be found somewhat deeper at the same location. Finally, because of the broad geographic sweep of this search, it was also occasionally necessary to fill in information gaps using site-specific public records, such as local environmental surveys for permitting waste-water injection wells and information from state geologic surveys (where available). With sparse supporting documentation in many areas, the task of assessing the size of a potential coupled-use resource and then assigning a representative water quality to the site may return highly speculative results.

Ultimately, it was possible to identify two areas (south-central Texas and inland central Florida) where a good case could be made for the presence of coupled-use formations. A third area (the South Georgia Basin) also looks promising from a depth standpoint; but no wells penetrate the relevant saline formations, so salinity remains largely uncharacterized. Searches over large areas along the Gulf Coast (west of the Florida Panhandle) and up into the Mississippi embayment proved unproductive for reasons already outlined in relation to the G1 and G4 SECARB pilot study sites. The next sections describe these three potential sites in more detail.

2.3.1 South Georgia Basin

The geology along the Carolina coast is typical of much of the Eastern seaboard within the confines of SECARB regional designation. Throughout the region, a basement of crystalline rocks (related to the formation of the Appalachian Mountains) is covered with a blanket of sediments that typically thicken eastward out under the Atlantic Ocean. Unfortunately, along most of the coast, the porous sandstones apparently do not reach a sufficient depth until far off the coast. Hence, the issue of groundwater chemistry was moot and not researched further (Smyth et al., 2007[3]).

The one exception to this generality is a feature known as the South Georgia Basin, which is actually nothing more than a down-warped part of the general thick accumulation of Tertiary-Cretaceous sediments (mixed sandstone, shale, and mudstone) that covers the Atlantic seaboard, sweeps around the southern toe of the Appalachians, continues up into the Mississippi embayment, and finally trends southwest along the Gulf Coast to beyond the Mexican border. What makes this collection of sediments more attractive than those on the Gulf Coast is that east of Alabama, the underlying salt basins are absent. Hence, no salt domes penetrate the younger strata, and the chances are greater of finding formations at depths that contain only modestly saline waters. On the coast in east Georgia, the 10,000 ppm TDS boundary appears to be around depths as great as 4,000 feet, but westward at the Alabama/Georgia border, the salinity boundary lies at a depth of just 2,500 feet and is even shallower further west (USGS, 1999). However, the initial research was unable to locate sufficient data indicating how far south of the 10,000 ppm TDS limit the 20,000–35,000 ppm TDS boundary might be or any record of water chemistry

[3] Smyth et al. (2007) illustrates this in Figures 2, 3 and 4 of their work.

from well depths in the 2,400–4,000 foot deep range. Additional insights from the USGS (1999) indicate that in the central Florida section, the mapped information also seems to confirm that sediment depths and water salinities could be conducive to coupled-use applications.

2.3.2 Central Florida (Lower Cedar Keys/Lawson Formations)

The second potential coupled-use site identified is situated in central Florida north of Lake Okeechobee. In much of central Florida, the bedrock geology determines the hydrogeology and is comprised of layers of sedimentary rocks, which tilt gently down to the south. The abundance of limestone in this stratigraphic section reflects that during Cretaceous and Tertiary times, this region was typically a shallow off-shore marine bank that largely escaped the influence of (sand and clay-rich) sediments washing off the North American continent. Thus, the dominant building block for the sediments was calcium carbonate (calcite and aragonite) shells and skeletons that subsequently turned into limestone. Limestone permeability is inherently low, but calcite readily dissolved to the point where hairline fractures widened to open channels, and very high storage capacities may be seen. At about 2,000 feet over the middle of the peninsula, at the base of the confining unit that separates the upper and lower Florida Aquifer system, there is a seawater/freshwater interface. This is defined near the boundary between Cretaceous and overlying Tertiary (Florida Aquifer) sediments (Meyer, 1989).

The main (and uppermost) regional water-bearing rock unit is the "Florida Aquifer." However, in spite of the generality of the nomenclature, the term actually refers to just the thick sequence of near-surface Tertiary rocks and not the whole section of water-containing sedimentary rocks underlying Florida. The boundary between the Tertiary Florida Aquifer and the water-bearing (Cretaceous) units beneath (e.g., the Cedar Keys Formation and Lawson Formation) is located in the middle of the Cedar Keys Formation. Thus, the Cedar Keys is confusingly referred to as being of both Tertiary and Cretaceous age. However, it is particularly important that the middle part of the Cedar Keys is relatively impermeable and likely to confine CO_2 injected into underlying (Cretaceous) formations. Hovorka et al. (2000) reports:

> Central Florida is the focus of this regional assessment because the lower Cedar Keys and Lawson Dolomites appear to contain a laterally extensive porous zone that is overlain by an anhydrite-dolomite sequence in the middle Cedar Keys Formation that is about 700 ft thick, forming an effective top seal (J. Haberfeld, Florida Department of Environmental Protection, personal communication, 2000).
>
> – Hovorka et al., 2000: p.1.

Additionally, they report that *laterally extensive porous zones* being referenced are locally called *boulder zones* and are unit cavernous intervals leached out by circulating groundwaters and locally can have very high storage capacities (Hovorka et al., 2000, p. 1). These features exist beneath the Florida Aquifer in the Lower Cretaceous Pine Key and Lawson Formations and in "Tertiary Cedar Keys and Avon Park Formations" (e.g., in the lower aquifer subdivision of the Florida system) (Hovorka et al., 2000, p. 1).

A note of caution, however, can be found in the USGS groundwater atlas (USGS, 1999: Figure 45), which indicates that boulder zones are found only south of a line trending northeast from

Fort Meyers to Cape Canaveral. It also appears that the boulder zones in the (Tertiary) Florida Aquifer system are not well enough confined to be serviceable for CO_2 sequestration:

> The Boulder Zones of the lower Floridan Aquifer are not presented in the GIS because they are generally too shallow, and the confining horizon within the middle and upper Oldsmar and lower Avon Park Formations generally has too high a leakage rate to be expected to retain gases (J. Haberfeld, Florida Department of Environmental Protection, personal communication, 2000), particularly along fracture zones**….**"
>
> – Hovorka et al., 2000: p.1.

Less is known of conditions in the aquifer immediately below the Florida Aquifer (e.g., separated from the Florida Aquifer by the middle Cedar Keys Formation), but the prognosis is guardedly optimistic as Hovorka et al. (page 1) states, "In general, however, there is currently very little information available. Nonetheless, Florida is a rapidly developing area, and the Lawson and Cedar Keys Dolomites are potential reservoirs for CO_2 sequestration."

Generally, all the water-bearing formations along the Florida coast suffer from salt-water intrusion to some degree depending on local groundwater pumping practices. This raises the TDS even at shallow depths to levels that may not be easy to desalinate. However, for some parts of inland central Florida, the situation may be more promising, but less so toward the southern end of the peninsula. Along a line from Naples to Fort Lauderdale, the salinity even in the (Tertiary) Florida Aquifer is too high to be of use at the 2,500 foot depth limit. Hovorka et al. (2000) supports this view and indicates (Figure 2-6, Table 2-4, well locations unknown) that below 1,700 feet, the water becomes more saline, which will increase the cost for treating extracted water for coupled-use applications and that the waters are typically of the sodium-chloride-sulfate type (Table 2-4).

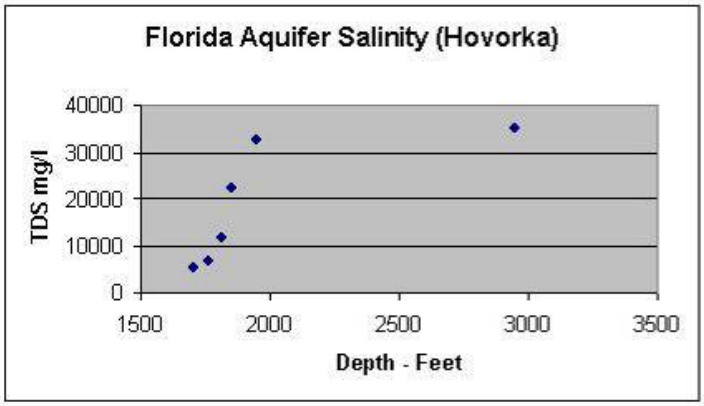

Figure 2-6: Salinity Values for Cedar Keys and Lawson Formations, South Florida.
(From Hovorka et al., 2000).

Table 2-4: Water Chemistry for Brines Recovered from the Cedar Keys and Lawson Formations, South Florida.

(Data Compiled From Hovorka et al., 2000; reference cited Vernon, R. O., 1970)

Temperature (degrees C)	Depth (meters)	TDS (ppm)	CA (ppm)	MG (ppm)	NA (ppm)	K (ppm)	HCO_3 (ppm)	SO_4 (ppm)	CL (ppm)	pH	F (ppm)	(SIO_2 (ppm)
22	1705	5690	171	218	1600	59	172	568	2950	8	1.1	11
22.2	1765	6830	203	262	1940	710	168	592	3650	7.9	1.1	10
22.2	1810	11700	276	415	3490	127	170	800	6500	7.9	1.2	10
21.7	1850	22500	405	755	6880	252	162	1440	12600	7.8	1.3	8.5
21	1950	32500	500	1200	9860	380	164	2280	18100	7.8	1.4	6.1
16	2947	35000	428	1300	10800	415	142	2660	19300	7.6	1.4	4.8

This general picture of the depth-salinity relationships in south Florida is further confirmed by Meyer et al. (1989) in an area extending south from the town of Stuart to the tip of the Florida peninsula and inland as far as Lake Okeechobee (as it relates to the Florida Aquifer system) (see Figure 2-6). Aside from the similarity between the two datasets, what is particularly interesting about the data reported by Meyer et al. (1989) is the sharp break in the salinity/depth plot again around the boundary between the upper and lower parts of the Florida Aquifer, suggesting that the two parts may be isolated from one another. This suggests that, at least locally, there may be a "cap" in the Florida Aquifer, which is not consistent with the view advanced by Hovorka et al. (2000) (see earlier quote) that the Florida Aquifer could not effectively contain CO_2. However, this is a region where the salinity in the lower aquifer is too high for a coupled-use application. As a consequence, this observation would only be useful in situations where water was withdrawn from a different (shallower) formation than that receiving any CO_2.

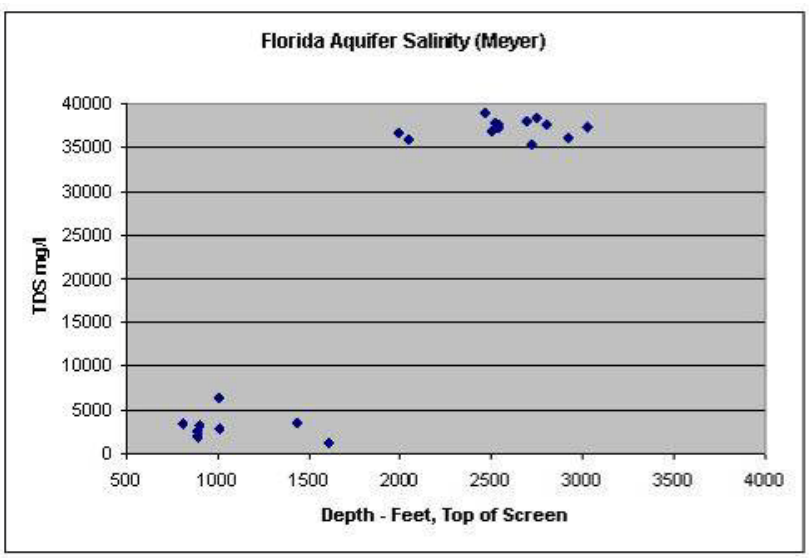

Figure 2-7: Water Chemistry in Florida Aquifer Southeast of Lake Okeechobee.

(Data Source: Meyer, F.W., 1989: Table 4)

Even higher salinities are reported for still deeper formation waters in south Florida. Meyer (1989) summarizes data on oil field brines produced from the Lower Cretaceous Sunniland Limestone (beneath the Cedar Key and Lawson dolomite) that indicate salinities in the 200,000 ppm TDS range. An additional regional analysis is provided by Hovorka et al. (2000), indicating

TDS values within the 130,000 – 150,000 ppm range. The NATCARB database indicates that wells in south-central Florida are related to pre-Cretaceous strata and also indicated TDS levels far in excess of the 35,000 ppm limit.

Maps from the USGS groundwater atlas (USGS, 1999) indicate that the base of the Florida Aquifer system remains below the 2,500 foot depth criterion until north of Polk County. Additionally, the salinity in the base of the Florida Aquifer system decreases northward to values compatible with a potential coupled-use application. Confinement issues in the Florida Aquifer still remain, but the low salinities at the bottom of the Tertiary aquifer might also indicate a similar situation beneath the confining unit in the middle of the Cedar Keys Formation.

Not much is known about the detailed hydrogeochemistry of deep water-bearing formations north of Lake Okeechobee, but a few isolated waste injection wells have been drilled in Polk County, Florida (Spechler and Kroening, 2006; O'Reilly et al., 2002; Navoy, 1986). These reports confirm that down to at least 2,300 feet, the water is still only moderately saline (Spechler and Kroening, 2006). This suggests that a possible coupled-use brine reservoir may underlie a large area of central Florida. However, issues such as the presence of an adequate upper confining bed and possible updip migration of a buoyant CO_2 plume still need to be evaluated, and more information needs to be gathered and verified about regional water quality.

2.3.3 South-Central Texas Resource

Hovorka et al., (2000) and the USGS (1999) documented the hydrologic resources in Texas to the point that it becomes apparent that the salinity of the Claiborne-Upper Wilcox Groups became an area of interest quickly. Combining the information from these sources, a potential coupled-use site may be found inland roughly 100 miles from the south Texas Coast.

Further discussion of the regional hydrology, and confirmation of a mildly brackish brine reservoir at sufficient depth, was found in documents prepared for the Texas Water Development Board (TWDB, 2003; Dutton et al., 2003; Kelley et al., 2004). The cross sections presented in a manual of brackish groundwater resources prepared for the state (TWDB, 2003) were particularly helpful in defining the extent of the brackish water resource in the Claiborne-Upper Wilcox Formations. Well data and geologic information were compiled to produce four geologic cross sections that show brackish water would be encountered at 2,500 feet. However, these sources also indicated that high-salinity water could also be encountered at a depth of just 1,000 feet. Consequently, not far southwest within this sediment package, the coupled-use resource may no longer exist. Furthermore, the presence of salt domes to the north yields shallow groundwaters below 2,500 feet that are too saline to meet coupled-use criteria.

Additionally, the USGS Produced Water Database (2002) contains many chemical analyses on waters obtained from the Wilcox and (overlying) Claiborne Groups. These data were first sorted by TDS levels. Approximately 21% of the wells in the database for this Texas formation qualified by having TDS levels between 10,000 and 35,000 ppm, as well as having depths greater than or equal to 2,500 feet. Wells that were too shallow, or for which no depth was listed, were also eliminated, leaving the tabulation of water chemistry that appears in Appendix 1: Table A1.

The data analysis showed that Wilcox-Claiborne Formation water chemistries were highly variable. This is particularly true for the proportions of chloride and bicarbonate and the presence (or absence) of sulfate. This reflects both the absence of inputs from concentrated NaCl brine sources (imposed by using an initial upper 20,000 – 35,000 ppm TDS cutoff limit) and the fact that sulfate may be consumed by bacterial action (in conjunction with organic matter) to produce bicarbonate (and sulfide, which typically is removed by forming the mineral iron pyrite, FeS_2). Hence, high-carbonate waters are also typically depleted in sulfate. This rule, however, may not be absolute, since formation waters may initially have had variable sulfate levels (reflecting, among other things, differing access to interbedded layers of gypsum in the sedimentary rocks), and encountered different amounts of organic matter relative to the amounts of sulfate initially present in the water.

2.4 Resource Size Evaluation

Three areas were identified with potential for coupled-use applications: the Carrizo-Wilcox-Claiborne brackish water-bearing formations in Texas, beneath the middle Cedar Keys Formation in central Florida, and the Black Warrior Basin. The Texas site has sufficient stratigraphic and hydrological control to allow for an initial volume estimate. In contrast, only a small amount of hydrologic and geochemical information could be found on the Florida site, so any volume estimate may be only a rough, initial estimate that would require further verification. The Black Warrior Basin is unique in that an exhaustive assessment of storage capacity has already been made, which needed only to be screened for our program-specific applications.

The Texas site (the Claiborne-Upper Wilcox hydrologic system, also referred to as the Carrizo-Wilcox system) lies in an elongated band parallel to the Gulf Coast but inland about 100 miles. The work by the USGS (1999) indicated that the length along a northeast-southwest trend for the deep, low salinity part of the saline formation is roughly 250 miles. Their work also suggested that the width of the band lying between 3000 and 10,000 ppm TDS is on the order of 15 miles. A 15 by 250 mile area equates to 3,750 square miles, and a vertical thickness for the saline formation would be at least 1,000 feet (TWDB, 2003). The porosity of the Carrizo sand is 30–40% (Pearson and White, 1967). The volume in a box 250 miles long, 15 miles wide, and 1,000 feet thick with porosity of 35% is, in total, 1.04×10^{12} cubic meters of pore space.

Somewhat better map coverage is available for the middle part of the area of interest (Dutton et al., 2003; Kelley et al., 2004), though again one has to work with contours that do not actually define the size of a region lying between 10,000 and 20,000 – 35,000 ppm TDS. In this case, the area over a linear distance of 220 miles between the 10,000 and 50,000 ppm TDS contours is approximately 3,700 square miles. Operationally, this is virtually the same area as was defined above, but it is likely that only about half would be underlain by brackish waters with less than 20,000 – 35,000 ppm TDS. Hence, there is actually a difference of a factor of roughly two in the two estimates. Part of the discrepancy arises because, with improved maps, it became evident that the width of the band of moderately brackish water swells and shrinks by a considerable factor along the trend. Thus, the 15 mile width estimate used previously may be a little too wide.

However, it is also evident that the area evaluated in the Dutton et al. (2003) and Kelley et al. (2004) studies encompasses only a part of the resource. The brackish water manual prepared for the TWDB (2003) suggests a southwest continuation into the part of Texas where the sequestration resource was originally identified based on the USGS groundwater atlas (USGS,

1999). Additional conformation of this southwest extension comes from evaluating the geographic distribution of wells from the USGS Produced Water Database (2002) (e.g., wells meeting both the depth and TDS criteria for the Wilcox Formation). Most of these wells are located along a trend leading northeast from Lavaca County toward Houston. However, there is also a cluster of qualifying wells to the southwest (e.g., in an area located inland from Corpus Christi, roughly half way to Laredo). This confirms that the size of the resource exceeds what would be inferred from the map coverage provided by Dutton et al. (2003) and Kelley et al. (2004).

In summary, the initial 15 mile band may have been somewhat wide, which was determined based on better maps of the middle part of the area that was evaluated. However, it is also evident that sequestration opportunities are available southwest of the areas considered by Dutton et al. (2003) and Kelley et al. (2004). Hence, it is likely that the original estimate of 1.04×10^{12} cubic meters is a reasonable initial measure of the size of the Carrizo-Wilcox (and Claiborne) sequestration resource. However, it is noteworthy that when CO_2 is injected into porous sandstone, not all of the brine can be displaced. When calculating the capacity, it is presumed (for consistency with other estimates) that 100% displacement could be achieved. In reality, a number much lower than this (e.g., perhaps closer to 10%) affecting the efficiency of the brine displacement process. The TWDB (2003) summarizes the finding well in the following paragraphs.

> The Carrizo-Wilcox aquifer consists of hydrologically connected, Tertiary age, interbedded sands, clays, silts, and some discontinuous lignite beds of the Wilcox Group and the overlying massive sands of the Carrizo Sand. Overlying the aquifer are the shales and clays of the Reklaw Formation in East and Central Texas, and the sands and clays of the Bigford Formation in South Texas, which serve as the confining units over the Carrizo-Wilcox. The thickness of the Carrizo-Wilcox varies widely across the state. In South Texas, saturated thickness in the outcrop is generally less than 100 feet, and in down-dip sections reaches only a maximum of 500 feet. <u>In South Central Texas, the aquifer thickens significantly, with as much as 700 feet of saturated thickness in the outcrop areas and up to 2,000 feet in down-dip portions of the aquifer</u>. In Central Texas, the aquifer thins somewhat, with outcrop saturated thickness of less than 500 feet, and thickness down-dip of 1,000 to 1,500 feet. In East Texas, saturated thickness in the outcrop is generally less than 500 feet and down-dip thickness is a maximum of 1,000 feet. Four general cross sections for the Carrizo-Wilcox are shown….
>
> Aquifer properties of the Carrizo-Wilcox aquifer vary across the state. In South Texas, transmissivities are relatively low, ranging from 5,000 to 10,000 gpd/ft. <u>In South Central and Central Texas, transmissivities are much higher, and can range from 50,000 to 150,000 gpd/ft.</u> In East Texas transmissivities are high, ranging from 30,000 to 50,000 gpd/ft. In general, the interbedded sands and clays of the Wilcox are less permeable than those of the Carrizo aquifer. Coefficients of storage for the Carrizo-Wilcox aquifer range from about 0.0001 to 0.001 in the artesian areas, and unconfined specific yields range from 0.05 to 0.30. Well yields from the more transmissive sections of the Carrizo-Wilcox can be thousands of gallons per minute. These characteristics are from the fresh sections of the

aquifer, and the aquifer is generally expected to be slightly less prolific in the down-dip areas where slightly- to moderately-saline water is found.

– TWDB, 2003, pp. 50-51.

At the Florida site (Figure 2-8), far less information is available on which to base a CO_2 sequestration capacity estimate. In fact, very little is known of the geochemistry of the lower Cedar Keys and Lawson Formation waters, but parameters relevant to estimating reservoir size have been considered by Hovorka et al. (2000). Porosities in the range of 24–28% are suggested, as is a formation thickness of 1,260 feet. However, the capacity calculations in this analysis use only a third of this thickness since, with increasing depth, it is likely that higher salinity levels will be encountered.

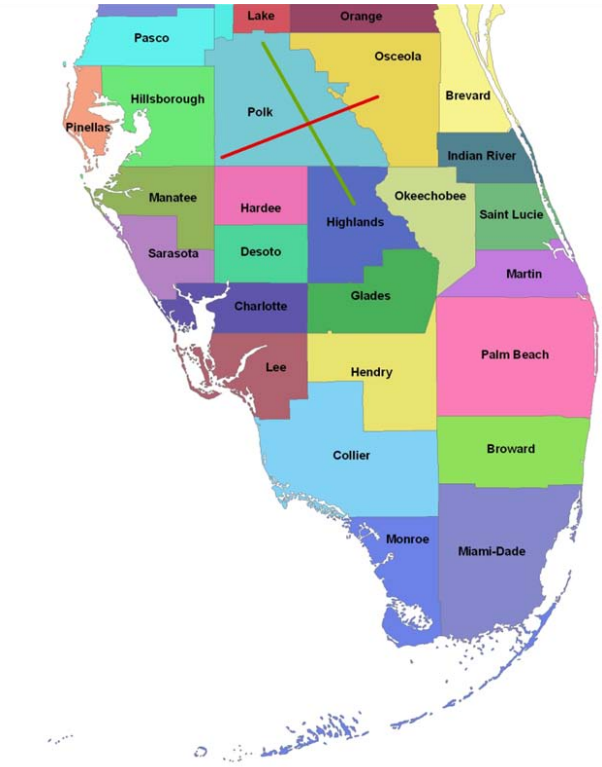

Figure 2-8: East-West and North-South Extent of Probable South-Florida CO_2 Sequestration Resource Area.

To obtain an estimate of the "north-south" extent of the area, the analysis focuses on the northern border of Polk County. The depth to the base of the Florida Aquifer system (and hence the top of the confining unit for the underlying lower Cedar keys–Lawson Aquifer) is about the minimum depth acceptable for CO_2 injection, 2,500 feet (see Figure 2-8). Further south, the formation is even deeper, meeting the depth criteria. At the relevant depths from Lake Okeechobee south (but in the Florida Aquifer in this case), the salinity may begin to reach levels considered too high for coupled-use applications, roughly 35,000 ppm TDS (Meyer, 1989: Table 4). Sprinkle (1989), however, suggests that the salinity (again in the lower Florida Aquifer) generally decreases northward to around 1,000 ppm TDS in northern Polk County, and the report presented by Spechler and Kroening (2006) seems to confirm low salinity at depth, at least in Polk County and in the lower Florida Aquifer. Hence, the initial assumption was made that the

salinity in the upper part of the underlying Cedar Keys–Lawson Aquifer might also be below approximately 20,000 ppm TDS for locations north of the middle of Highlands County, but further verification would be necessary to validate this assumption. In the "east-west" direction, the width of the box (assuming a similar correspondence between the Florida and underlying aquifer systems) would be a line extending from the eastern border to Polk County to the middle of Osceola County, again based on a reading of the salinity contours illustrated in Sprinkle (1989).

This defines a rectangular area that is roughly 60 by 80 miles. Using porosities and thicknesses discussed previously, this leads to a very preliminary reservoir pore volume calculation of 4.3 x 10^{11} cubic meters. As previously mentioned, the degree to which the brine can be displaced by CO_2 is subject to debate. In this case, however, the displacement may be larger than in the Texas example, since the solution channels formed in carbonate aquifers are typically both large and interconnected (e.g., such formations are very "transmissive").

Finally, the Black Warrior Basin illustrates a third assessment for an initial storage capacity estimate. Our earlier survey suggested that using depth criteria designed for porous sandstones resulted in only a relatively small area (a 10 by 25 mile square) being identified as suitable. However, the volume calculation methodology for CBM sites is different from that for sandstone, and fortunately, the basin as a whole has already been assessed in detail.

With this estimate in hand, the question is whether water-quality factors would substantially diminish the size of the apparent resource. In fact, water quality is relatively good throughout much of the basin, and the main concern might actually be that some fraction of the deep water might still be protected as a potential drinking water source (e.g., less than 10,000 ppm TDS currently, but 3,000 ppm TDS in the published study). For current purposes, it is likely sufficient to use the Pashin et al. (2003) report as a baseline; converting five trillion cubic feet of CO_2 (see below) translates into about 2.6 x 10^{11} kg of carbon dioxide (TCF is trillion cubic feet of gas at 60 ^{o}F and one atmosphere pressure).

> Applying the geologic screening model indicates that significant parts of the coalbed methane fairway are not accessible because of fault zones, coal mines, coal reserves, and formation water with TDS content less than 3,000 ppm. Excluding these areas leaves a sequestration potential of 60 MMst (4.7 Tcf), which is equivalent to 1.9 years of emissions. Therefore, if about 10 percent of the flue gas stream from nearby power plants is dedicated to enhanced coalbed methane recovery, a meaningful reduction of CO_2 emissions can be realized for nearly two decades. If the fresh-water restriction were removed for the purposes of CO_2 sequestration, an additional 10 MMst (0.9 Tcf) of CO_2 could feasibly be sequestered. The amount of unswept coalbed methane in the fairway is estimated to be 1.49 Tcf at a pressure of 50psi. Applying the screening model results in an accessible unswept gas resource of 0.44 Tcf. Removal of the fresh-water restriction would elevate this number to 0.57 Tcf. If a recovery factor of 80 percent can be realized, then enhanced recovery activities can result in an 18 percent expansion of coalbed methane reserves in the Black Warrior basin.
>
> – Pashin et al, 2003, p. iv.

Table 2-5 summarizes the capacity estimates described in this section.

Table 2-5: Summary of SECARB Region Coupled-Use Sequestration Capacities.

Site	Approximate Storage Capacity
Black Warrior Basin	**2.6×10^{11} kg** of CO_2 (Pashin et al., 2003)
Central Florida	4.3×10^{11} m^3 and **2.6×10^{14} kg** @ 100% CO_2 Occupancy*
S. Central Texas**	1.04×10^{12} m^3 and **6.2×10^{14} kg** @ 100% CO_2 Occupancy*

*Modeling needed to assess what fraction of the porosity is actually accessible. **The CO_2 density was assumed to be 0.6 g/cm^3. Although 100% brine displacement is used to compute metrics for the Texas site, a more conservative value for our modeling purposes would be closer to 10% of the capacity in this table.

2.5 Representative Water Chemistries

To complete the coupled-use study, it is necessary not only to assess the size of the sequestration resource, but also to define chemistries for the brine potentially being displaced by the injected gas. Given the challenging processes needed to identify the sites in the first place, it therefore proves difficult to define representative water chemistries. For the central Florida site, the regional literature (particularly O'Reilly et al., 2002, and Navoy, 1986) suggests a sharp increase in salinity near the depth relevant to CO_2 sequestration with chloride concentrations close to 10,000 ppm. Hence, the 1,850 foot depth sample from Hovorka et al. (2000) was selected to represent likely water chemistry from the Florida Aquifer. Table 2-3 contains both shallow- and deep-water chemistries for the Black Warrior Basin, and the range in water chemistries given for the deeper water is likely representative of what would actually be available for coupled-use applications. As noted earlier, the water chemistry in the Wilcox (Carrizo, Claiborne) Group is highly variable. For this reason, the analysis uses the "average chemistry" provided on the first line of data in Table 2-5 initially. Later, if important distinctions become apparent, other selections from the table can be used to address specific issues.

2.6 General Summary

The SECARB area has a complex geologic history and hence diverse hydrology. It follows that locating a suitable coupled-use site will be a challenging task. Only a few areas were determined to be preliminary candidates such that they met both the requisite criteria to hold a porous water-bearing formation while also at sufficient 2,500 foot depth. As summarized in Table 2-6, the Black Warrior Basin CBM site seemed to (marginally) meet the requisite criteria, and a broader regional analysis identified only two (perhaps three) other workable areas. The two regional potential locations with the best documentation are in central Florida and, in particular, the inland site in south-central Texas. Southeastern Georgia (the Georgia Basin) also seems promising, but there are insufficient water-quality data from this region to make a definitive recommendation.

Table 2-6: Representative Formation Water Chemistry Data.

Component	Alabama Black Warrior Basin Low TDS	Alabama Black Warrior Basin High TDS	Florida Cedar Keys/ Lawson	Texas Wilcox/ Claiborne
Sodium *	5,705	7,337	6,880	7308
Magnesium	130	200	775	68
Potassium	6.3	20	252	Not Given
Calcium	460	740	405	475
Bicarbonate	170	390	162	1066
Sulfate	Not Given	Not Given	1440	507
Chloride	9,900	13,000	12600	11310
Silica	1.9	7.2	8.5	Not Given
Iron	0	30	Not Given	Not Given
pH	7.7	8.0	7.8	7.2

*Small adjustments made to literature values for sodium to achieve exact charge balance.

Additionally, porous sandstone and limestone aquifers generally hold more promise than coal bed methane plays, since the available sequestration volumes appear to be much greater.

Beyond site-selection issues, there is also a fair amount of learning to be done regarding sequestration processes in the different rock types. In the limestone present in Florida, the porosity is likely to be in the form of large vugs and cracks, so capillary forces are not likely to impede displacing the brine with CO_2. However, finding the porous zones in limestones at depth can be quite difficult and may require advanced geophysical techniques. Just the opposite is true for porous sandstones found in Texas. The porosity of the rock is likely to be somewhat predictable throughout much of a formation, but capillary forces greatly complicate the process of modeling how much of the brine can be displaced during gas injection. For the true percent of displacement, a test case could be expected to show that the brine displaced by way of CO_2 injection is highly site and condition-specific. The percent of water recovered from the pore volume will greatly affect the engineering, economics, and overall viability of any potential coupled-use site. An additional consideration is whether reservoir sequestration capacity may be improved when water is actively pumped out of the formation. Finally, coal beds (Black Warrior Basin, Alabama) retain CO_2 by multiple mechanisms. In addition to just displacing the brine from existing pores, the coal can incorporate carbon dioxide into the molecular structure of the coal and surrounding strata. Carbon dioxide binds to indigenous methane, which is why CO_2 is already being injected in some regions to facilitate methane production (e.g., without explicitly accounting for any benefit to sequester the CO_2). This process then causes the coal to swell, which affects porosity and the gas gaining access to the bulk of the coal.

A final finding was that there may be many more coupled-use possibilities if the formation receiving the CO_2 does not have to be the same as that supplying the water for desalinization. It has been established for some time (Hovorka et al., 2000, and many others) that the CO_2 sequestration capacity of deep, high TDS, brine-filled formations along the Gulf Coast is immense. Additionally, during the search for coupled-use sites, it was common to find records indicating the presence of relatively shallow (1,000–1,500 feet deep) mildly brackish waters

sitting above the deeper high-salinity aquifers. Additional details obtained from the NATCARB database provided this analysis with additional insights into the location of potential brackish water resources in the SECARB region (see Appendix 1 for supplemental details). Hence, it may be relatively straightforward for utilities to find sites where wells of differing depths could meet both the sequestration and (brackish) water supply and CO_2 storage requirements for fossil fuel-fired power plants and other industrial sources of CO_2.

Among all of the sites examined for this geoassessment, the Black Warrior Basin and the Carrizo-Wilcox system met most of the geoassessment criteria. To complete the analysis of potential sites for coupled-used systems, Section 3 examines a preliminary geomodeling of CO_2 injection in the Carrizo-Wilcox system, and Section 4 incorporates the information developed in the initial geoassessment of the four general areas outlined in yellow boxes in Figure 2-1 within the SECARB region and adds the power plants to complete the first-round analysis of locating a candidate site for a more formal geomodeling activity. By choosing this site, the analysis will give a full start-to-finish method that can be followed to determine the geological, spatial, power plant technology, and finally geomodeling components of a full-site characterization and assessment analysis. With this example framework, future sites may be included to determine the high-level information required to formally assess their suitability as a coupled-use site for carbon sequestration and water extraction and treatment.

3. Storage Constraints for CO_2 in Sloping Formations with No Structural Closure: Carrizo-Wilcox Formations of East Texas

Abundant sedimentary wedges exist along the eastern coastal United States, associated with the Triassic-aged opening of the Atlantic Ocean and Gulf of Mexico, which could serve as storage sites for atmospheric CO_2. At relatively large depths, these formations bear saline pore (connate) waters, which could be used in the proposed coupled-use scenarios we propose for coal-fired power plants. As these formations slope gently seaward, they offer no structural "traps" for buoyant CO_2, and thus the question arises as to the fate and transport of CO_2 injected at depth. A central question to be answered is "Can sufficient CO_2 be stored in these sedimentary systems over sufficient time to avoid contact with potable water sources in more shallow aquifers by upwardly mobile carbon dioxide plumes?"

Nicot and colleagues (Nicot, 2008; Nicot et al., 2009) investigated, via single-phase modeling using MODFLOW and CMG-GEM, the influence of injection of CO_2 at industrial-scale rates on updip freshwater supplies in coastal plain aquifers. They showed minimal impact, although localized effects could exist. The limitations of the models permit no inclusion of salinity effects or dissolution of CO_2 into the brine phase, so our study is in part motivated by concerns of saline and aqueous supercritical or gas phase CO_2 intrusion on shallow groundwater aquifers. These authors also assume maximal capillary entry pressure for the overlying seal and, by design, do not allow upward migration through seal bypass systems, which most likely occurs at least to some extent in all gas reservoirs. For example, the upward vertical flow observed in the Central Carrizo-Wilcox calibrated groundwater availability model (Dutton et al., 2003) suggests some amount of upward groundwater flow in our study area. One unknown is how much upward migration of CO_2 as a supercritical phase and/or as a dissolved constituent in brines would be accommodated by this flow system.

To develop a regional scale numerical model of CO_2 injection and storage in Texas Gulf Coast Basin saline formations, we finalized an earth or geologic framework model for the Carrizo-Wilcox and Queen City Sparta saline formations and began preliminary TOUGH2 simulations of CO_2 injections. The TOUGH2 model is based on a MODFLOW model that forms part of the central Groundwater Availability Model (GAM) prepared for the TWDB by staff from INTERA, Inc., and the Texas Bureau of Economic Geology (Kelley et al., 2004). Figure 3-1 shows the grid of the central model (shown in grey) and a subset, outlined in black, in use for the TOUGH2 simulations. This model runs from the outcrop of the Carrizo-Wilcox (shown as tan strip in the north to southwest portion of the model grid) to the updip limit of the Wilcox growth fault zone (blue line running northeast to southwest), which also marks the transition from hydrostatic to geopressured regions of the Carrizo-Wilcox Group Formations. Choice of model location was also dictated by proximity to coal-fired power plants discussed later in this report. Shown as green lines are contours of salinity (as TDS in ppm) in the deeper portions of the formations. The TOUGH2 simulation scenarios initiate with CO_2 injection within this region and extraction of saline groundwater, tracking both the evolution of CO_2, groundwater salinity and fluid

pressure. The light green- yellow dots in Figure 3-1 show locations of groundwater wells in the Carrizo-Wilcox Aquifer system that will limit the extent of updip migration of CO_2 plumes in the simulations (i.e., the simulations are aimed at determining how long CO_2 can remain down-dip of the freshwater zones and if substantial CO_2 migration could take place vertically through the caprock). This assumes that injection would stop once some indication of CO_2 plume migration is detected in the groundwater wells.

The background gray grid is from the Central Carrizo-Wilcox GAM (Dutton et al., 2003); each square denotes one square mile. The blue line denotes the Wilcox Growth Fault boundary and also approximately delineates the western extent of geopressure in the Wilcox Formation. The green contours plot regions of varying salinity in the Carrizo-Wilcox updip of the overpressured region. The purple, red, blue, and yellow dots show most groundwater well locations that produce from the Carrizo-Wilcox (purple indicates wells completed in the Hooper Formation, red indicates Simsboro, blue indicates Calvert Bluff, and yellow, the Carrizo Formation wells), and the brown swath denotes the location of the Wilcox outcrop and recharge area in east Texas. Simsboro (our proposed injection target) and Reklaw (proposed regional caprock) are outlined in blue and burgundy respectively. The purple/black dots show locations of oil and gas exploration and production wells. Total dissolved solids in ppm, if available, are given next to the well locations. The large black dot shows the location of the Fayette Power Project coal-fired power plant, which outputs 11.9 M tonnes of CO_2 per year.

To properly assess the extent to which CO_2 injection influences both pressure, flow regime, and salinity changes in overlying sediments, as well as the potential for CO_2 intrusion, we have initiated both analytical and numerical investigations of CO_2 injection and storage in Carrizo-Wilcox clastic formations. In our numerical models, we use the TOUGH2 family of codes (Pruess et al., 1999; Pruess, 2005), which allow for multiphase CO_2-brine effects but do not permit (in our version) hysteresis in capillary pressure and thus are not equipped to properly address trapping of CO_2 as a residual gas phase. Appendix 2 describes most of the techniques used to model the CO_2 in the Carrizo-Wilcox Formation. The simulations provide guidance for this and future analyses as to the size of the CO_2 plume, size of the formation, and the rate of the plume's migration over time, given a set of geological and geophysical conditions. An analytical model that addresses the updip migration and retention of CO_2 by capillary trapping in sloping formations with no structural closure is given in Appendix 2. Similarly, a TOUGH2 3D numerical model of CO_2 injection and migration coupled with brine migration relevant to the geography and geology shown in Figure 3-1 is presented in Appendix 2.

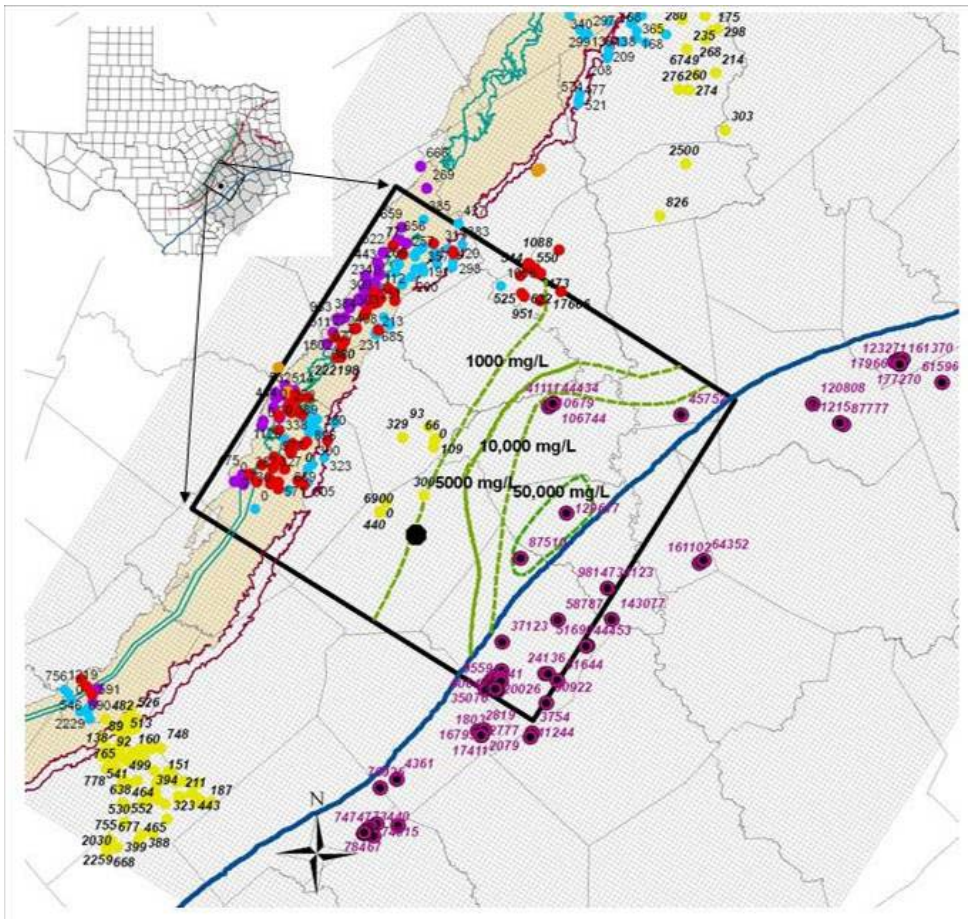

Figure 3-1: Location of TOUGH2 Simulation Domain (Black Rectangle) in Central Gulf Coast Region of East Texas.

4. Regional Analysis: Representative Power Plants and Potential Water Treatment

4.1 Spatial Analysis of Formation and Power Plant Matching

The SECARB region of the U.S. has been evaluated for characteristics promising for coupled-use for simultaneous withdrawal of groundwater for beneficial use coupled with injection replacement with CO_2. Specifically, all minor regions within the major SECARB region have been analyzed and down selected to determine their suitability as a location from a coupled carbon sequestration and saline formation water extraction perspective while accounting for the types and numbers of power plants within those regions.

To address a potential site for coupled use, locations were identified within the SECARB region containing brackish waters that could be extracted for power plant operations while simultaneously providing porous formations where CO_2 might be sequestered long-term underground. The initial assessment outlined the geological formation requirements and then identified representative power plants relatively close to those formations. The specific criteria for identifying potential coupled-use formations are as follows:

- Groundwater must be between 10,000 and 35,000 ppm TDS and
- Formation receiving the CO_2 must be greater than 2,500 feet deep (800 meters) below the surface (Allis et al., 2003, NETL 2008a).

Table 4.1 summarizes the findings regarding the coupled-use of formations for water supply and simultaneous CO_2 storage.

Table 4-1: Suitability of SECARB Pilot Test Sites for Coupled-Use Applications.

Site and Type	Depth Criteria Met?	Water Quality Considerations
G1 – Porous sandstone aquifer Cranfield	Yes	Unlikely – Formation waters are very saline
G2 – Coal bed methane Central Appalachian Basin	Yes	Unlikely – Formation waters probably very saline but very little groundwater chemistry is available for this site.
G3 – Coal bed methane Black Warrior Basin	**Partly**	**Meets criteria**
G4 – Porous sandstone aquifer, Mississippi Saline Aquifer	Yes	Unlikely – Formation waters very saline

Note: Analysis provided by Jim Krumhansl.

Figure 4-1 (a reproduction of Figure 2-1) shows an expanded view of the SECARB region with the areas highlighted in yellow boxes indicating potential coupled-use locations. It is apparent when viewing the SECARB region that much of the area lacks sufficient well data to conclusively determine coupled-use locales. Based on the available data, the yellow boxed areas are the most promising.

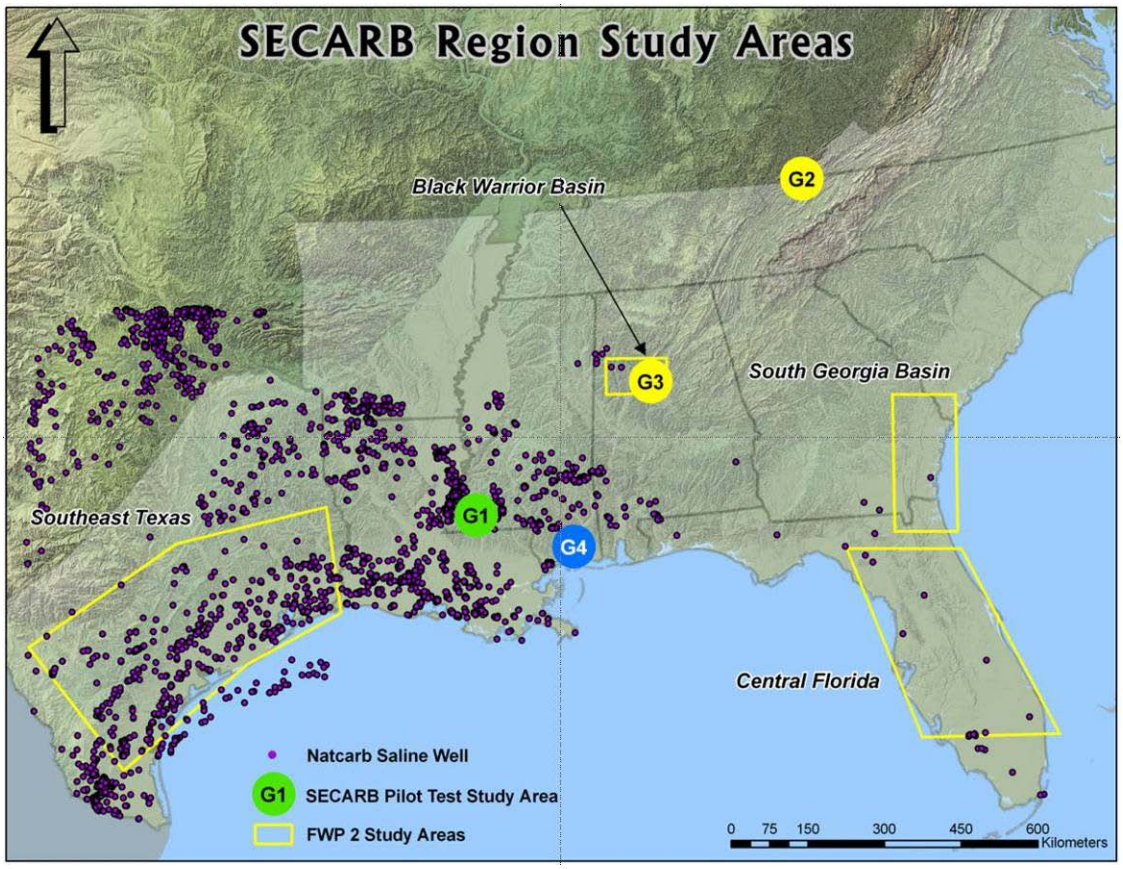

Figure 4-1: Location of Coupled-Use Formations in SECARB Region.
(Data Source: NATCARB, 2008; NETL, 2008a, 2008b.)

To further refine our study, locations of existing power plants were overlaid with the coupled-use data. Figure 4-2 shows the location of existing power plants within the SECARB region. The southeast part of Texas, the Black Warrior Basin, and a portion of Central Florida are the only locations identified in the initial geoassessment where existing power plants overlap saline formations that may be considered for potential coupled use with CO_2 sequestration. Once again, it should be noted that saline water data in the regions other than Southeast Texas and the Black Warrior Basin are quite limited.

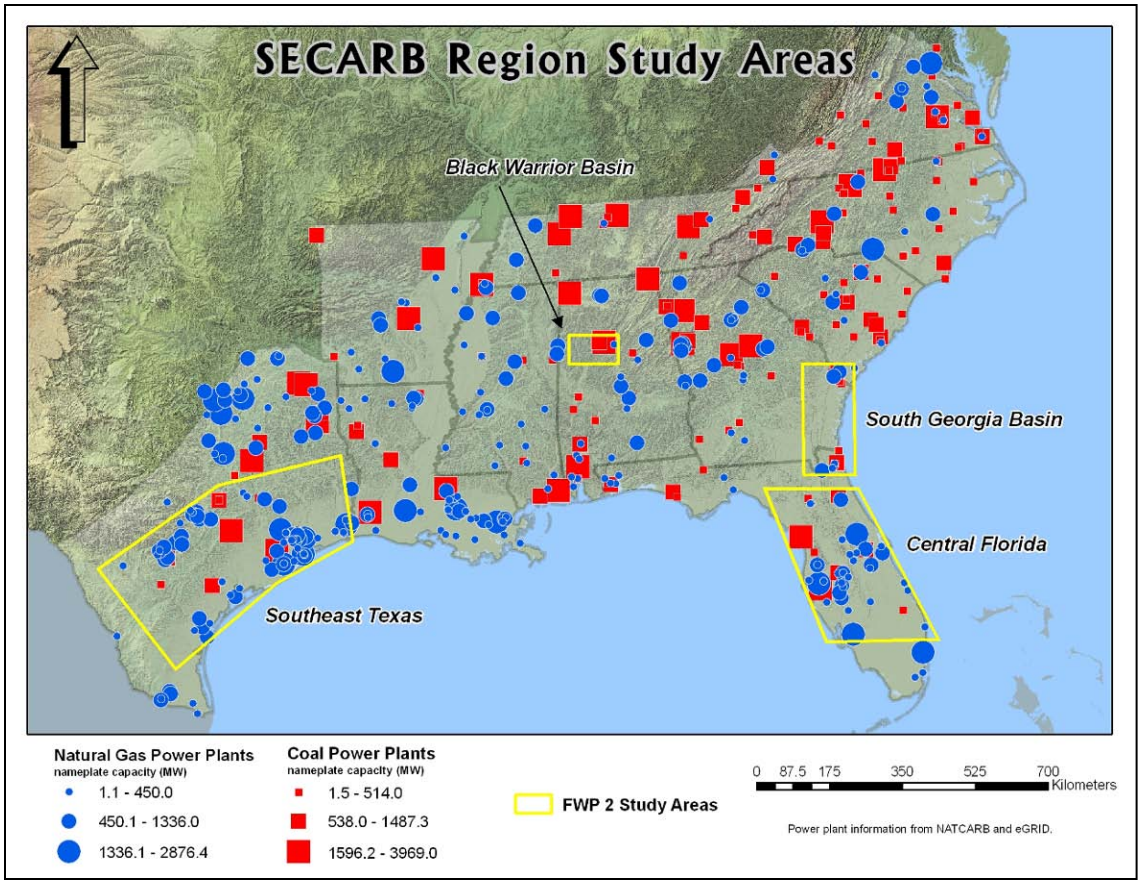

Figure 4-2: SECARB Region – Location of Existing Power Plants.

The TDS level in the Black Warrior Basin is in the range of 16,700 to 21,200 ppm, whereas the average TDS level in the southeast Texas region is 15,390 ppm. The remainder of the area is either very saline (>40,000 ppm TDS) or data are very limited and hence no conclusions can be made.

4.2 Illustrating the Geoassessment

Of the areas identified in Figure 4-2, formation water chemistry in proximity to existing power plants was analyzed in detail. Each figure shows the nameplate capacity of coal and natural gas power plants and nearby well locations with information including well depth and formation water TDS. Some of these potential areas have more wells than others, and in some locations, the wells intersect a formation at a desired depth of 2,500 ft and greater, with a water chemistry of 10,000 to 35,000 ppm TDS. Other areas may also have favorable subsurface geology with the desired depth and chemistry, but there are no wells that can be used to evaluate these formations. Therefore, the analysis is limited to those areas where existing well data were available for screening these four areas.

Within these four areas, the analysis selected the largest power plants with the highest volume of CO_2 emissions within a range of up to 60 miles from what was roughly considered a key location above the formations of interest. It is likely cost prohibitive to consider distances between a

potential formation and a power plant that is greater than 60 miles. Table 4.2 shows the power plant information obtained from the Emissions & Generation Resource Integrated Database (eGRID) (EPA, 2009). This information was used to determine the most suitable location for a coupled system with CO_2 injection and brackish water extraction and treatment.

4.2.1 Black Warrior Basin

The Black Warrior Basin map shows the outcrop locations of the Pottsville Formation, a potential saline formation for CO_2 sequestration, as well as both nearby coal- and natural-gas–fired power plants. Previous studies identified existing CBM fields with CO_2 capacity at 350 psi (Bcf), and those data are shown in Figure 4-3 with a color chart ranging from green (low capacity) to red (high capacity). Based on the water chemistry from produced water wells that terminate in the Pottsville Formation, a TDS contour estimate of 10,000 ppm is shown on the map. Figure 4-4 shows the CBM capacities with the formation overlay removed for additional clarity.

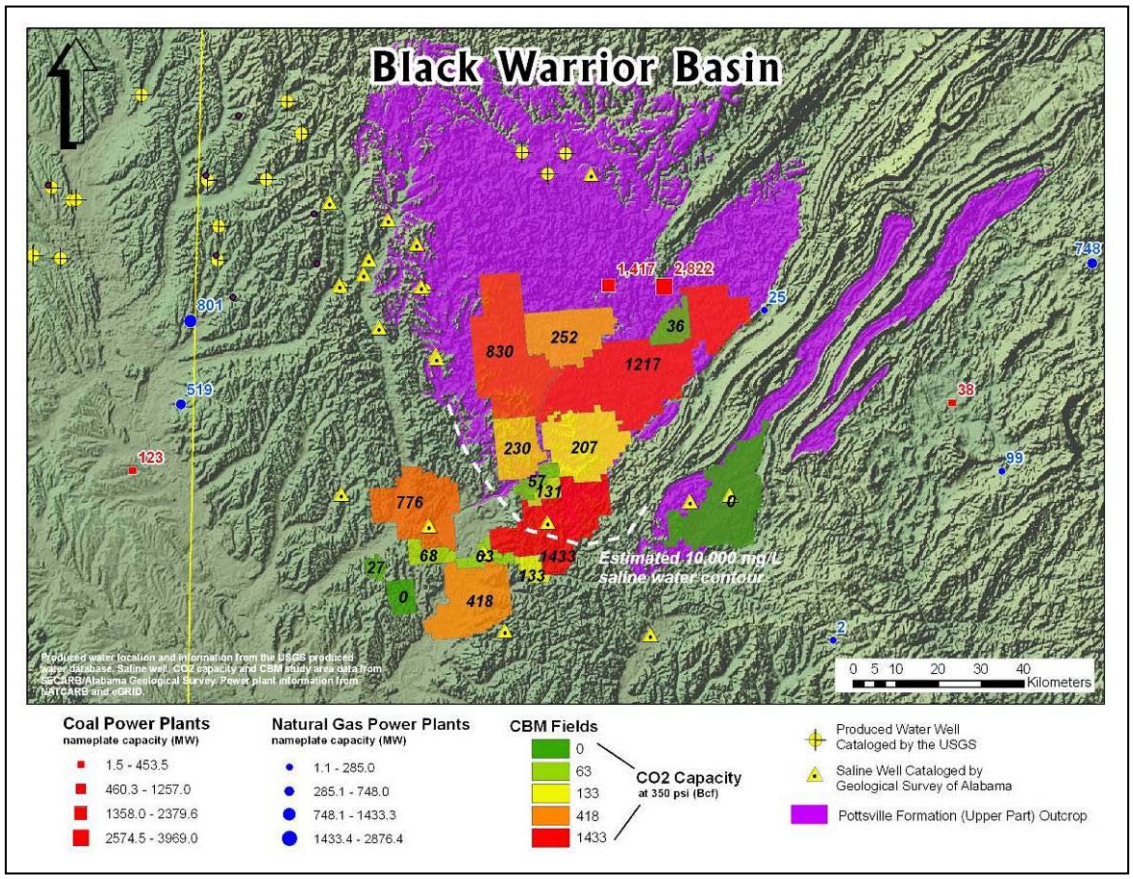

Figure 4-3: Power Plants, Produced Water Wells and CBM Fields – Black Warrior Basin.

Narrowing down the nearest power plants to the best formation leaves three power plants just north of existing CBM fields that have been previously analyzed for sequestration by the Alabama Geological Survey. Table 4-2 shows the details of each power plant as well as the distance to the center of the closest CBM field with the largest CO_2 capacity.

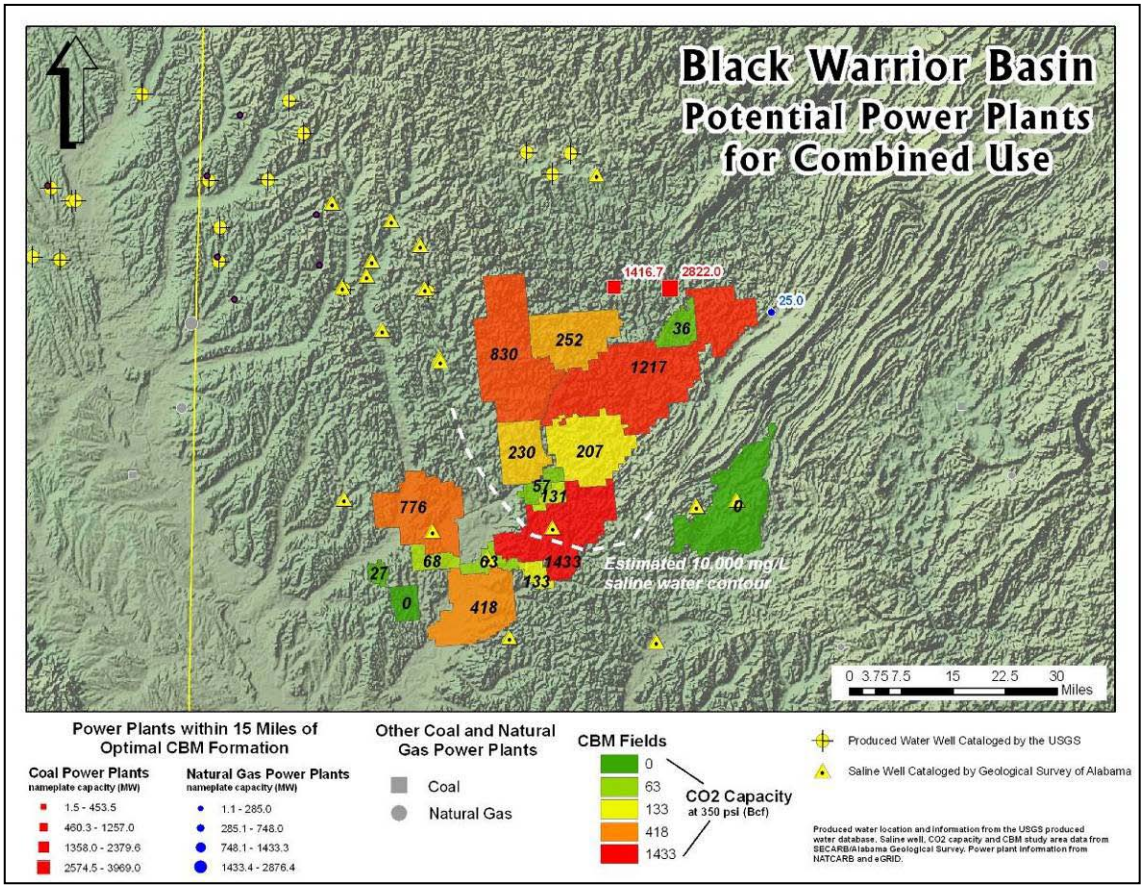

Figure 4-4: Selected Power Plants – Black Warrior Basin.

Table 4-2: Potential Power Plants near Combined-Use Formations – Black Warrior Basin.

(Office of Regulatory Information Systems Plant Location (ORISPL))

ORISPL (Plant identifier number)	Power Plant Name	Fuel Type	Capacity Factor	Nameplate Capacity (MW)	Plant Built Date	Distance to CBM field (~miles)	Notes
8	Gorgas	Coal	0.6374	1416.7	See Notes Column	15	5 generators, 1951, 1952, 1956, 1958 and 1972
6002	James H. Miller Jr.	Coal	0.8628	2882.0	See Notes Column	14	4 generators, 1978, 1985, 1989, and 1991
50359	Sloss Industries, Inc.	Coke Oven Gas	0.1863	25.0	1958	22	2 generators

4.2.2 Central Florida

Figure 4-5 is a map of Central Florida showing the location of an identified saline formation along with produced water wells, all near existing coal- and natural-gas–fired power plants. The water quality is somewhat saline with all wells above 35,000 ppm.

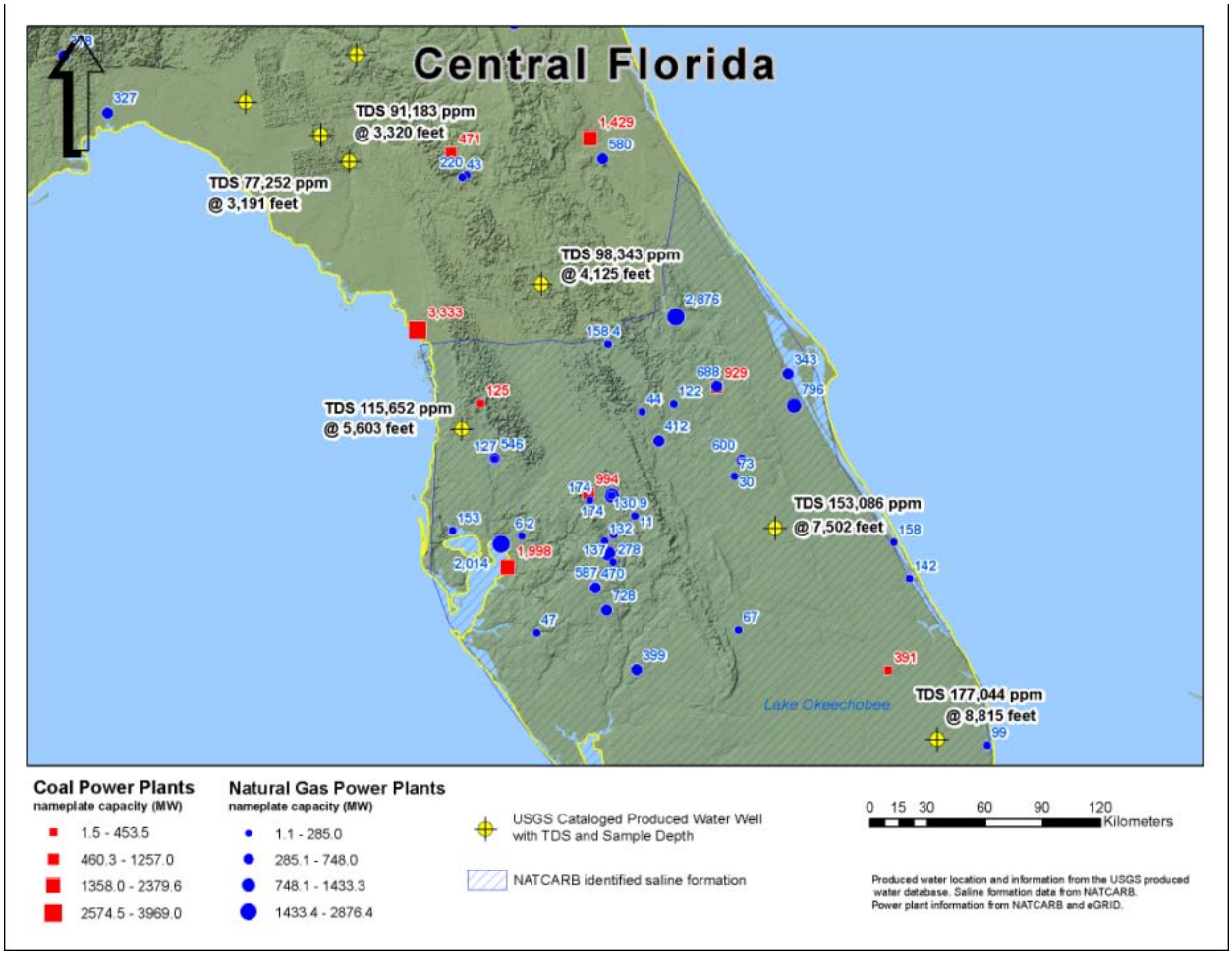

Figure 4-5: Power Plants and Produced Water Wells – Central Florida.

The area in Central Florida with an assumed saline formation that could be utilized is located on the north end of the NATCARB identified saline formation (blue hatched line in Figure 4-6). There is one coal and seven natural gas power plants located in the vicinity. Because there are no well data available in what is considered the best location geographically, a determination on whether this formation meets the coupled-use criteria cannot be made. With regard to available well data, two wells located northwest and southeast and different depths have very high TDS, which is not suitable as determined by the combined-use constraints.

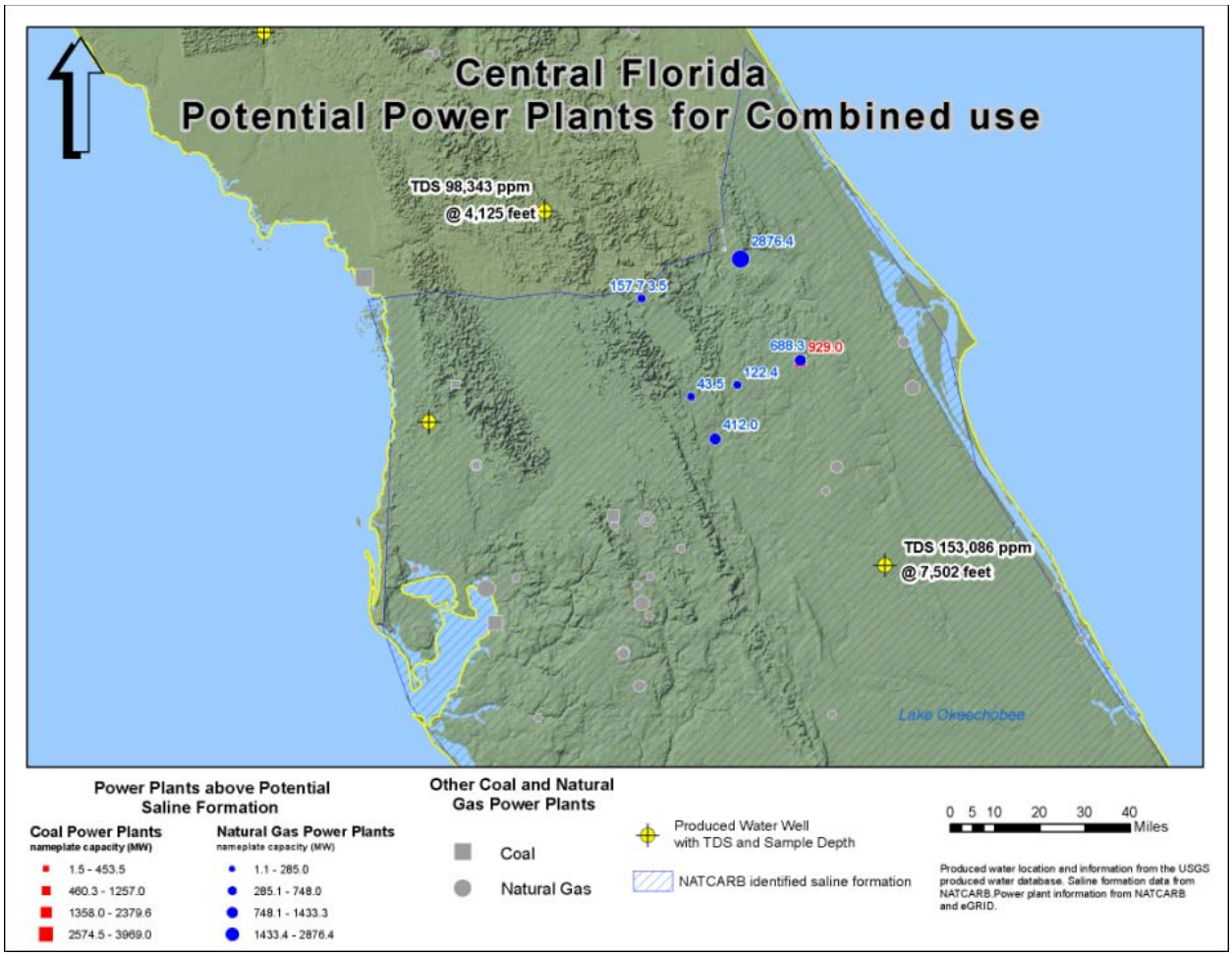

Figure 4-6: Selected Power Plants – Central Florida.

Narrowing down the nearest power plants to the best formation leaves eight power plants located in the northeast of an area identified by NATCARB as having an underlying saline formation. Table 4-3 shows the characteristics of each power plant in this area. Nearby produced water wells to the northwest and southeast have very high TDS values and may not be suitable for combined use. Wells were not identified in the area near the power plants, and therefore, desired water quality at the preferred depth is not available to evaluate.

Table 4-3: Potential Power Plants near Combined-Use Formations – Central Florida.

ORISPL	Power Plant Name	Fuel Type	Capacity Factor	Nameplate Capacity (MW)	Plant Built Date	Notes
564	Stanton Energy Center	Coal	0.7684	929.0	See Notes Column	2 generators, 1987 and 1996
54466	Orlando Cogen LP	Gas	0.8042	122.4	1993	
620	Sanford	Gas	0.5314	2876.4	See Notes Column	11 generators, 1959 (oil), 1969, 1974, 2002 (7), and 2003
7238	Cane Island	Gas	0.3906	412.0	See Notes Column	4 generators, 1994, 1995 (2), 2002 (2)
7294	Central Energy Plant	Gas	0.1920	43.5	1989	2 generators, 1987 and 1996
55821	Curtis H Stanton Energy Center	Gas	0.4621	688.3	2003	3 generators
10020	Cutrale Citrus Juices USA	Gas	0.0000	3.5	1987	
54423	Lake Cogen Ltd	Gas	0.3235	157.7	1993	3 generators

4.2.3 South Georgia Basin

Figure 4-7, the South Georgia Basin map shows produced water wells in the vicinity of existing coal- and natural gas-fired power plants. Water chemistries show a TDS and depth completed in the Tuscaloosa formation near the coast that might fit the criteria for CO_2 sequestration and saline water use. Based on a well located further west in Alabama, there appears to be a rough 20,000 ppm TDS contour that extends west to east in the southern part of Georgia (see Figure 4-7).

The South Georgia Basin has only one known produced water well that intersects a saline formation near the desired depth and TDS. The only known power plants are located south of the well in Florida. The NATCARB database identified a saline formation (blue hatched line) that extends to the Georgia/Florida state line. Six coal power plants and three natural gas power plants were identified with distances between 30 and 60 miles of the produced water well. Power plant details are presented in Table 4-4.

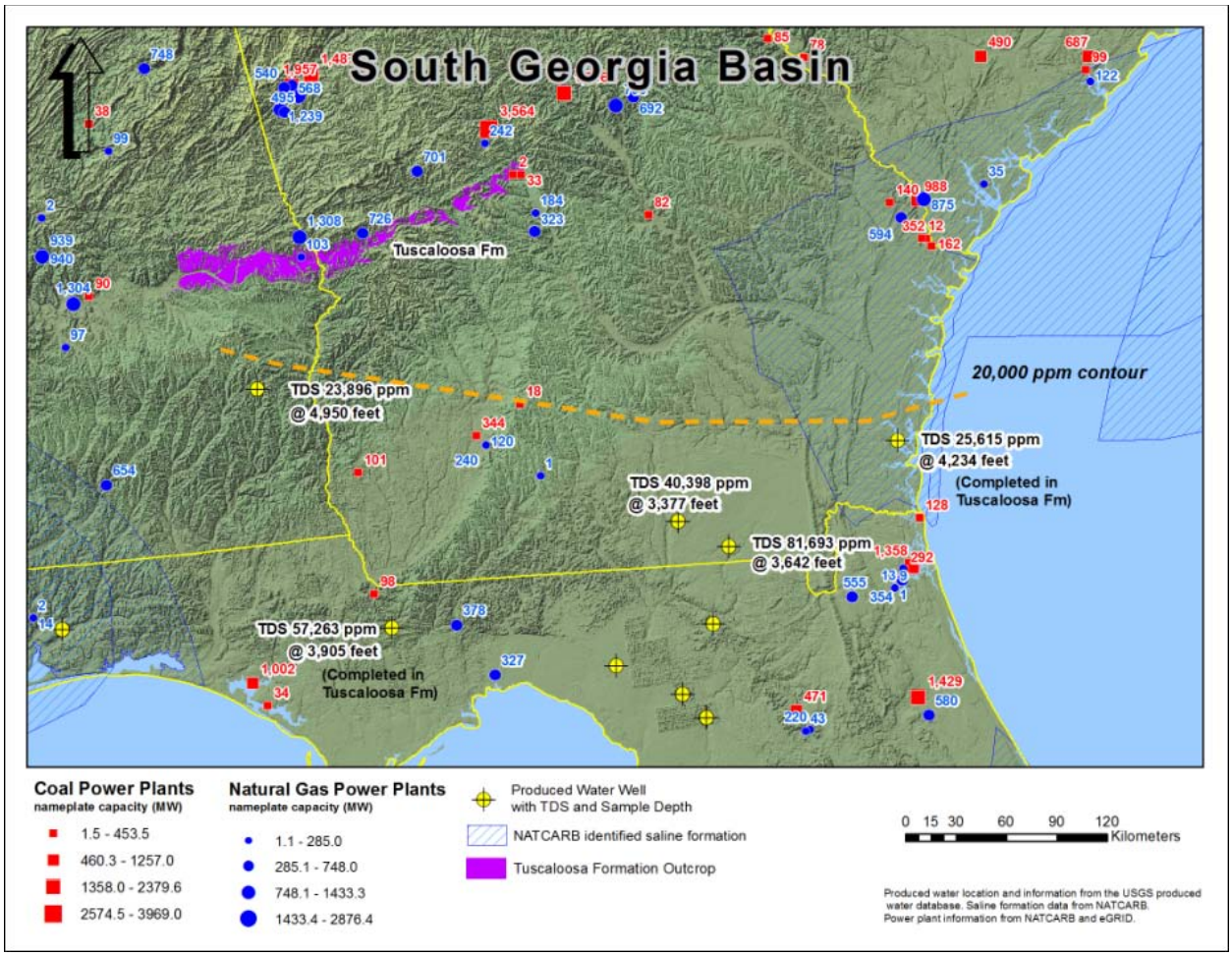

Figure 4-7: Power Plants and Produced Water Wells – South Georgia Basin.

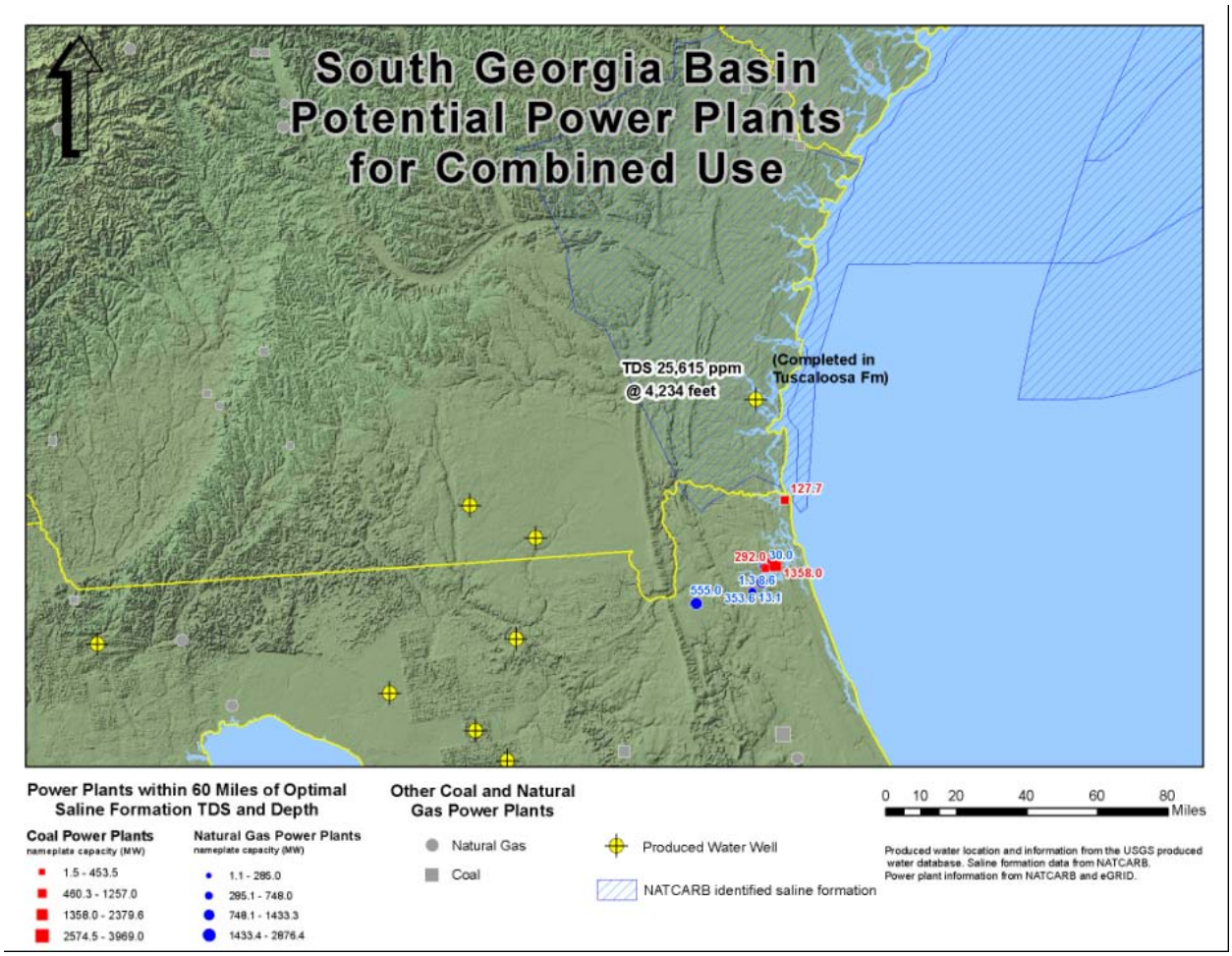

Figure 4-8: Selected Power Plants – South Georgia Basin.

Table 4-4: Potential Power Plants near Combined-Use Formations – South Georgia Basin.

ORISPL	Power Plant Name	Fuel Type	Capacity Factor	Nameplate Capacity (MW)	Plant Built Date	Distance to Well in Optimal Formation (miles) approximation	Notes
207	St Johns River Power Park	Coal	0.7311	1358.0	See Notes Column	47	2 generators, 1987 and 1988
10672	Cedar Bay Generating LP	Coal	0.7617	292.0	1984	48	
10202	Jefferson Smurfit Fernandina Beach	Coal	0.5604	127.7	See Notes Column	30	2 generators, 1982 and 1988 (wood waste)
54535	St Vincent's Medical Center	Gas	0.0084	1.3	1991	54	
50803	Stone Container Seminole Mill	Gas	0.3628	30.0	1957	46	
10431	Anheuser Busch Jacksonville	Gas	0.0057	8.6	1987	54	
10008	Baptist Medical Center	Gas	0.4782	13.1	See Notes Column	54	7 generators, 1973 (2), 1972, 1982, 1983, 1986, 1993
7846	Brandy Branch	Gas	0.1645	555.0	See Notes Column	60	4 generators, 2001 (3), 2005
666	J D Kennedy	Gas	0.0187	353.6	See Notes Column	54	4 generators, 1973 (3 oil), 2000

4.2.4 Southeast Texas

Southeast Texas has an abundance of power plants and water chemistry information from produced water wells. Figure 4-9 shows the outcrop of Eocene formations in blue and locations of produced water wells that intersect this outcrop at depths between 2,000 and 4,000 feet. The map also shows the location of coal- and natural gas-fired power plants. The water chemistries of these wells vary based on sample depth and appear to be good potential candidates for the combined use criteria for CO_2 sequestration and saline water use.

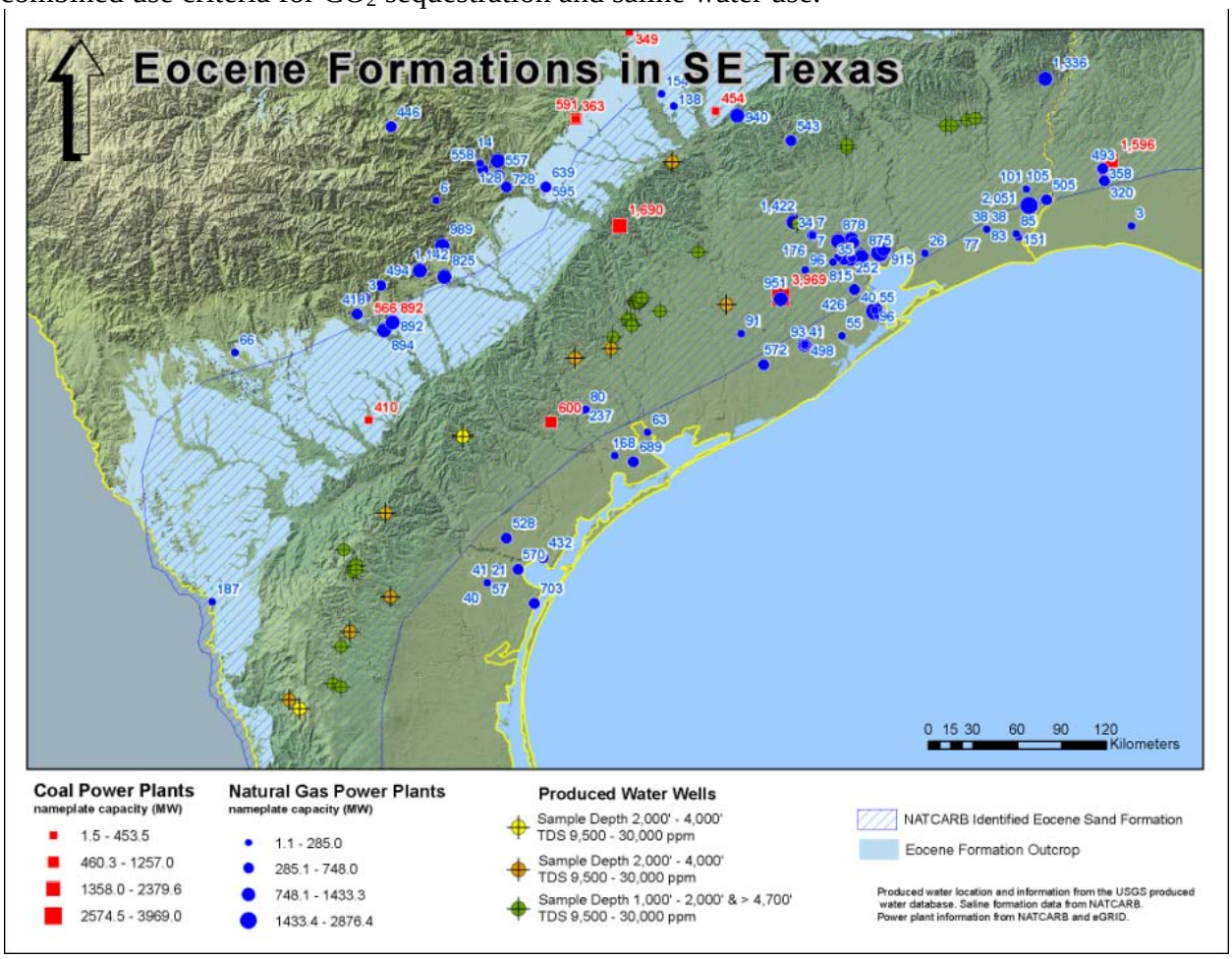

Figure 4-9: Power Plants and Produced Water Wells – Southeast Texas.

For a more detailed assessment of power plants to produced water wells, Figure 4-10 shows the saline formations (Eocene Sands) that the NATCARB database identified in a blue hatched pattern. All the produced water wells that intercept that formation at the desired TDS and depth create a linear feature that trends from southwest to northeast. A buffer of that linear feature was created to capture the existing coal and natural gas plants within 30 miles of the buffer center. Other power plants not captured by the buffer are grayed out. The power plants of interest for this study area include two coal-fired and 13 natural gas plants. Table 4-5 shows the identifying information for each power plant.

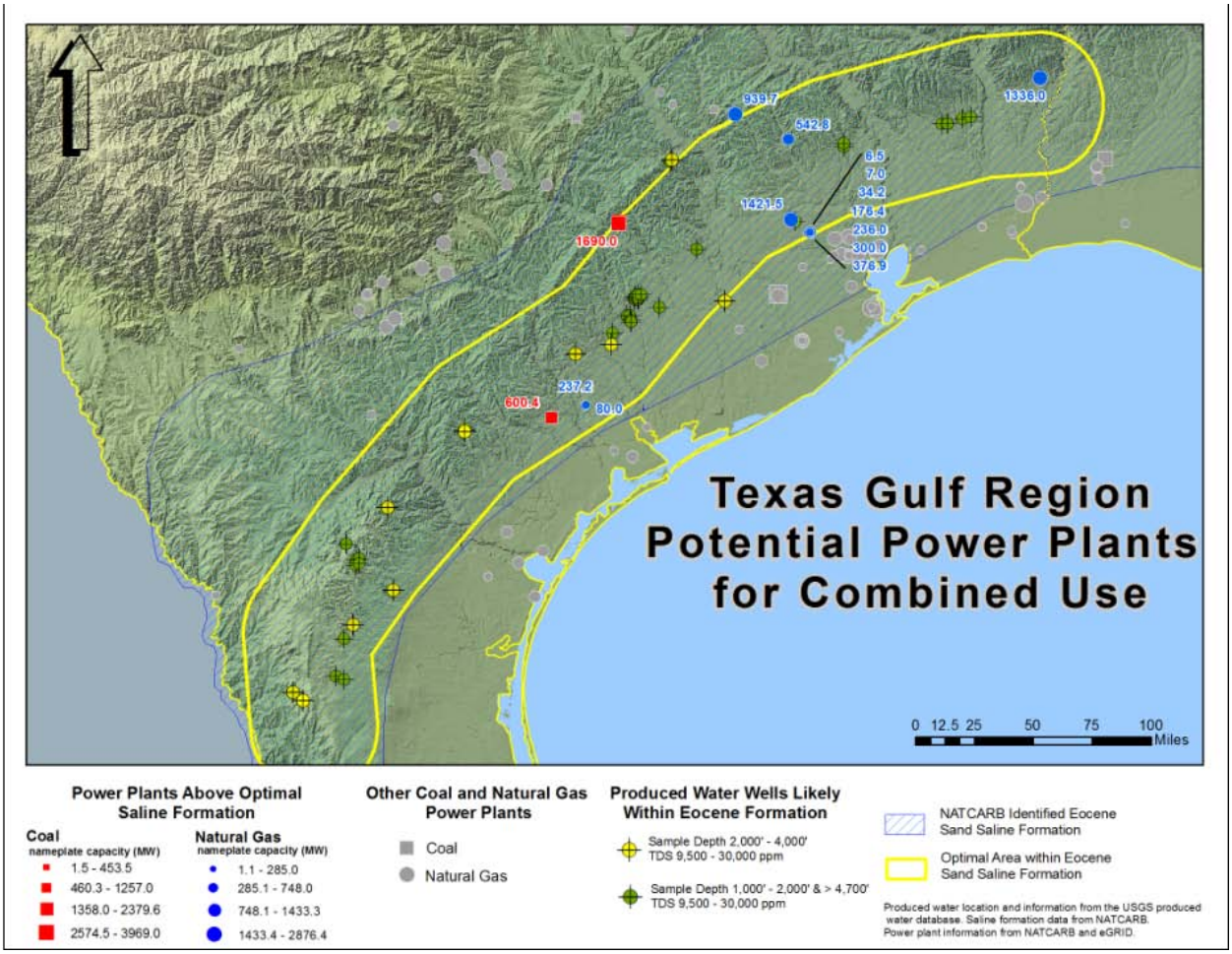

Figure 4-10: Power Plants and Produced Water Wells – Southeast Texas.

Table 4-5: Potential Power Plants near Coupled-Use Formations – Southeast Texas.

ORISPL	Power Plant Name	Fuel Type	Capacity Factor	Nameplate Capacity (MW)	Plant Built Date	Notes
6178	**Coleto Creek**	**Coal**	**0.9703**	**600.4**	**1980**	
6179	**Fayette Power Project**	**Coal**	**0.7470**	**1690.0**	**See Notes Column**	**3 generators, 1979, 1980, and 1988.**
3469	**T H Wharton**	**Gas**	**0.1309**	**1421.5**	**See Notes Column**	**18 generators with span of 1960 to 1975 for on-line date. Most in mid 1970s.**
55062	Tenaska Frontier Generation Station	Gas	0.5609	939.7	2000	4 generators, all 2000
52012	Valero Refining Texas Houston	Gas	0.5026	34.2	1990	2 generators, both 1990
10790	Victoria Texas Plant	Gas	0.5749	80.0	1987	
10298	Bayou Cogen Plant	Gas	0.6977	300.0	See Notes Column	4 generators. 2, 1984 and 2, 1985
55358	Cottonwood Energy Project	Gas	0.2250	1336.0	2003	8 generators, all 2003
55365	Exelon LaPorte Generating Station	Gas	0.0397	236.0	2001	4 generators, all 2001
10692	ExxonMobil Baytown Turbine	Gas	0.7621	376.9	See Notes Column	3 generators in 1989, 1 in 1997 and 1 in 2004 (5 total)
3457	Lewis Creek	Gas	0.4039	542.8	See Notes Column	2 generators, 1 in 1970 and 1 in 1971
10638	Pasadena	Gas	0.1276	6.5	1985	
50054	Rice University	Gas	0.5017	7.0	See Notes Column	2 generators, 1 in 1986 and 1 in 1989
3631	**Sam Rayburn**	**Gas**	**0.2405**	**237.2**	**See Notes Column**	**Mix of natural gas and diesel (9). 1964 (2), 1965 (1), 2003 (4), 1991 (2 diesel).**
7325	San Jacinto Steam Electric Station	Gas	0.7959	176.4	1995	2 generators

4.2.5 Selection of Study Area for Coupled Use

Southeast Texas was chosen for study of the economic feasibility of coupled use because of the high concentration of power plants, available saline formations meeting the TDS, and depth criteria. For the water treatment analysis, two coal and two natural gas power plants were chosen because of their proximity to the saline formation. These power plants are highlighted in Table 4-5. Figure 4-11 shows the relative location of these four power plants to nearby produced water wells. Both shallow and deep waters were assessed to evaluate the cost trade-offs of pumping lower TDS waters from greater depth vs. higher TDS waters from shallower depths. Table 4-6 shows the well depths, TDS values, and the distances from the selected power plants. It is assumed that any water treatment installation would be located with a power plant.

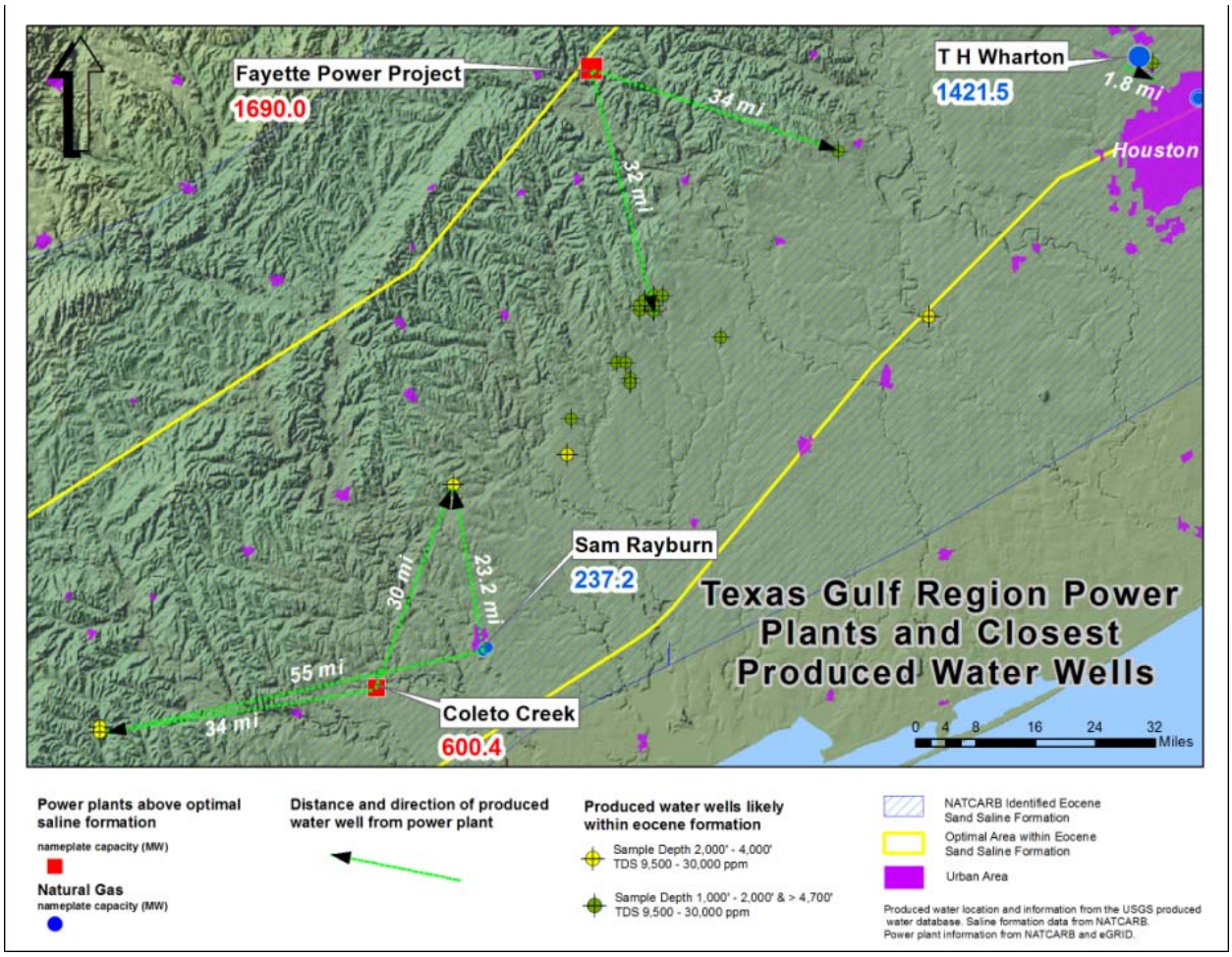

Figure 4-11: Geographic Distribution of Four Power Plants Highlighted in Table 4-5.

Table 4-6: Selected Power Plant Water Treatment Characteristics.

Power Plant Name	County	Fuel Type	Well Depth (feet)	TDS Level (ppm)	Wellhead Distance to Power Plant (miles)
Coleto Creek	Goliad	Coal	3,631	13,900	34
Coleto Creek	Goliad	Coal	2,700	27,562	30
Fayette Power Project	Fayette	Coal	3,500	11,660	32
Fayette Power Project	Fayette	Coal	2,800	22,848	34
T. H. Wharton	Harris	Gas	2,800	19,568	1.8
Sam Rayburn	Victoria	Gas	2,700	27,562	23.2
Sam Rayburn	Victoria	Gas	3,631	13,900	55

4.3 Evaluation of Other Water Demands

To fully appreciate the potential value of the saline water displaced by the sequestered carbon, one must consider it in the context of growing water needs of the region. To assist with this analysis, we make use of the 2007 State Water Plan for Texas and related resources (TWDB 2002, 2007). The state water plan is based on a bottom-up consensus-driven approach to water planning that involved 16 regional water planning groups (Figure 4-12). According to Texas Water Development Board guidelines, each regional planning group reviewed water use projections and water availability estimates in dry or drought-of-record conditions to develop a water budget. Where shortfalls in the budget were identified, the planning groups recommended water management strategies to meet the need.

The Carrizo-Wilcox Aquifer represents a viable water resource in four of the state's 16 water planning regions; regions h, k, l, and n. Projected water demands from 2010 to 2060 for each of the regions are given in Table 4-7. Total water use is projected to increase from 4.2 to 6.3 million acre-feet per year, a 50% increase. The largest increase occurs in the municipal sector where water use grows from 1.5 to 3 million acre-feet per year, a 200% increase. Other large water users include irrigation (1.5 million acre-feet in 2000) and manufacturing (0.8 million acre-feet in 2000). The fourth largest user of water across these planning regions is the thermoelectric sector at 0.2 million acre-feet per year in 2000. However, the thermoelectric sector is also the fastest growing, projected to experience a 249% increase by 2060 (0.57 million acre-feet in 2060). Ultimately, these projections suggest that the thermoelectric sector is in fierce competition for "new" water supplies from the municipal and manufacturing sectors (note that irrigation demand declines by about 19% between 2010 and 2060).

As part of the water planning process, each planning region also assessed available water supplies under drought conditions. These supplies were compared to the demands of Table 4-7 in efforts to identify potential shortfalls. Table 4-8 shows the projected shortfalls under drought for each of the four regions in 2010 and 2060. The projected shortfalls are on the order of 25 to 33% of the total water demand. In other words, water use would need to be curtailed by a quarter to a third in the event of a strong drought. Disruption of water supply is an issue of particular concern to the electric power industry.

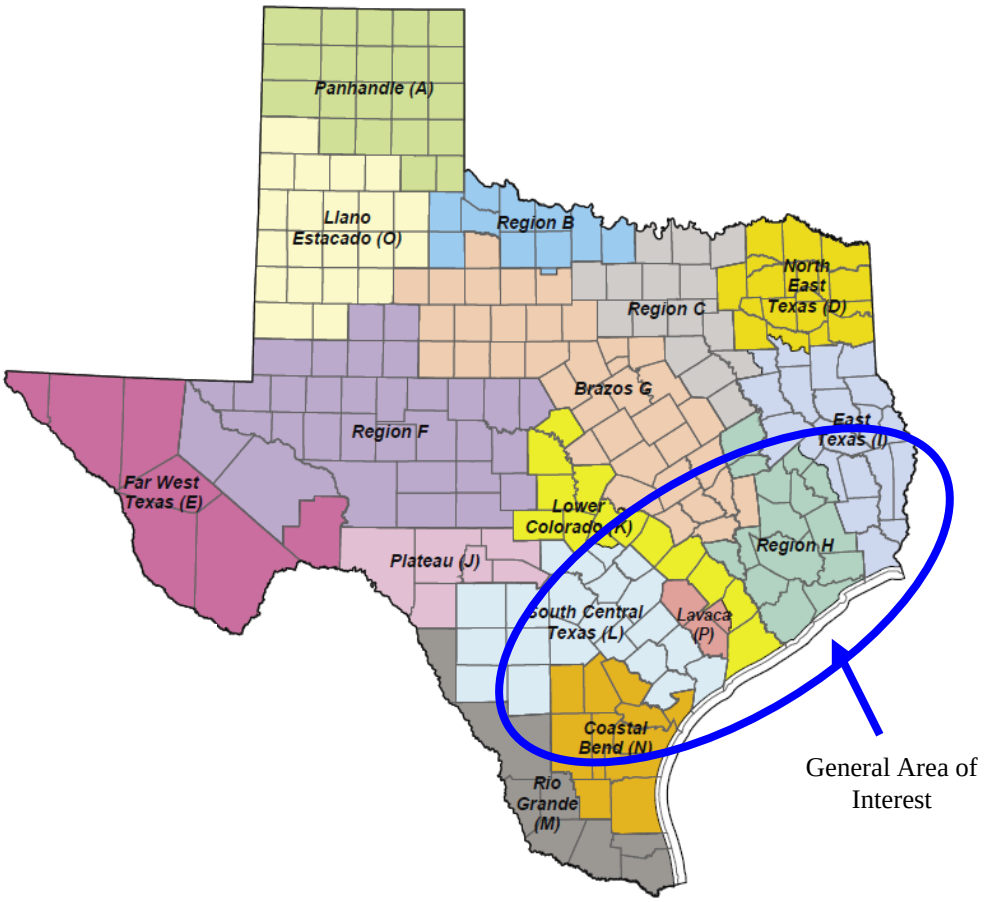

Figure 4-12: Location of the 16 Regional Water Planning Areas in Texas.
(Adapted from TWDB, 2007)

In response to the projected shortfalls, each region proposed various water development projects to mitigate the effects of drought. Projects include such actions as interbasin transfers, expanding current well fields, water reuse, conservation, and new reservoir construction. Table 4-9 provides the total projected improvement in water supply and accompanying cost for all projects aggregated at the planning region level. Additionally, the cost per acre-foot of water yielded is also provided. Values range from a low of $415/acre-foot to a high of $7,219/acre-foot. These projected costs provide a rough measure of the value of water in the planning region.

Another interesting point is that a number of the proposed water projects involve utilization of desalinated seawater and brackish aquifer water. In total, 137,000 acre-feet of such projects are proposed.

While the focus has largely been on saline formations in this analysis, it is also important to recognize that the use of alternative water supplies for use at power plants has been examined in the larger research community. Examples include evaluating mine pool water from underground coal mines (Veil et al., 2003; Veil and Puder, 2006); the feasibility of using coal bed methane (CBM) produced water and finally reclaimed water.

Treated municipal and industrial waste water, often referred to as reclaimed water, may be an attractive alternative (Veil, 2007). The report by Veil (2007) states that there are approximately 57 power plants within 16 states currently using reclaimed water for power plant cooling, and some are also using it for air pollution control equipment. Additionally, the report states that nearly all regulatory requirements related to the use of reclaimed water are found at the state level.

As stated clearly by Veil:

> Reclaimed water must meet at least secondary treatment standards. Often the state agency that authorizes reclaimed water use for cooling will require tertiary treatment or some form of filtration and disinfection. In addition to treating the reclaimed water for public health and environmental reasons, operators often treat for process reasons. Reclaimed water typically contains chemical parameters that may create problems of scaling, corrosion, biofouling, or stress cracking of some metal surfaces.
>
> – Veil, 2007, p. 28.

Thus, potentially utilizing so called reclaimed water for alternative uses (such as cooling water in power plants) presents a different set of treatment challenges to those of extracting deep saline formation waters, but it is a viable combination given the appropriate conditions.

Table 4-7: Projected Water Demands 2020–2060 for the Four Planning Regions That Utilize the Carrizo-Wilcox Aquifer as a Water Source.

(Adapted from TWDB, 2007)

		Projected Water Demands (Acre-feet)						
Region	**Category**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
H	**Irrigation**	464,330	450,175	438,257	433,686	430,930	430,930	430,930
	Livestock	12,228	12,228	12,228	12,228	12,228	12,228	12,228
	Manufacturing	628,025	722,873	783,835	836,597	886,668	927,860	950,102
	Mining	49,473	57,043	60,782	63,053	65,285	67,501	69,457
	Municipal	850,091	980,544	1,116,660	1,253,607	1,391,710	1,552,375	1,732,608
	Steam Electric	83,262	91,231	112,334	131,332	154,491	182,720	217,132
	Total	2,087,409	2,314,094	2,524,096	2,730,503	2,941,312	3,173,614	3,412,457
K	**Irrigation**	620,930	589,705	567,272	545,634	524,809	504,695	468,763
	Livestock	13,395	13,395	13,395	13,395	13,395	13,395	13,395
	Manufacturing	28,887	38,162	44,916	56,233	69,264	77,374	85,698
	Mining	23,945	30,620	31,252	31,613	26,964	27,304	27,598
	Municipal	213,303	252,637	304,735	352,737	394,101	439,049	484,170
	Steam Electric	103,875	153,522	156,894	194,396	208,982	214,783	222,058
	Total	1,004,335	1,078,041	1,118,464	1,194,008	1,237,515	1,276,600	1,301,682
L	**Irrigation**	383,332	379,026	361,187	344,777	329,395	315,143	301,679
	Livestock	25,660	25,954	25,954	25,954	25,954	25,954	25,954
	Manufacturing	100,195	119,310	132,836	144,801	156,692	167,182	179,715
	Mining	11,757	14,524	15,704	16,454	17,212	17,977	18,644
	Municipal	340,030	395,996	451,111	503,375	547,136	592,343	637,235
	Steam Electric	35,379	50,427	56,792	66,397	78,104	92,378	109,776
	Total	896,353	985,237	1,043,584	1,101,758	1,154,493	1,210,977	1,273,003
N	**Irrigation**	21,971	20,072	18,611	17,077	15,703	14,470	13,365
	Livestock	8,838	8,838	8,838	8,838	8,838	8,838	8,838
	Manufacturing	54,481	63,820	69,255	73,861	78,371	82,283	88,122
	Mining	11,897	15,150	16,524	16,640	17,490	18,347	19,114
	Municipal	99,951	111,495	122,861	132,063	139,425	146,036	151,474
	Steam Electric	8,799	7,316	14,312	16,733	19,683	23,280	27,664
	Total	205,937	226,691	250,401	265,212	279,510	293,254	308,577

Table 4-8: Projected Shortfall in Water Supply under Drought Conditions (units are in acre-feet per year).
(Adapted from TWDB, 2007)

Region/Year	2010	2060
H	279,996	1,119,307
K	246,055	557,311
L	156,598	416,859
N	3,404	53,432

Table 4-9: Costs of Proposed Projects to Mitigate Drought Related Shortfall.
(Adapted from TWDB, 2007)

Region	Additional Water (acre-feet)	Capital Costs ($)	$/Acre-foot
H	1,300,639	5,460,520,392	4198.34
K	861,930	358,174,068	415.55
L	732,779	5,222,408,000	7126.85
N	149,496	789,515,000	5281.18

4.4 Freshwater Needs for Thermoelectric Power Plants and Carbon Capture Technology

Water consumption for new and existing power plants depends on the type of process used to generate electricity. The Department of Energy (DOE) and the NETL developed several relative water use metrics for power plants as illustrated in Figure 4-13. The types of power plant technologies outlined by DOE/NETL (2007a) include new pulverized coal (PC) and integrated gasification combined cycle (IGCC) plants with and without carbon sequestration technology installed.

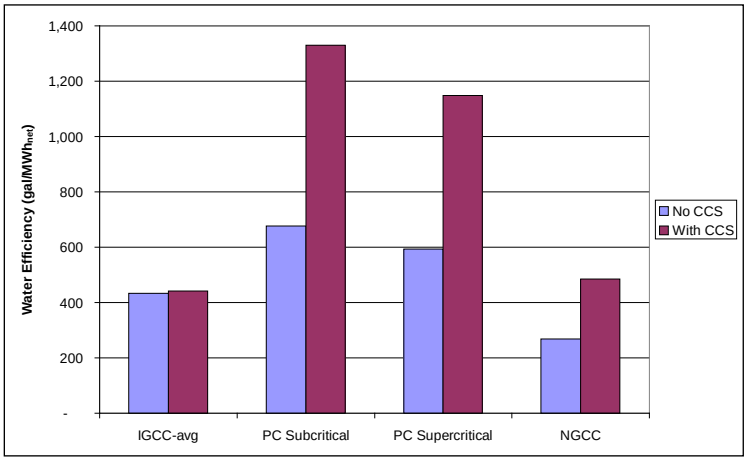

Figure 4-13: Relative Water Usage of New PC and IGCC Plants.

(Carbon Capture and Sequestration (CCS); Integrated Gasification Combined Cycle (IGCC); Pulverized Coal (PC); Natural Gas Combined Cycle (NGCC)) (adapted from DOE/NETL, 2007a).

Expansion at power plants will require additional water if wet cooling towers are to be used. Non-freshwater (e.g., brackish water or produced water) will require desalination prior to use. Dry cooling towers could be employed, but there is an energy penalty as well as site-specific operational constraints (DOE, 2007b, c; EPRI, 1982, 2003, 2006).

Another potential solution is to identify a technology that utilizes the waste heat currently sent to the condenser system or in the flue gas for desalination or other process use. This could allow for an alternative water source high in TDS to be utilized economically, as well as help in the energy penalty associated with carbon sequestration. The National Energy Technology Laboratory has been evaluating thermal membrane distillation techniques that utilize power plant waste heat as a desalination technology.

4.5 Detailed Summary of Desalination Options Studies for the Model

Once the potential coupled-use formations within the SECARB region were identified in Table 4-5, feasible desalination options were studied using a basic spreadsheet analysis. All options utilized reverse osmosis (RO) for desalination and varied in the mode of waste water disposal. Currently, RO is the most cost-effective method for treating saline water. Other membrane options and thermal distillation methods exist, but RO has proven to be the most effective option for the price. Thermal membrane distillation is a promising option that could be cost competitive with RO if the energy for the process comes in the form of relatively low-grade power plant waste heat. This technology is currently under evaluation in various forms to determine its feasibility to provide another option for nontraditional water treatment. For this project, the practical options studied were as follows:

Option A	Desalination & Gathering Equipment only; no concentrate disposal
Option B	Desalination & Gathering Equipment only; 59.5 acre evaporation ponds for concentrate disposal
Option C	Desalination & Gathering Equipment only; 3000 ft injection pipeline and well for concentrate disposal
Option D	Desalination & Gathering Equipment – HERO™ (HERO™ +Brine concentrator retrofit (original DiFilippo (2006) report numbers are based on higher TDS)

Each of the options studied required calculations for the capital and operational and maintenance (O&M) costs. Most of the calculations are based on the *USBR Desalting Handbook for Planners* (USBR, 2003). The important parameters for estimating purposes are summarized in Table 4-10. Basically, each treatment scenario assumes a design flow rate of 2.0 MGD, an annual flow rate of 400 Mgal/year based on an 85% plant capacity utilization rate. Additional assumptions regarding capital and O&M costs are included in Table 4-10. The primary difference in costing of the different options comes from the parameters that are site specific, such as groundwater TDS concentration, the distance from the wellhead to the water treatment facility, and the well depth. This working methodology draws heavily from work that first appeared in Kobos et al., 2009, and projects underlying that report.

Summary costs of the four treatment options for each power plant/wellhead choice are shown in the Tables 4-11, 4-12, 4-13, and 4-14. The costs include capital and O&M for each option. It

should be noted that concentrate disposal only considers engineering process costs. Issues such as permitting and/or land availability can significantly affect costs or limit options; however, they are beyond the scope of this study. Table 4-15 roles up the significant cost information from Tables 4-11 through 4-14. For this analysis, Option A is considered the baseline case. It includes standard RO treatment with no disposal of the waste concentrate. Option B includes RO treatment with disposal to evaporation ponds with the assumption that there is land available for the ponds. Option C includes RO treatment with concentrate re-injection into the formation, and finally, Option D is the High Efficiency Reverse Osmosis HERO™ in association with a brine concentrator.[4] The brine concentrator eliminates the need for concentrate management at the plant design flow rate of 1850 gpm. If the flow rate were to exceed 4,640 gpm, then evaporation ponds or re-injection would become necessary. Table 4-15 compares Options B, C, and D to the baseline A. It is anticipated that concentrate management will always be required; however, costing without it is included to shed light on concentrate disposal costs. In general, when concentrate management is considered, Option C (RO treatment with concentrate re-injection) is the least expensive option, followed by Option D (the HERO™ System) followed by Option B (RO treatment with evaporation ponds).

Note that the costs vary considerable (as much as 50%) among the options; however, costs vary only slightly across the different sites. This means that RO water treatment costs do not vary significantly when TDS levels are within the desired range for the technology. RO is a proven, well-documented technology with known limitations. Operation outside the prescribed range will result in much higher costs. The cost variation from site to site is a result of variations in TDS levels, well depth, and distance from treatment facility.

Note also that the costs have been developed by using TDS level; however, if an actual system were installed, a more detailed analysis of the water chemistry would be required prior to final design. For example, if the water had high iron or sulfate content, a pre-treatment would likely be required, resulting in increased costs. In conclusion, the costs are representative of typical saline water treatment costs, but a final design must include a more detailed evaluation of input parameters.

These results are an initial analysis for the named power plants, while accounting for a 2.0 MGD desalination facility on site and compares each of the options considered. The desalination costs are in line with both the DiFilippo (2006) study, as well as others (Miller, 2003; USBR, 2003) who have studied the cost of desalination.

[4] HERO™ is a registered trademark of Debasish Mukhopadhyay.

Table 4-10: Summary of RO Input Parameters and Cost Components.

RO Input Parameter	Description	Value
Water TDS (ppm)	Specific to each well	Actual value
Design flow rate (gpm)	based on 24/7 pumping of brackish aquifer, and % CO_2 capture	1,807
Design flow rate (MGD)	Used 2.0 MGD desalination output (treated water)	
Design annual flow (Mgal/yr)	based on 0.85 plant capacity factor (USBR recommendation)	400
Electrical cost ($/kwh)		0.1
Pipeline distance from brackish well to desal plant (mi)	based on radial distance,	Actual value
Well Depth (ft)	based on well data	Actual value
Cost Components	Reference Source	
Capital Costs:		
Pump & Pipe – produced water gathering capital	Used USBR *Desalting Handbook*, 2009: Figure 9-18	$2,000/ft
Piping from gathering station to desal Plant	Used USBR *Desalting Handbook*, Figure 9-11	$126,810/mi
Concentrate disposal pipeline & well	Used USBR *Desalting Handbook*, Figure 9-11 & 9-13	
Evaporation ponds	Used USBR *Desalting Handbook*, Figure 9-12	
Desalination Total Construction Cost	Used USBR *Desalting Handbook*, Figure 9-7	$2000/ppm TDS for options A-C DiFilippo (2006) value for option D
O&M		
Labor (for 2 MGD)	Used USBR *Desalting Handbook*, Figure 9-37	
Electrical-brackish water reverse osmosis (BWRO) (for 6,000 ppm TDS, 2 MGD)	Used USBR *Desalting Handbook*, Figures 7-8 & 9-45	
Electrical-GW (groundwater) pumping (for 1807 gpm/2 MGD)	Used equations to estimate pump power.	
Membrane replacement	Used USBR *Desalting Handbook*, BWRO	$0.08/1000 gal plant capacity
Chemicals (used surface water)	Used USBR *Desalting Handbook*, Figure 9-41	
Other maintenance	Used USBR *Desalting Handbook*	1.5% of capital

Table 4-11: OPTION A – RO Treatment with No Disposal.

	Power Plants						
Total Cost of Treatment (incl. concentrate disposal, Surface & GW pumping, $U.S. 2000)	**Coleto Creek (deep)**	**Coleto Creek (shallow)**	**Fayette Power Project (deep)**	**Fayette Power Project (shallow)**	**TH Wharton**	**Sam Rayburn (shallow)**	**Sam Rayburn (deep)**
	$/1000 gal	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**
Annualized Total Capital	$2.44	$2.27	$2.39	$2.28	$1.79	$2.16	$2.80
Annual O&M	$3.35	$3.09	$3.53	$2.90	$2.79	$2.71	$3.33
Electrical	$1.58	$1.35	$1.77	$1.16	$1.14	$0.98	$1.49
Membrane Replacement	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Chemicals	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91
Other	$0.78	$0.75	$0.77	$0.75	$0.66	$0.73	$0.85
Total Cost (O&M+cap)	**$5.79**	**$5.36**	**$5.92**	**$5.19**	**$4.58**	**$4.86**	**$6.13**
Cost of Desalination only – includes only equipment & O&M for desalination (i.e., no ponds, no GW pumping)	**Coleto Creek**	**Coleto Creek**	**Fayette Power Project**	**Fayette Power Project**	**TH Wharton**	**Sam Rayburn**	**Sam Rayburn**
	$/1000 gal	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**
Annualized Total Capital	$1.49	$1.49	$1.49	$1.49	$1.49	$1.49	$1.49
Annual O&M	$2.25	$2.22	$2.38	$1.98	$2.00	$1.88	$2.10
Electrical	$0.48	$0.48	$0.62	$0.24	$0.35	$0.16	$0.26
Membrane Replacement	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Chemicals	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91
Other	$0.78	$0.75	$0.77	$0.75	$0.66	$0.73	$0.85
Total Cost (O&M+cap)	**$3.74**	**$3.71**	**$3.87**	**$3.47**	**$3.49**	**$3.37**	**$3.59**

Table 4-12: OPTION B – RO Treatment with Evaporation Pond Disposal.

Total Cost of Treatment (includes concentrate disposal, GW pumping, $U.S. 2000)	**Power Plants**						
	Coleto Creek (deep)	**Coleto Creek (shallow)**	**Fayette Power Project (deep)**	**Fayette Power Project (shallow)**	**TH Wharton**	**Sam Rayburn (shallow)**	**Sam Rayburn (deep)**
Annualized Total Capital	$4.77	$4.61	$4.72	$4.62	$4.13	$4.49	$5.14
Annual O&M	$3.79	$3.53	$3.97	$3.34	$3.23	$3.14	$3.77
Electrical	$1.58	$1.35	$1.77	$1.16	$1.14	$0.98	$1.49
Membrane Replacement	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Chemicals	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91
Other	$1.22	$1.19	$1.21	$1.19	$1.10	$1.17	$1.29
Total Cost (O&M+cap)	**$8.56**	**$8.14**	**$8.69**	**$7.96**	**$7.36**	**$7.64**	**$8.90**
Cost of Desalination only – includes only equipment & O&M for desalination (i.e., no ponds, no GW pumping)	**Coleto Creek (deep)**	**Coleto Creek (shallow)**	**Fayette Power Project (deep)**	**Fayette Power Project (shallow)**	**TH Wharton**	**Sam Rayburn (shallow)**	**Sam Rayburn (deep)**
	$/1000 gal	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**
Annualized Total Capital	$1.49	$1.49	$1.49	$1.49	$1.49	$1.49	$1.49
Annual O&M	$2.68	$2.65	$2.82	$2.42	$2.44	$2.32	$2.54
Electrical	$0.48	$0.48	$0.62	$0.24	$0.35	$0.16	$0.26
Membrane Replacement	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Chemicals	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91
Other	$1.22	$1.19	$1.21	$1.19	$1.10	$1.17	$1.29
Total Cost (O&M+cap)	**$4.17**	**$4.14**	**$4.31**	**$3.91**	**$3.93**	**$3.81**	**$4.03**

Table 4-13: OPTION C – RO treatment with Concentrate Re-injection.

	Power Plants						
Total Cost of Treatment (incl. concentrate disposal, GW pumping, $U.S. 2000)	**Coleto Creek (deep)**	**Coleto Creek (shallow)**	**Fayette Power Project (deep)**	**Fayette Power Project (shallow)**	**TH Wharton**	**Sam Rayburn (shallow)**	**Sam Rayburn (deep)**
	$/1000 gal	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**
Annualized Total Capital	$2.88	$2.21	$2.83	$2.73	$2.23	$2.60	$3.25
Annual O&M	$3.44	$2.91	$3.62	$2.99	$2.88	$2.79	$3.42
Electrical	$1.58	$1.35	$1.77	$1.16	$1.14	$0.98	$1.49
Membrane Replacement	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Chemicals	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91
Other	$0.87	$0.57	$0.86	$0.84	$0.75	$0.82	$0.94
Total Cost (O&M+cap)	**$6.32**	**$5.12**	**$6.45**	**$5.72**	**$5.11**	**$5.39**	**$6.66**
Cost of Desalination only – includes only equipment & O&M for desalination (i.e., no ponds, no GW pumping)	**Coleto Creek (deep)**	**Coleto Creek (shallow)**	**Fayette Power Project (deep)**	**Fayette Power Project (shallow)**	**TH Wharton**	**Sam Rayburn (shallow)**	**Sam Rayburn (deep)**
	$/1000 gal	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**
Annualized Total Capital	$1.49	$1.49	$1.49	$1.49	$1.49	$1.49	$1.49
Annual O&M	$2.34	$2.04	$2.47	$2.07	$2.09	$1.97	$2.19
Electrical	$0.48	$0.48	$0.62	$0.24	$0.35	$0.16	$0.26
Membrane Replacement	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Chemicals	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91	$0.91
Other	$0.87	$0.57	$0.86	$0.84	$0.75	$0.82	$0.94
Total Cost (O&M+cap)	**$3.82**	**$3.53**	**$3.96**	**$3.56**	**$3.58**	**$3.46**	**$3.68**

Table 4-14: OPTION D – HERO™ System.

	Power Plants						
Total Cost of Treatment (incl. concentrate disposal, GW pumping, $U.S. 2000)	**Coleto Creek (deep)**	**Coleto Creek (shallow)**	**Fayette Power Project (deep)**	**Fayette Power Project (shallow)**	**TH Wharton**	**Sam Rayburn (shallow)**	**Sam Rayburn (deep)**
	$/1000 gal	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**
Annualized Total Capital	$2.82	$2.66	$2.77	$2.67	$2.18	$2.54	$3.19
Annual O&M	$4.48	$4.22	$4.66	$4.03	$3.92	$3.83	$4.46
Electrical	$2.62	$2.39	$2.81	$2.20	$2.18	$2.03	$2.53
Membrane Replacement	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Chemicals	$0.93	$0.93	$0.93	$0.93	$0.93	$0.93	$0.93
Other	$0.85	$0.82	$0.84	$0.82	$0.73	$0.80	$0.92
Total Cost (O&M+cap)	**$7.30**	**$6.88**	**$7.43**	**$6.70**	**$6.10**	**$6.37**	**$7.64**
Cost of Desalination only – includes only equipment & O&M for desalination (i.e., no ponds, no GW pumping)	**Coleto Creek (deep)**	**Coleto Creek (shallow)**	**Fayette Power Project (deep)**	**Fayette Power Project (shallow)**	**TH Wharton**	**Sam Rayburn (shallow)**	**Sam Rayburn (deep)**
	$/1000 gal	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**	**$/1000 gal**
Annualized Total Capital	$1.87	$1.87	$1.87	$1.87	$1.87	$1.87	$1.87
Annual O&M	$3.38	$3.35	$3.51	$3.11	$3.13	$3.01	$3.23
Electrical	$1.52	$1.52	$1.66	$1.28	$1.39	$1.20	$1.31
Membrane Replacement	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Chemicals	$0.93	$0.93	$0.93	$0.93	$0.93	$0.93	$0.93
Other	$0.85	$0.82	$0.84	$0.82	$0.73	$0.80	$0.92
Total Cost (O&M+cap)	**$5.25**	**$5.22**	**$5.39**	**$4.98**	**$5.00**	**$4.88**	**$5.11**

Table 4-15: Summary of Total Desalination Costs by Option.

	POWER PLANTS						
OPTION (including disposal & GW pumping) ($U.S. 2000)	**Coleto Creek (deep)**	**Coleto Creek (shallow)**	**Fayette Power Project (deep)**	**Fayette Power Project (shallow)**	**TH Wharton**	**Sam Rayburn (shallow)**	**Sam Rayburn (deep)**
	TOTAL ANNUALIZED COSTS (CAP + O&M) ($1000/gal)						
A	$5.79	$5.36	$5.92	$5.19	$4.58	$4.86	$6.13
B	$8.56	$8.14	$8.69	$7.96	$7.36	$7.64	$8.90
C	$6.32	$5.12	$6.45	$5.72	$5.11	$5.39	$6.66
D	$7.30	$6.88	$7.43	$6.70	$6.10	$6.37	$7.64
% Difference vs. Baseline Case (Option A)							
A	-	-	-	-	-	-	-
B	48 %	52 %	47 %	53 %	61 %	57 %	45 %
C	9 %	-4 %	9 %	10 %	12 %	11 %	9 %
D	26 %	28 %	26 %	29 %	33 %	31 %	25 %
OPTION (with no disposal or GW pumping)	**TOTAL ANNUALIZED COSTS (CAP + O&M) ($1000/gal)**						
A	$3.74	$3.71	$3.87	$3.47	$3.49	$3.37	$3.59
B	$4.17	$4.14	$4.31	$3.91	$3.93	$3.81	$4.03
C	$3.82	$3.53	$3.96	$3.56	$3.58	$3.46	$3.68
D	$5.25	$5.22	$5.39	$4.98	$5.00	$4.88	$5.11
	% Difference vs. Baseline Case (Option A)						
A	-	-	-	-	-	-	-
B	11 %	12 5	11 5	13 %	13 %	13 %	12 %
C	2 %	-5 5	2 5	3 %	3 %	3 %	3 %
D	40 %	41 5	39 5	44 %	43 %	45 %	42 %

5. Summary

The analysis determined that using a sequential framework examining the geologic, power plant, and geomodeling criteria, several regions of the U.S. have potential sites for a coupled carbon dioxide sequestration, water extraction, and treatment system. They all have unique attributes and issues requiring a thorough site-specific examination of the geology type, depth, geochemistry, and extent before placing a full-scale coupled-use system as illustrated in Figure 2-1 on these sites. A few of the salient lessons learned from the data collection and analysis from the geological assessment include: (1) more data on deep saline formation water TDS (e.g., geochemistry) may need to be collected to more fully evaluate regional sequestration options for carbon dioxide and (2) the relative, calculated size of the formations (and hence their useful lifetime for sequestering carbon or extracting water for treatment and subsequent use) is highly dependent on assumptions that must be verified (such as formation porosity and permeability) perhaps through pilot projects. With this information, a more accurate assessment could be developed for regions of the southwestern United States with respect to CO_2 storage in saline formations, the potential for water extraction and use, and the interactive effects between these two types of systems as they relate to power plant demands for water today and in the coming decades.

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Appendix A

An alternate approach to locating potential study sites in the SECARB area was made possible by gaining the ability to access the entire contents of the NATCARB brine chemistry database. However, the database initially needed to be processed so that just useful entries remained. This involved deleting duplicate entries (based on "ID_Code"), entries that lacked locations (no latitude or longitude), entries that lacked well-depth information, and entries with insufficient water chemistry data. After this, three approaches were used to extract useful insights from the database.

Initially, all data pertinent to the SECARB region were sorted by salinity level into three groupings: data reflecting salinities less than 10,000 parts per million dissolved salts (protected by regulation as potential drinking water resources), data reflecting salinities between 10,000 and 35,000 ppm TDS (suitable to programmatic uses), and data with TDS values greater than 35 ppb TDS (too salty to be desalinated economically). Data in each grouping were then "mapped," plotted based on their longitude and latitude, to see if different geographic regions could be defined where one might encounter high- or low-salinity waters (Figure A1 a,b,c). However, the outcome of this assessment was that the locations for the three classes of fluids overlapped and that geographic areas with the sorts of brackish waters useful to this program could not be uniquely identified with this strategy.

The second approach involved trying to find discriminating locations for different brine classes based on the depth of the wells; for example, shallower wells might be presumed to be less saline. From Florida west to the Mexican border, the layers of porous sedimentary rocks tilt gently downward toward the south. Thus, inland the formations change from old Cretaceous-age strata on the surface while these same rocks are buried many thousands of feet deep beneath Tertiary sediments on the Gulf Coast. The process of assessing vertical salinity gradients then consisted of making plots of depth vs. distance northward from the southern boundary of the cluster of well locations in question (Figure A1 a,b,c) for each of the salinity classes identified earlier. For the wells located in west Texas, the plotted "latitude" (e.g., the north-south distance used on the horizontal axis of the plot) first had to be corrected for the fact that the pattern of well locations bends to the south as one works westward across the state.

Figure A2 a,b,c (south-central Louisiana) and Figure A3 a,b,c (south Texas) are typical of the results from such investigations. Basically, as with the map views, this approach also failed to reveal any significant discrimination (either vertically or laterally) between wells having low, intermediate, and high salinities. The one caveat is that for the band of wells closest to the Gulf Coast, the ratio of low- to high-salinity wells seems slightly higher in the northernmost sections of the plots. This agrees with the earlier identified potential for a reservoir of brackish underground water in the Carrizo-Wilcox Formation north of the well locations compiled in the NATCARB database (e.g., in the northern part of the yellow box outlined in Figure A1 a,b,c). The brackish water-containing formations identified earlier in the report would not have been expected to show up in a NATCARB-based analysis (NATCARB, 2008) because NATCARB (at least in this region) contains information on produced waters (e.g., waters co-produced during hydrocarbon—gas or oil—production), and no hydrocarbons are produced from the Carrizo-Wilcox in the area identified in the main body of the report.

The final approach to locating areas with brackish waters at sufficient depth returned to the concept of making "maps" (e.g., plotting longitude vs. latitude of wells), but this time, the database was presorted so that wells would be grouped by the formation in which they were completed. In doing so, several features became apparent. First, not all the wells that passed the initial sort criteria actually have useable formation names or formation ages entered in the NATCARB database. In fact, only about 70% of the wells have useable formation names associated with them, and only about 64% of the wells have a geologic age for the rock they were completed in. Further statistical analysis is made difficult because occasionally a formation name will be provided without its corresponding age and vice versa.

Second, in going through the resulting tabulation (ultimately to locate formations with an auspiciously large number of lower salinity hits), it became apparent that only a few formations contained data distributed over a large enough area to define the sorts of regional hydrologic trends useful to this program. In fact, the NATCARB database contains numerous clusters of wells with virtually identical longitudes and latitudes but without stratigraphic correlations extending beyond the boundary of a particular oil or gas field. Of the formations that appeared on a regional basis, only two (the Tertiary-age Claiborne Formation, Figure A4, and the Cretaceous-age Vicksburg Formation, Figure A5) seemed to contain areas where one might expect to find *relatively* uncontaminated low- to intermediate-salinity waters at appropriate depths. All the other (far more numerous assessments) followed the typical pattern where, low-, intermediate-, and high-TDS wells are thoroughly intermixed. Additionally, even where favorable areas were defined (Figures A4 and A5), the designation is generally based on fewer than ten wells (or well clusters) spread out for more than a hundred miles along a relatively narrow trend.

Thirdly, although the regional maps (Figure A1 a,b,c) seemingly contain dense clusters of points, the reality is that individual wells (or dense well clusters with the same assigned longitude and latitude) are most often separated by many miles. On one hand, this makes ruling out the possibility that even a single intermediate TDS well hit could reflect the presence of a *locally* substantial brackish water resource. On the other hand, verifying this may require supplementing the data contained within NATCARB to complete the analysis.

To summarize, relative to applying NATCARB data in the SECARB region:

a. Coverage provided by the NATCARB database is incomplete and provides essentially no coverage for large areas of the SECARB region where neither oil nor gas wells have been drilled.

b. Where pertinent NATCARB data do exist, the dominant picture is that *on a regional scale*, a first-order analysis will likely find that useable wells are intermixed with both higher- and lower-salinity wells. Consequently, instead of trying to define specific formations as potential sources for brackish water, additional analyses may prove more useful by attaching probabilities to tracts of land that define the likelihood of successfully drilling into a body of brackish water.

c. Difficulties in geographical discrimination notwithstanding, the NATCARB database in total does suggest that brackish water resources in the SECARB region are larger, and more widely distributed, than had been deduced previously based on our review of the conventional geo-hydrologic literature.

d. Because most wells are significant distances from the next well listed in the NATCARB database, even a single well with reliable, detailed information might still identify a locally important brackish water resource. Hence, an alternate search strategy for future analyses might be to find the nearest well with an acceptable TDS and assume a storage capacity defined by a circle with a radius of half the distance to the nearest well that is not suitable. Additionally, the distance to the nearest well in the same formation that is unsuitable could be examined.

Table A1. Wilcox & Claiborne Formations Sorted by TDS 10,000 – 35,000 ppm TDS and Well Depth.

(Note: Italic values at the top of each column are averages of the individual well water analyses, USGS (2002)).

Record #	Upper	Lower			HCO3	SO4	Cl	Na	Ca	Mg
"UNIQID"	Depth	Depth	TDS	pH	ppm	ppm	ppm	ppm	ppm	ppm
---	*9869*	*9928*	*20.8*	*7.2*	*1066*	*507*	*11310*	*7304*	*475*	*68*
42019052	7800		33.2	7	672	98	19560	12379	480	31
42251942	8184	8190	33.2	5.55	0	0	20402	10595	1547	403
42016434	9234	9282	33.1	6.8	1248	49	19020	12600	170	22
42006708	10261	10270	32.7	7	798	74	18845	12042	374	39
42012431	10240	10278	32.6	6.7	670	8	17665	136	10054	20
42257510	8802	8815	31.7	7.4	783	42	18681	11258	661	262
42257780	10680		30.7	5.9	163	214	18350	11063	690	56
42019111	9440	9452	29.9	6.8	1230	0	17100	11300	240	0
42018947	9440	9452	29.6	6.8	1190	0	17100	11300	180	12
42016677	8578	8588	28.3	8.7	1111	36	16260	10614	170	101
42009946	8400		27.4	7.62	1681	50	15170	10232	128	10
42017147	7676	7680	26.5	7	1415	-3	15000	9562	400	122
42006717	8379	8382	26.5	8.2	1733	55	14591	9619	119	200
42006714	8379	8382	26.4	7.6	1728	23	14544	9933	96	22
42006716	8379	8382	26.2	7.3	1693	21	14468	9826	129	31
42257778	10620	10680	25.9	7	814	76	15000	9678	201	84
42011895	10261	10270	25.8	7.3	624	26	14659	9239	318	74
42006712	8382	8385	25.7	7.9	1815	33	14435	9821	157	33
42257677	9335	9380	25.7	6.8	913	-3	14950	9376	452	77
42006713	8382	8385	25.6	7.9	1853	36	14182	9698	141	30
42256923	11480	11491	25.6	6.65	216	97	15355	8311	1389	96
42258082	9598	9608	25.4	6.45	242	0	15360	8673	895	160
42257724	8972	8976	24.1	6.85	550	560	13800	8080	934	122
42258089	9100	9125	24.0	7.7	1144	8	13653	8983	170	57
42005127	9503	9520	23.9	7.3	1320	3150	10400	7610	1370	49
42004344	10207		23.7	8	1460	11000	3300	7560	300	36
42006706	8364	8369	23.6	7.5	2074	26	12606	8658	228	27
42009448	10052	10090	23.0	7.31	1258	8	12949	8462	195	59
42257825	10590	10878	22.9	6.42	285	20	13700	7820	604	190
42257822	10858	10938	22.7	7.3	431	0	13482	8238	356	122
42258080	8656	8665	22.0	7.72	1290	75	12200	8290	121	0
42018945	9448	9453	21.9	6.8	982	375	11600	8570	310	97
42018717	9295	9328	21.9	7.4	1830	114	11700	8110	80	68
42257473	11070	11080	21.7	7.55	1410	320	11709	7849	371	0
42257785	8740	8763	21.6	6.05	410	52	13063	5741	1604	510
42257468	15242	15290	21.5	7.85	1669	360	11340	7838	277	0
42018730	9322	9331	21.3	6.5	2210	0	11100	7910	80	18
42018952	10144	10154	20.9	8	1420	317	11200	7840	60	24
42004741	10672	10677	20.8	7.01	1303	58	11413	7793	150	7
42257467	12432	12498	20.6	5.6	140	10	12758	4798	2160	526
42016956	10553	10574	20.4	6.4	214	25	12300	6950	750	134
42019883	7310	7314	20.3	7.2	580	-3	11900	7314	486	29
42258090	10862	10936	20.1	7.93	1625	88	10745	7327	64	67
42257705	10850	10960	20.0	7.9	1352	280	10771	7403	113	22
42257706	10850	10860	19.9	7.9	1329	200	10771	7357	113	22
42005128	9529		19.9	7.7	1220	9770	2400	5890	600	61
42257801	10883	11404	19.6	8.4	1135	25	10824	7353	118	12
42016517	10860	10870	18.7	7.4	1415	12	10200	6800	180	79
42257480	11697	12511	18.7	6.84	1160	20	10360	6915	140	12
42257820	9392	9414	18.0	8.45	344	0	10693	6279	421	148
42018601	11052	11062	17.9	7.3	1520	35	9600	6560	172	34
42257755	8038	8053	17.6	7.65	490	360	9928	6612	81	17
42004345	10065	10067	17.6	7.8	878	7900	2900	5660	150	91
42257493	5747	8766	17.4	7.35	1368	-3	9431	6457	125	17
42258324	14153	14381	17.4	8.33	654	108	9940	6028	565	21
42257817	9360	9424	17.3	7.05	272	0	10315	6001	502	100
42257451	12150	12170	16.8	7.7	1460	0	8975	6149	153	0
42257465	12432		16.7	7.86	1340	235	8820	6050	230	15
42257757	8485	8493	16.6	6.8	223	82	9792	5740	287	142
42018600	10646	10682	16.5	7.1	1770	90	8500	6000	140	35
42252781	8232	8247	16.4	7.23	1079	242	8862	5986	180	40
42257466	12432		15.4	6.6	610	4	8883	5505	394	16
42258297	14974	14997	15.2	6.84	637	212	8520	5291	481	0
42009897	11090	11118	14.9	7.32	2000	69	7310	5398	61	12
42257509	9042	9060	14.5	7.93	1219	520	8463	5689	184	160
42018065	8967	8990	14.2		2315	30	6709	5075	14	3
42004759	6064	6081	14.1	7.38	1139	12	7666	4985	252	75
42257469	15245	15290	14.0	7.4	938	620	7219	4650	545	31
42006894	7102	7130	13.9	6.8	1390	1	7300	5170	54	16
42257683	9360	9396	12.9	5.7	200	0	7626	4632	280	36

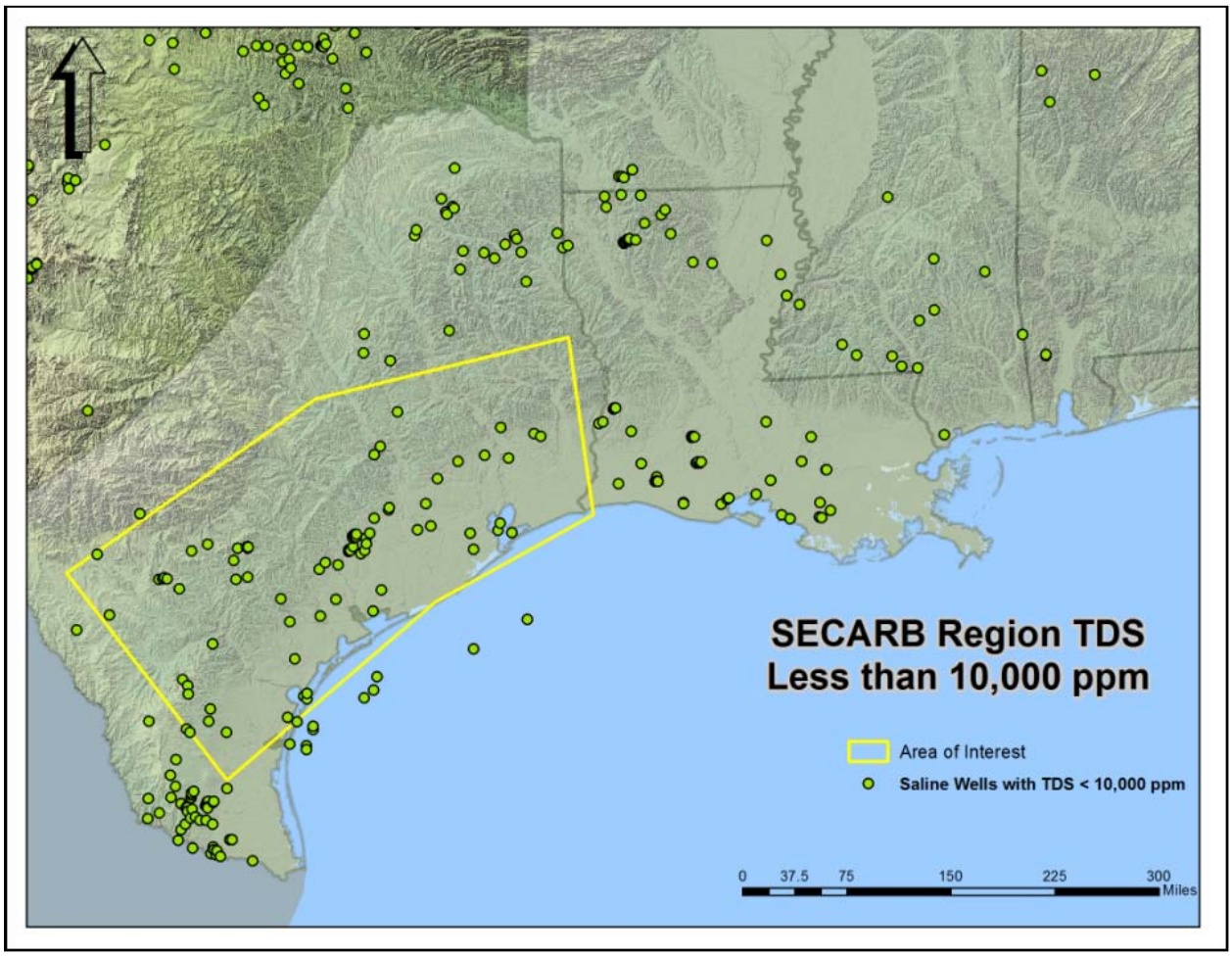


Figure A1a: NATCARB Wells in the SECARB Area with TDS Values below 10,000 ppm.

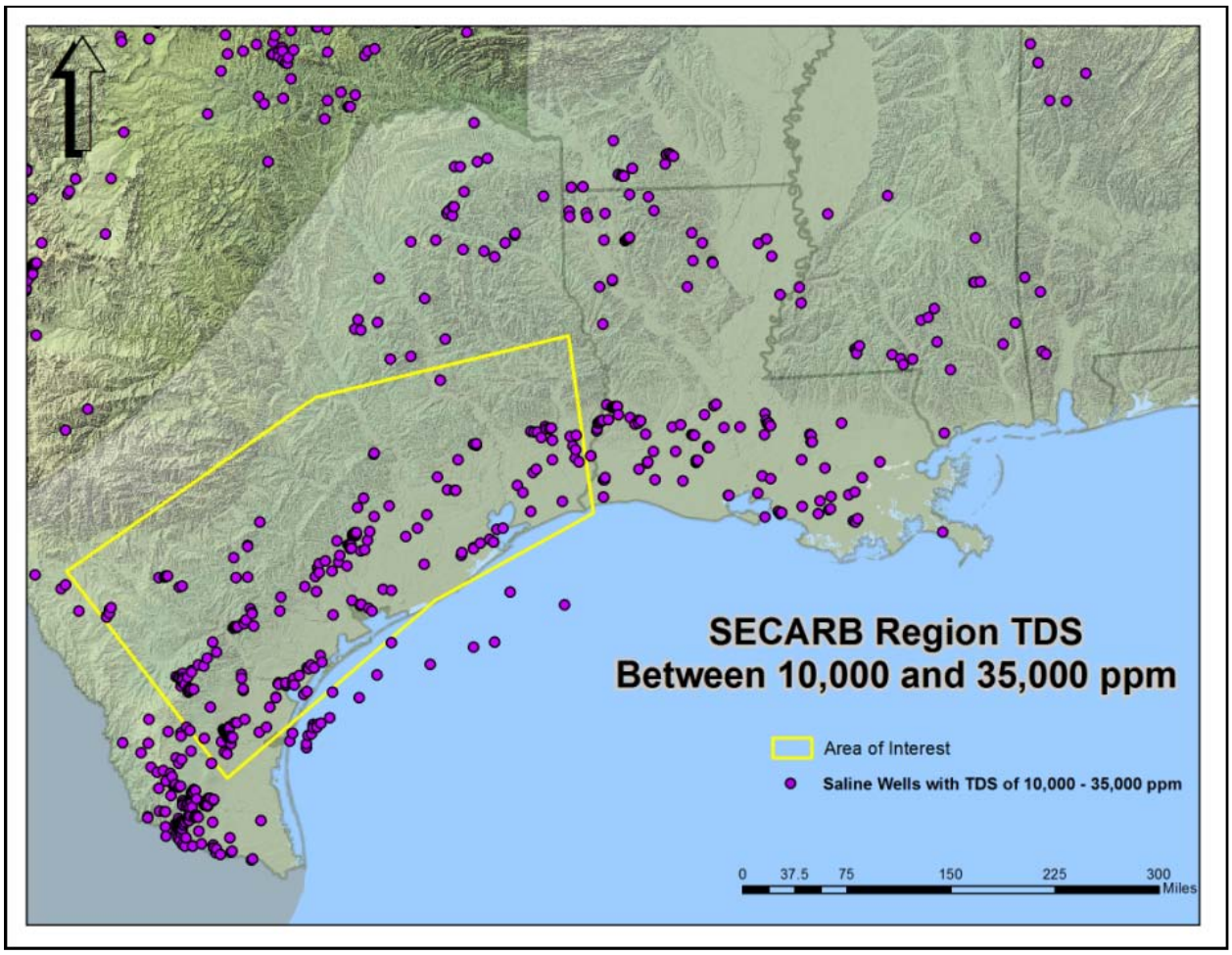


Figure A1b: NATCARB Wells in the SECARB Area with 10,000 – 35,000 ppm TDS Values.

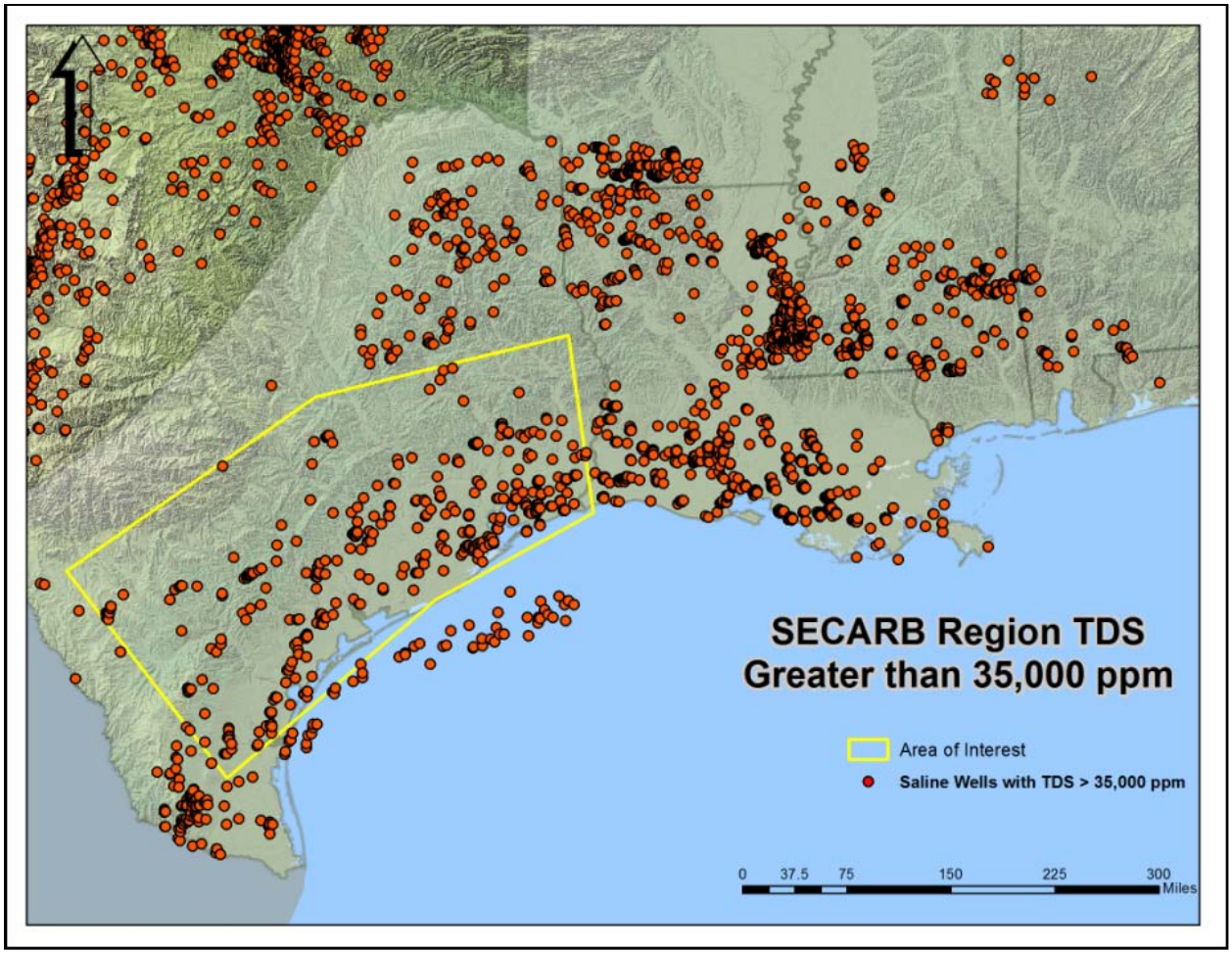
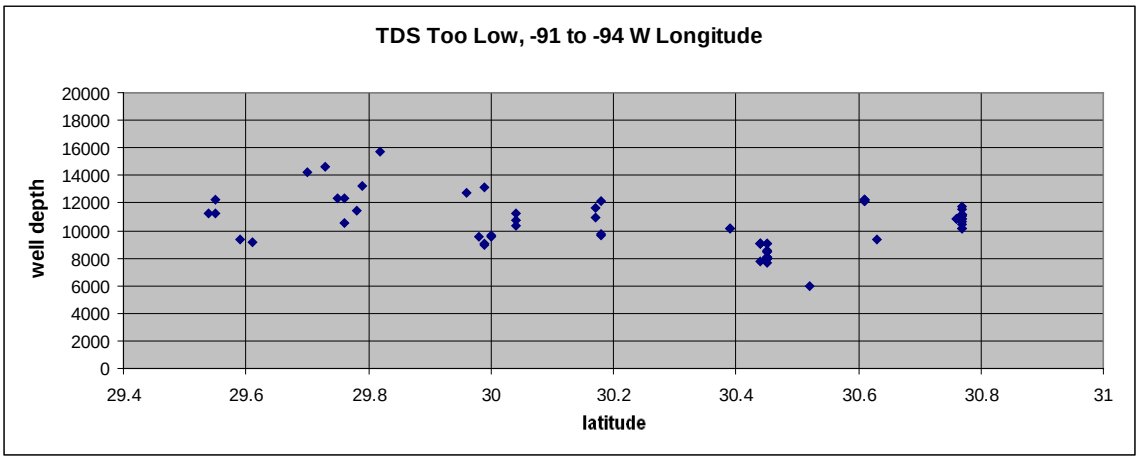
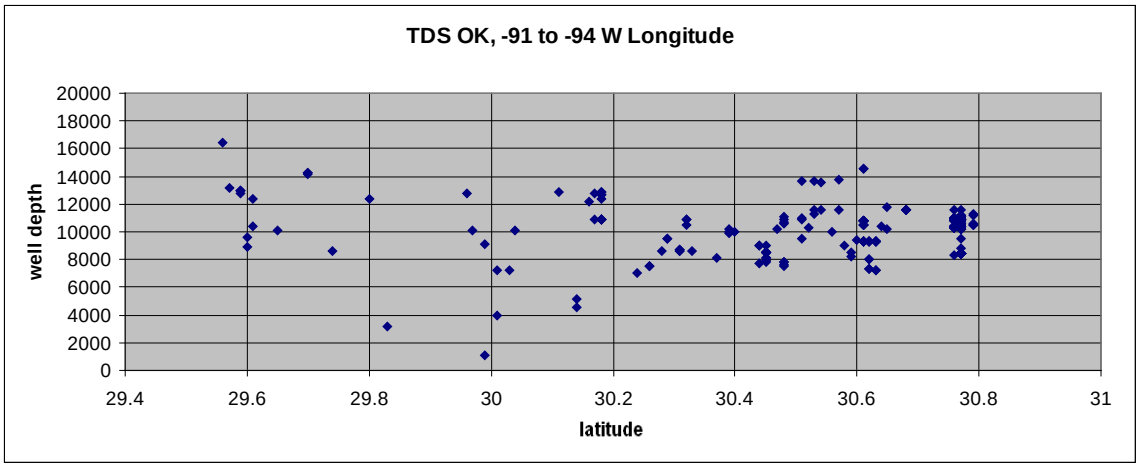


Figure A1c: NATCARB Wells in the SECARB Area with TDS Values Greater Than 35,000 ppm.





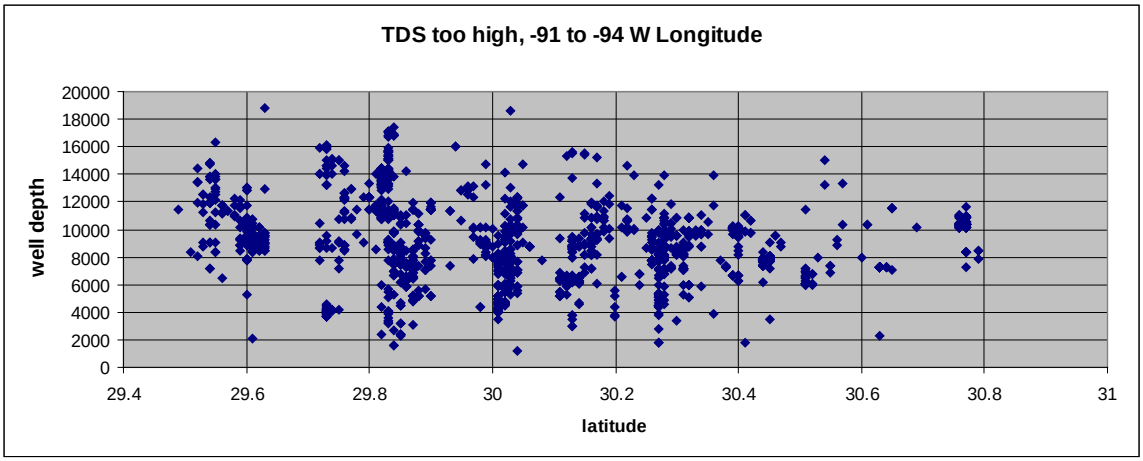
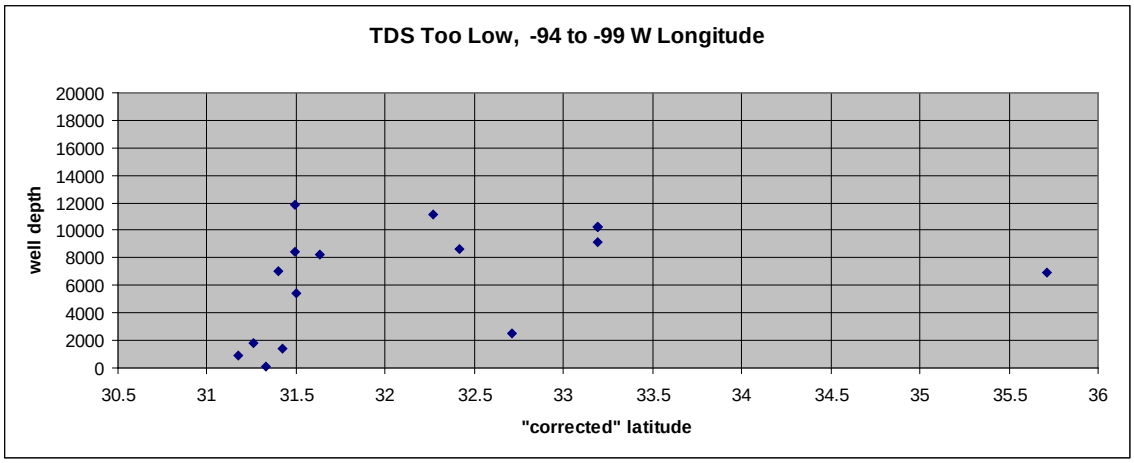
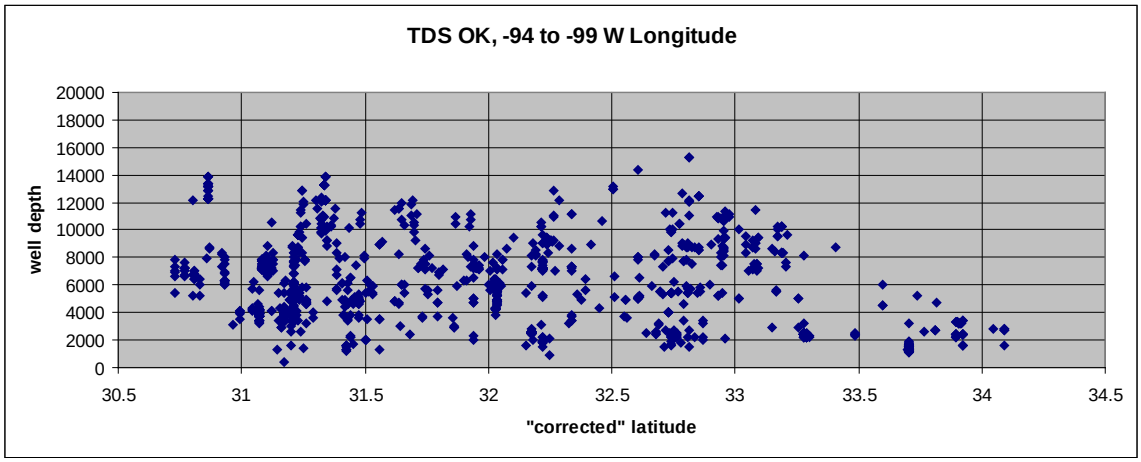


Figure A2 a,b,c: Vertical Section Illustrating Well Depth vs. Latitude for Low-, Medium-, and High-Salinity Fluid Wells in an East-West Swath Crossing Southern Louisiana, along with Well Depth in Feet.





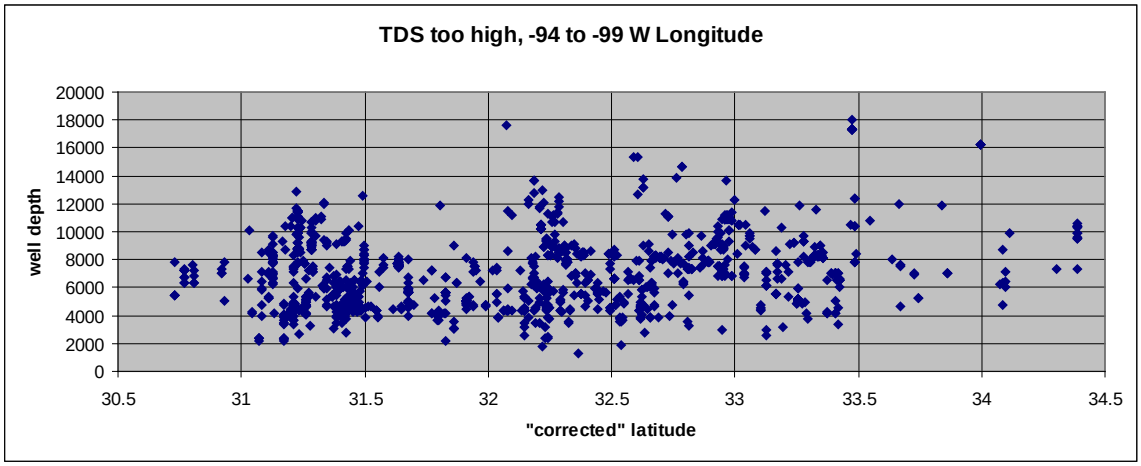


Figure A3a,b,c: Vertical Section Illustrating Well Depth & 'Corrected' Latitude for Low-, Medium-, and High-Salinity Fluid Wells in a Southwest-Northeast Trending Swath, Southern Texas, along with Well Depth in Feet.

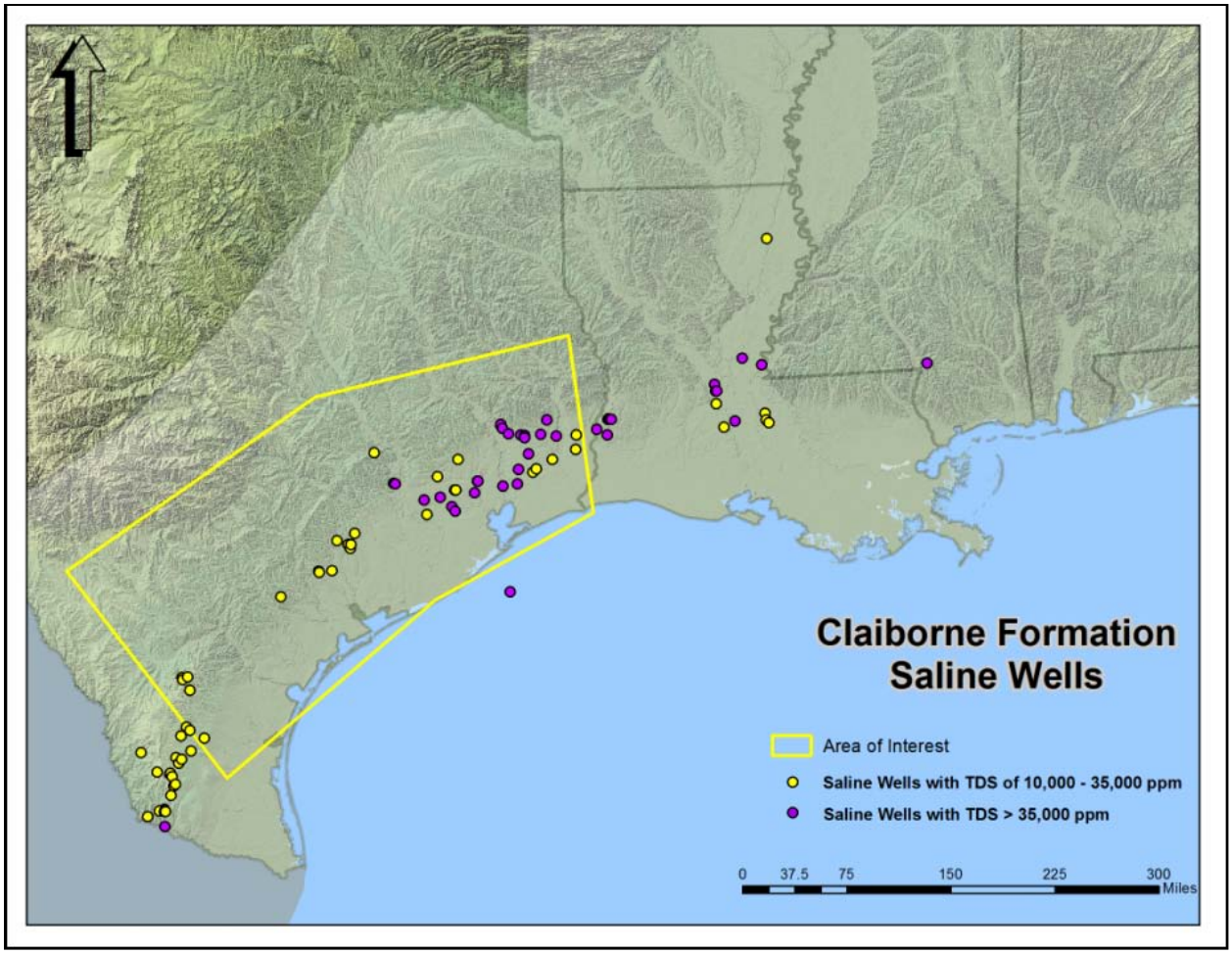


Figure A4: Distribution of High (Purple) and Mid-Salinity (Yellow) Wells, Claiborne Formation.

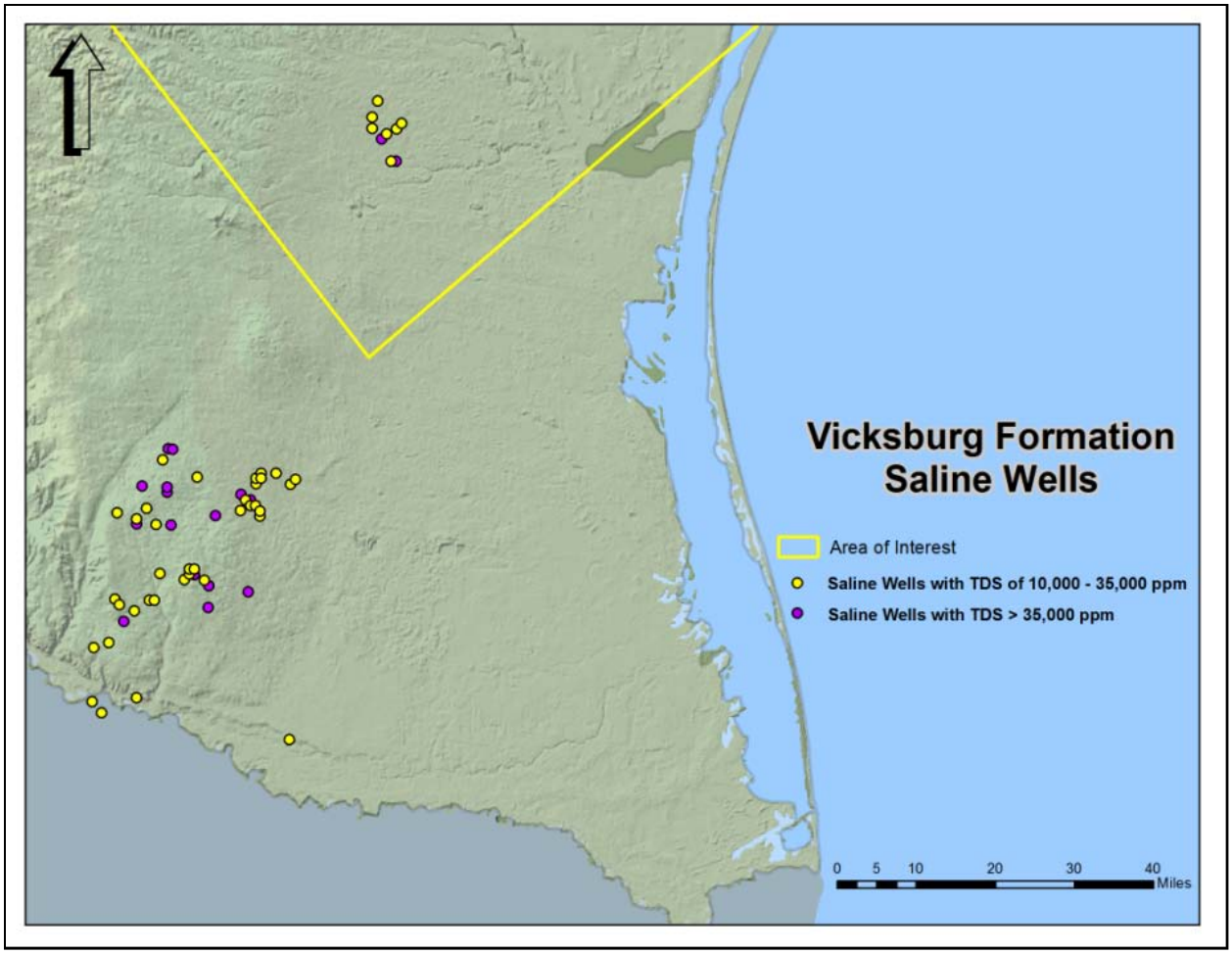


Figure A5: Distribution of High (Purple) and Mid-Salinity (Yellow) Wells, Vicksburg Formation.

Notes and Useful General Information Sources used to develop the extended Geoassessment presented in Appendix 1:

1. The USGS groundwater atlas: Referenced as USGS, 1999, U.S. Geological Survey GROUND WATER ATLAS of the UNITED STATES. The "home page" for the on-line version of the atlas can be found at http://pubs.usgs.gov/ha/ha730/gwa.html. However, while compiling this summary, numerous figures were extracted so, where applicable, the actual URL for that figure will appear with the figure caption.

2. For general USGS publications: http://pubs.er.usgs.gov/, and for the 2002 version of the USGS produced water database: http://energy.cr.usgs.gov/prov/prodwat/index.htm.

3. The NATCARB database contains a large compilation of well water chemistries from various formations; it can be accessed from
http://drysdale.kgs.ku.edu/natcarb/eps/natcarb_alpha_content.cfm As of October 26, 2009.

4. Hovorka, S. D., M. L. Romero, A. G. Warne, W. A. Ambrose, T. A. Tremblay, R. H. Treviño, and D. Sasson, 2000, "*Sequestration of Greenhouse Gases in Brine Formations*"; Texas Bureau of Economic Geology: http://www.beg.utexas.edu/environqlty/co2seq/dispslsaln.htm. Then go to "Examine Data" and to "Data Matrix."
Alternatively, regional brine chemistry summaries can be accessed directly through:
http://www.beg.utexas.edu/environqlty/co2seq/co2data.htm.

5. Energy Citations Database: http://www.osti.gov/energycitations/

6. Texas formation water chlorides database: http://gswindell.com/texasrw.htm#accesstxrw

7. USGS Produced Water Database, released 2002:
http://energy.cr.usgs.gov/prov/prodwat/index.htm

8. Georgia Geological Survey, 1999.

9. Geological Survey of Alabama, 2006.

Appendix B

Analytical Model

This section addresses the question of supercritical CO_2 migration in a gently sloping confined saline formation with no structural closure. This situation could arise, for example, following injection of CO_2 into Gulf Coast saline formations. This may be a concern because the buoyant CO_2 could migrate toward the earth's surface beneath a caprock and intersect the surface where the caprock/reservoir contacts outcrops. Use of a reservoir simulator (e.g., TOUGH2) to address this question was completed; however, the long transport distances in question require long numerical times for adequate resolution. A quicker, simpler way to constrain migration distances is to use a simplified numerical approach as was examined recently in Hesse et al. (2008; 2009).

Hesse et al. (2008; 2009) derive a simple model for the temporal and spatial evolution of the (assumed) sharp interface between injected CO_2 and brine, and account for residual trapping of CO_2 in the wake of the gravity current (buoyant CO_2 moving along the saline formation/caprock interface). These authors consider the flow of supercritical CO_2 with density ρ and viscosity μ_c, within a brine reservoir with brine density and viscosity of $\rho+\Delta\rho$ and μ_b respectively. The buoyant CO_2 flows within a sloping infinite saline formation of constant thickness H and dip angle θ. They neglect velocities in the z (vertical) direction and assume that pressure in each fluid type is hydrostatic. They also assume that capillary equilibrium is maintained. These are somewhat standard assumptions in studies examining sweep efficiency and fluid displacement made by petroleum engineers (see Hesse et al., 2008, for references). Other simplifying assumptions include constant and homogeneous saline formation flow properties and porosity.

Using conservation of mass principles, these authors derive the following model for the post-injection evolution of the CO_2 plume thickness h (which also locates the CO_2 brine interface in the 2-D aquifer studied).

$$\frac{\partial h}{\partial t} = \kappa \frac{\partial}{\partial x}\left[\frac{h(H-h)}{h(M-1)+H}(-\sin\theta + \frac{\partial h}{\partial x}\cos\theta)\right] \qquad (1)$$

Where M is the mobility ratio (measuring the contrast in the 2-phase mobilities across the advancing or contracting interface; $M = \frac{k_{rc}}{\mu_c}\frac{\mu_b}{k_{rb}}$ for k_{ri} = relative permeability of phase i) and the CO_2 conductivity κ is given by

$$\kappa_1 = \frac{k\lambda_c \Delta\rho g}{\phi(1-S_{br}-S_{cr})} \;\; for \;\; \frac{\partial h}{\partial t} < 0 \quad and \quad \kappa_0 = \frac{k\lambda_c}{\phi(1-S_{br})} \;\; for \;\; \frac{\partial h}{\partial t} > 0 \qquad (2)$$

Here the residual brine saturation S_{br} and the residual CO_2 saturation S_{cr} are assumed constant.

Letting $\eta = \frac{h}{H}, \xi = \frac{x}{L}, \sigma = \frac{\kappa}{\kappa_1}, and\ \tau = \frac{t}{L(\kappa_1 \sin\theta)^{-1}}$ and substituting into (1) yields the following dimensionless equation (L is the width of the initial injected plume):

$$\frac{\partial \eta}{\partial \tau} = -\sigma \frac{\partial f}{\partial \eta}\frac{\partial \eta}{\partial \xi} + \frac{\sigma}{P_e}\left[\frac{\partial f}{\partial \eta}\left(\frac{\partial \eta}{\partial \xi}\right)^2 + f\frac{\partial^2 \eta}{\partial \xi^2}\right] \tag{3}$$

with σ expressing the step function in equation (2) as

$$\sigma = 1\ when \frac{\partial \eta}{\partial t} < 0\ (thinning\ plume)\ and\ = 1-\varepsilon\ when\ \frac{\partial \eta}{\partial t} > 0\ (thickening\ \ plume) \tag{4}$$

Here $\varepsilon = \frac{S_{cr}}{1-S_{br}}$. In (3), the Peclet number Pe is given by $A_0\tan\theta$, and the flow function f is given by:

$$f = \frac{\eta(1-\eta)}{\eta(M-1)+1} \tag{5}$$

A numerical solution to (3), (4), and (5) is conveniently found using the NDSolve routine in MATHEMATICA (Wolfram, 2003). As an example, we use the discussion and parameters in Hesse et al. (2008), relevant to the storage of CO_2 in the Carrizo-Wilcox saline formation (Figure B1) derived from the study by Nicot (2008). Parameters are as follows: H = 200 km, k = 500 mD, ϕ = 0.15, average injection depth equals 2.7 km and so $\Delta\rho$ = 300 kg/m^3, dip angle θ = 1.5^o, S_{cr}=S_{br}=0.2, μ_b/μ_c=10, k_{rc}=0.2, and k_{rb}=1. At the end of 50 years of injection, the average horizontal size of the plume L is given as 10 km, and the initial aspect ratio of the plume A = L/H = 50. This yields parameters for (3) of P_e = 1.4, ε = 0.25 and M = 5.

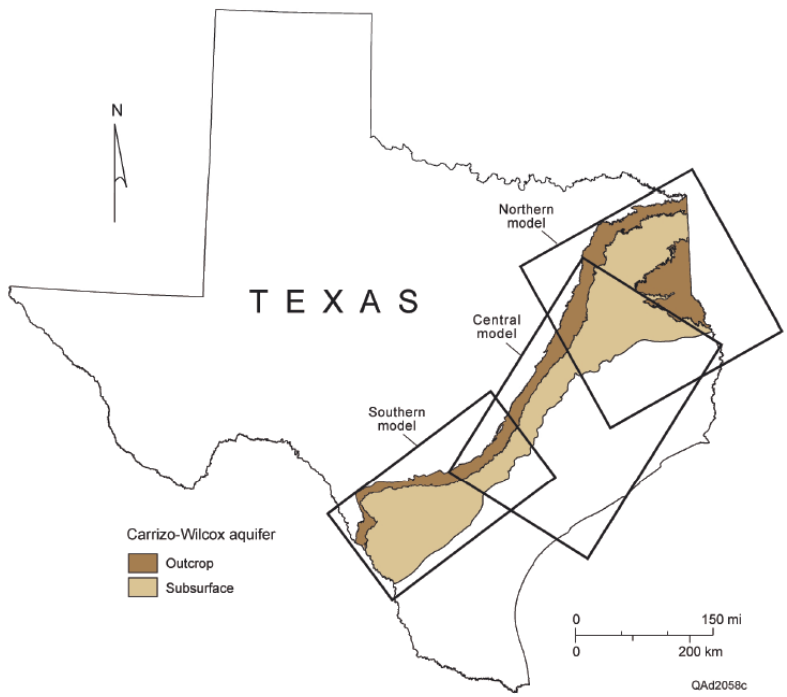


Figure B1: Outcrop and Subsurface Extent of Carrizo-Wilcox saline formation.
(from Dutton et al., 2003)

With these parameters, the solution to (3-5) is shown graphically below for dimensionless times τ = 0, 15, 75, 100, and 150 (updip is in the direction of increasing ξ). Here we plot only the remaining plume (i.e., we do not plot the residual CO_2 trapped behind the gravity wave).

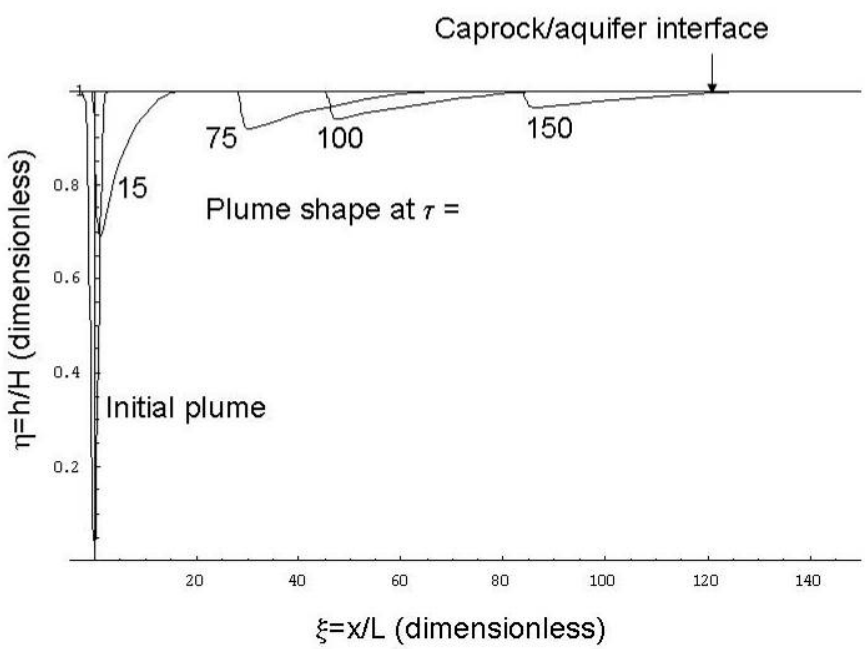


Figure B2: Temporal and Spatial Evolution of Plume of Mobile Supercritical CO_2, from Numerical Solution of Model in Equations (3, 4, and 5).

The full time evolution of the morphology of the front is depicted in Figure B3:

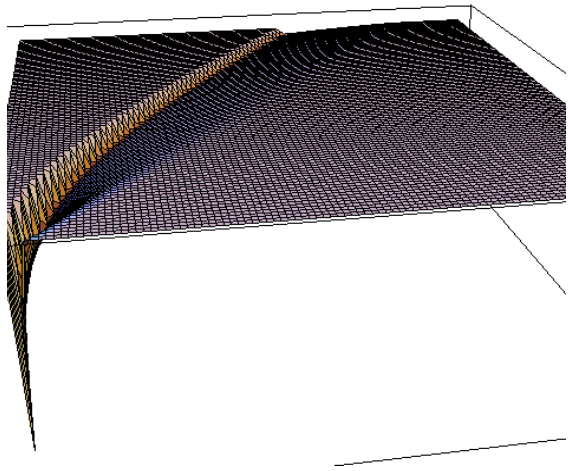


Figure B3: 3-D View of Plume Shape Evolution.

The values of τ = 15, 75, 100, and 150 have maximum ξ distances roughly equal to 15, 65, 85, and 125 respectively. For L = 10 km, k = 1.93e-5 m/s, yielding a characteristic time t_a ~ 820 years. In dimensional form, these τ and ξ values correspond to the following:

τ_{max}	ξ_{max}	t_{max}(thousand years)	x_{max} (km)
15	15	12	150
75	65	61	750
100	85	82	1000
150	125	123	1500

With an average distance from subsurface to outcrop in the Carrizo-Wilcox saline formation of, say, 100 km (Figure B1), these results suggest that in no way will all CO_2 be trapped as an immobile residual phase; that is, CO_2 will remain mobile to the surface. In addition, it would take on the order of 9,000 years to reach the surface if this model and the above parameters are at all representative. Note that in addition to all the above-mentioned assumptions and simplifications inherent in this model, there is no account of the phase change that would encounter the CO_2 (i.e., from supercritical to gas phases) as it rises through the saline formation.

This analysis could easily be adapted to address similar question of CO_2 migration and extent in other Gulf Coast saline formations. Note for simplicity, we used an initial plume shape equivalent to a Gaussian distribution and that other initial plume forms could be used.

Figure B4 shows a geologic framework model of the layered clastic system prepared from formation tops extracted from the Dutton et al. (2003) and Kelley et al. (2004) GAMs and kriged using C-Tech's MVS software. This framework model was used to construct the TOUGH2 grid as shown in Figure B5. The coarse grid has been refined to allow for good numerical resolution around injection and abstraction wells. Formation permeability and heterogeneity therein have been mapped onto the model grid using the distribution of hydraulic conductivity derived from

the GAM. This approximates the down-dip fining of the regressive sand-silt-shale sequences, locations of fault systems, and the sandier portions of fluvial-deltaic sequences making up these formations (which may act as CO_2 conduits).

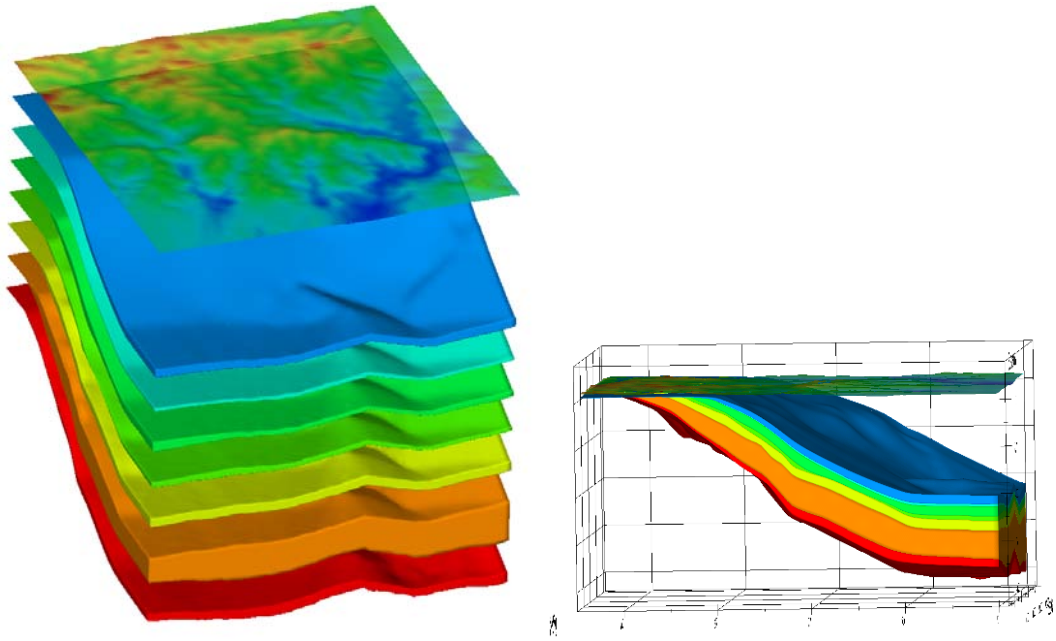


Figure B4. Geologic Framework Model for Carrizo-Wilcox System. This refers to the bold rectangle in Figure 3-1, created using formation tops and thicknesses from the Texas Water Development Board (TWDB) Groundwater Availability Model. Both left and right figures assume a 20x vertical exaggeration

In the Figure B4, the exploded view (left) and cross section (right) assume 20x vertical exaggeration. The red layer is the Simsboro Formation, orange is the Calvert Bluff (both of the Wilcox Group) yellow-green is the Carrizo Formation, and the remaining overlying layers are the Reklaw, the Queen City, Weches, and Sparta Formations in order of decreasing depth. The top surface shown is derived from a USGS digital elevation model for the region. The cross section on the right is a little south of the cross section line depicted by Nicot (2008).[5]

Boundary conditions for the TOUGH2 model assume closed flow boundaries on the sides and at the Wilcox growth fault boundary and are open to flow at the top. Later versions of this model will explore allowing heavy CO_2-laden aqueous solutions to sink by gravity into the lower Hooper Formation of the Wilcox Group (currently disabled).

[5] Nicot (2008) illustrate this in Figure 1 of his work.

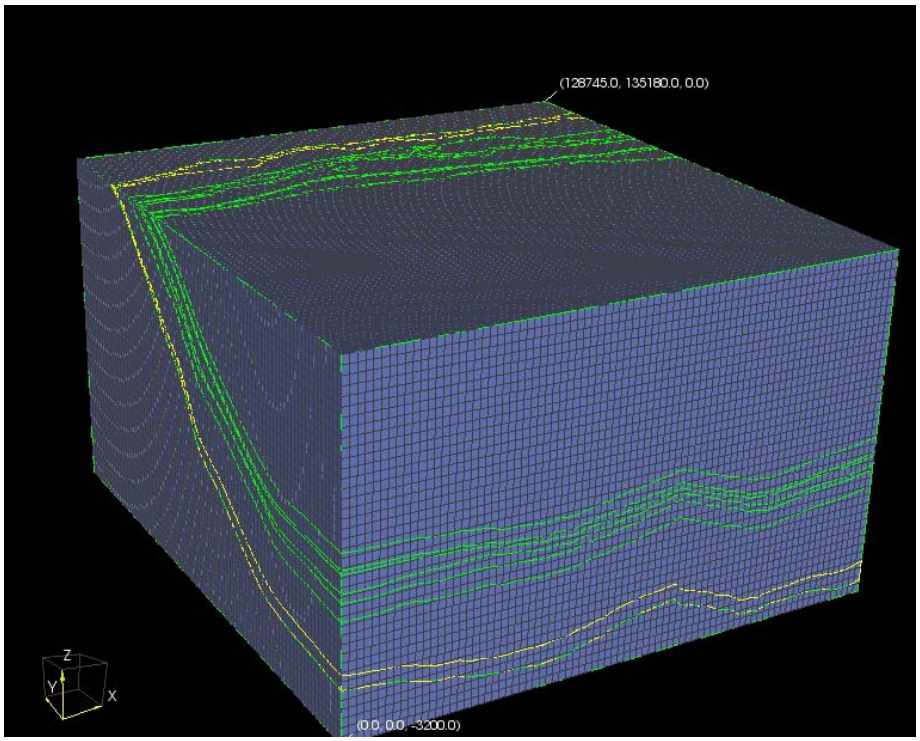


Figure B5: TOUGH2 Simulation Domain.
Coarse gridding at approximate size of 1.5 km in x and y and 80 m in z, with 20x vertical exaggeration. The Simsboro Formation shown in yellow and the overlying Calvert Bluff and Carrizo Formations are suggested targets for CO_2 storage.

Simulations

Preliminary TOUGH2 runs have been completed on a simplified version of the grid because of size constraints by TOUGH2 gridblock naming conventions, which limit the total number of gridblocks to 99,999 cells. For these runs, we use a grid system 20x42x80 in x, y, and z. Our region is 0 to 128747 m in x, 0 to 135185 m in y, and -3540 to 0.0 in z (for simplicity, we have taken the top of our domain to be at sea level). This produces a grid block size of 6437.4 m in x, 3218.7 m in y, and 40.25 m in z. This is not as good as the horizontal resolution of the Carrizo Wilcox GAM (1 square mile) but improves on the vertical resolution (the GAMs use 1 grid block per layer for 6 layers). An injection well was completed over a 100 m interval at {x,y,z}= {5.5255e4, 2.7514e4, -2.85412e3} where the z value denotes bottom hole. At this depth, all CO_2 is injected as a dense supercritical fluid, but as density decreases as a CO_2 plume rises as a result of temperature and pressure decreases, the volume occupied by the same mass of CO_2 increases.

This coarse grid is shown in Figure B6. Cells down-dip of the Wilcox Growth Fault region are disabled as are cells beneath the target Simsboro Formation. The growth-fault zone is thus taken as a hydrological boundary as was done for the Carrizo-Wilcox GAM. A pressure gradient of 0.01 MPa/m, with surface pressure of 0.1 MPa, was applied as an initial condition. An initial temperature distribution was given by a surface temperature of 15 °C and a vertical gradient of 25 °C/km. Finally, a salinity gradient equaling 50,000 ppm per 3,000 m was applied initially, with a surface TDS of 500 ppm (assuming all dissolved solids as NaCl), was applied to the

model. A linear increase of salinity with depth is seen in virtually all Gulf Coast formations (Dickey, 1969); our range is consistent with observed salinities in the normally-pressured portion of the Wilcox Formation of interest here (Figure 3-1) but is less than is observed farther north in the Wilcox off the coast of Texas and Louisiana where Wilcox groundwater salinities show impact by presence of salt domes.

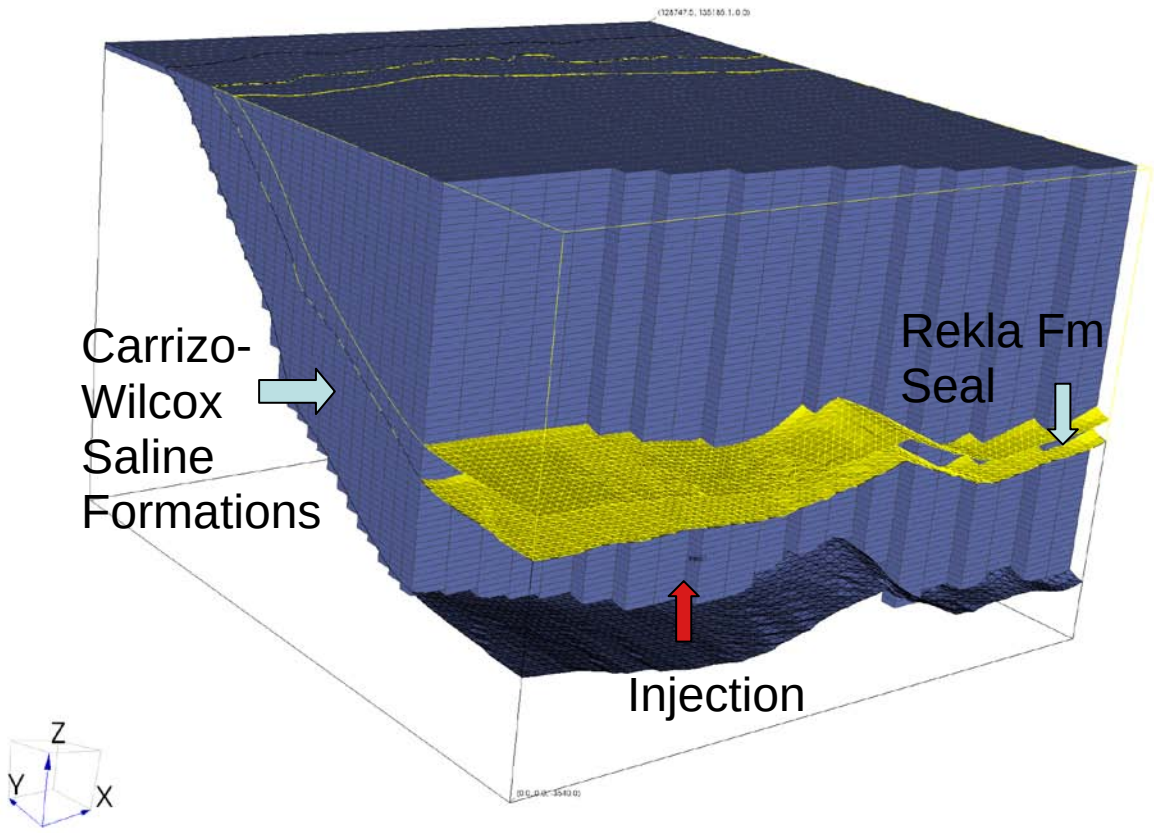


Figure B6: Updip Limit of Wilcox Growth Fault System (which acts as the eastern hydrologic boundary, and coarsened grid for regional TOUGH2 simulations). Yellow surfaces mark the upper and lower extent of the Eocene Reklaw Formation, which acts as a regional hydrologic seal. Injection zone in the Simsboro Formation of the Wilcox Group is shown by red arrow. Figure has 20x vertical exaggeration.

A series of CO_2 injection simulations was undertaken to check sensitivities of unknown parameters. Injection of CO_2 was maintained constant at 1 MTonnes/year. The most uncertain of the parameter set for the Carrizo-Wilcox GAM and required by the TOUGH2 runs is vertical permeability (Dutton et al., 2004). Anisotropy in hydraulic conductivities (denoted as a ratio of vertical to horizontal conductivities = Kv/Kh) ranges from unity to 10^{-4}. Although heterogeneity in hydraulic conductivity was constrained by the calibrated MODFLOW models in the GAM, we assume average permeabilities for each of the

formations (calculated from the GAM—we will investigate the influence of permeability heterogeneity as part of our ongoing study—this will be reported elsewhere) and examine variations in the Kv/Kh values. Figures B7 to B10, corresponding to a Kv/Kh value of 1.0, 0.1, 0.01, 0.001 respectively, show a range of behaviors from complete vertical leakage at Kv/Kh = 1.0, to nearly complete sealing and updip migration of the CO_2 plume through mostly the Carrizo Formation at Kv/Kh = 0.01. Reasonable values of Kv/Kh in the Reklaw Formation range from 0.01 to 0.001 (Dutton et al., 2003; Kelley et al., 2004), so it seems reasonable to expect that while most CO_2 will migrate updip, a substantial amount will leak into the Reklaw and above formations.

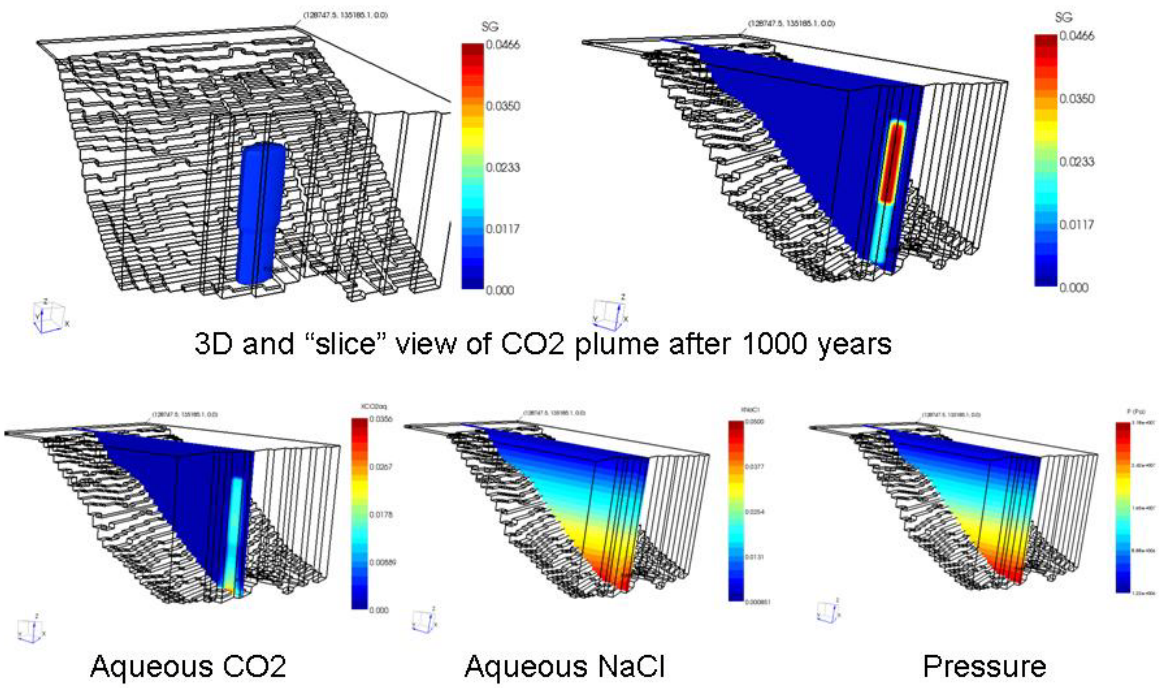


Figure B7: CO_2 Saturation, Aqueous CO_2, Aqueous NaCl, and Pressure (in Pa) in an Injection Scenario where CO_2 Is Injected at a Rate of 1 MTonnes/Year. The Reklaw seal in this case is taken to have homogeneous isotropic permeability equal to 3.0e-15 m^2. In this case, the CO_2 plume ponds beneath the Rekla, but dominantly migrates vertically displacing aqueous NaCl and pressure slightly upwards into the overlying strata. Figure shows 20x vertical exaggeration.

In Figure B7, with isotropic and homogeneous permeability in the Reklaw seal (which is two orders of magnitude less than the average permeability in the underlying Carrizo-Wilcox System), CO_2 is seen to migrate vertically through the overlying strata and not confined beneath the Reklaw seal. Breakthrough to the surface occurs in ~1,500 years. There is a slight perturbation of salinity and fluid pressure above the rising plume in the overlying formations.

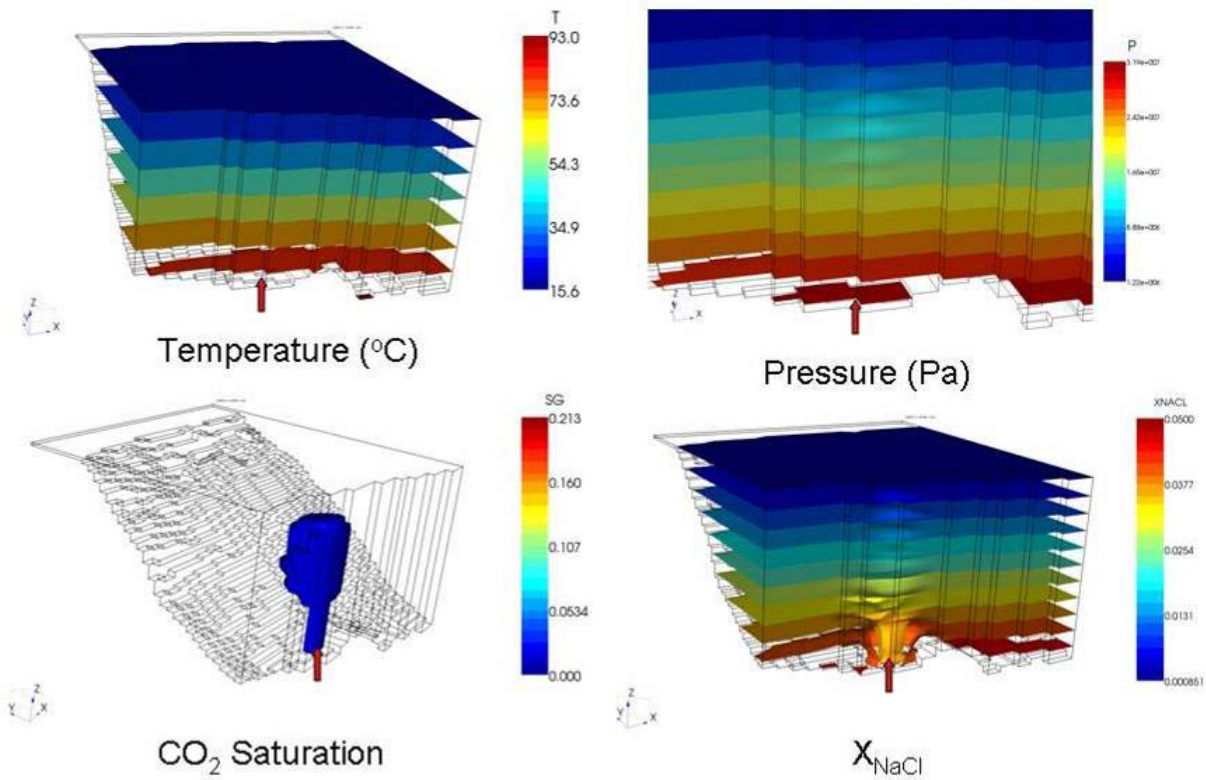


Figure B8: Temperature, Pressure, Gas Saturation, and Mass Fraction of Aqueous NaCl after 4,770 Years of CO_2 injection at Constant Rate of 1 MTonnes/Year with Kv/Kh = 0.1. Figure shows 20x vertical exaggeration.

In Figure B8, showing a similar simulation but with a slight Kv/Kh ratio of 0.1, there is more ponding of the CO_2 plume, but movement is still dominantly vertical, and breakthrough to the surface occurs after ~5,000 years. Pressure is slightly elevated above the plume in the shallow portions of the model. The CO_2 "ponds" beneath the Reklaw seal and spreads, but substantial vertical leakage is observed. Salinity is seen to "dry-out" from the pore spaces occupied by the CO_2 plume, and some amount of more saline water is seen to intrude into the overlying formations.

In Figure B9, with Kv/Kh of 0.01, the Reklaw here acts as a decent seal and CO_2 is confined to updip migration within the Carrizo Formation. Decreasing the Kv/Kh to 0.001 (Figure B8) ensures a reasonable capillary seal to vertical migration, and the CO_2 plume migrates just beneath the Reklaw within the Carrizo Formation. The migrating "tongue"- shaped plume reaches the location of existing groundwater wells in the Carrizo (shown in yellow in Figure 3-1) after approximately 5,000 years. Enriched aqueous CO_2-bearing waters will reach the Carrizo wells sometime just prior to arrival of gas-bearing waters. It is important to note also that of the 5,000 MTonnes (5e12 kg) injected in this model, about half (2,512 MTonnes) exists as a supercritical phase, and half (2489 MTonnes) is dissolved in the surrounding aqueous phase.

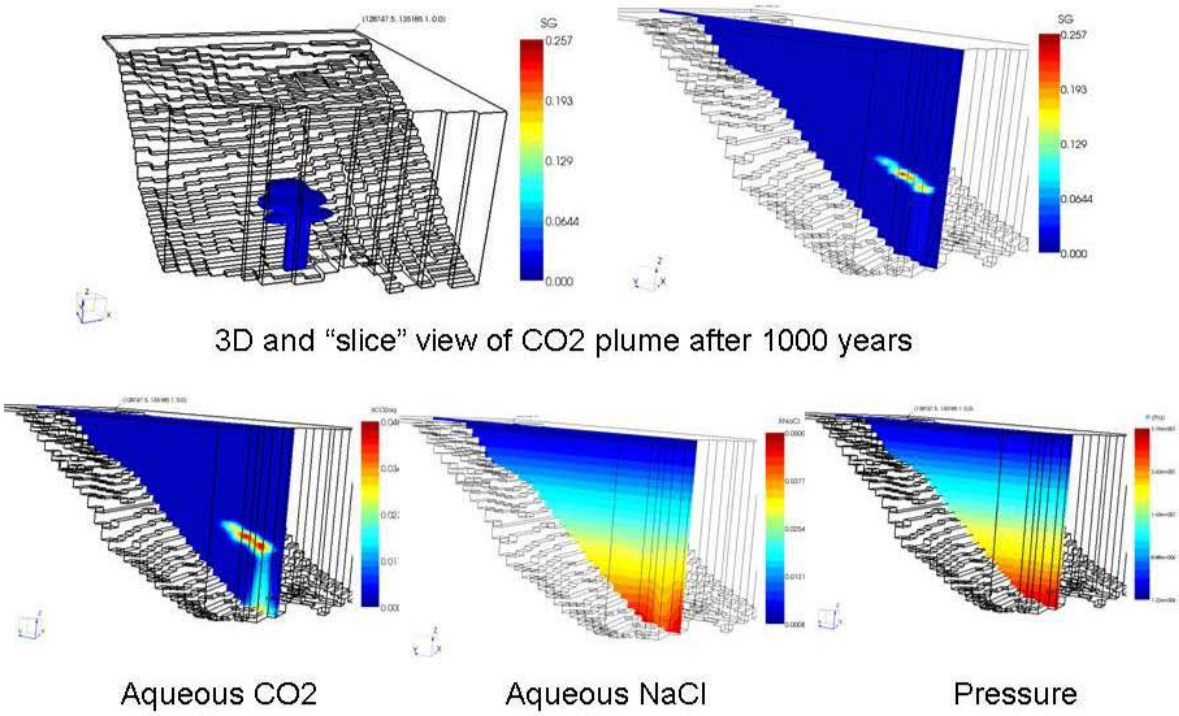


Figure B9: CO_2 Saturation, Aqueous CO_2, Aqueous NaCl, and Pressure (in Pa) in an Injection Scenario Where CO_2 Is Injected at a Rate of 1 MTonnes/Year. The Rekla seal in this case is taken to have a Kv/Kh ratio of 0.01, and as a result, the CO_2 is retained beneath the Reklaw and migrates up dip through the Carrizo formation. There is little displacement of the pressure contours, and a slight updip migration of salinity, after 1000 years. Figure shows 20x vertical exaggeration.

Future work could include the effects of including permeability heterogeneity, particularly the updip increase in vertical permeability, taken from the Carrizo-Wilcox and Queen City-Sparta TWDB GAMs (Dutton et al., 2003; Kelley et al., 2004). Also, one could include additional injection wells within the simulation domain to accommodate 90% of the 11.9 Mtonnes of CO_2 output by the nearby Fayette Power Project plant and associated water-withdrawal wells for power plant usage.

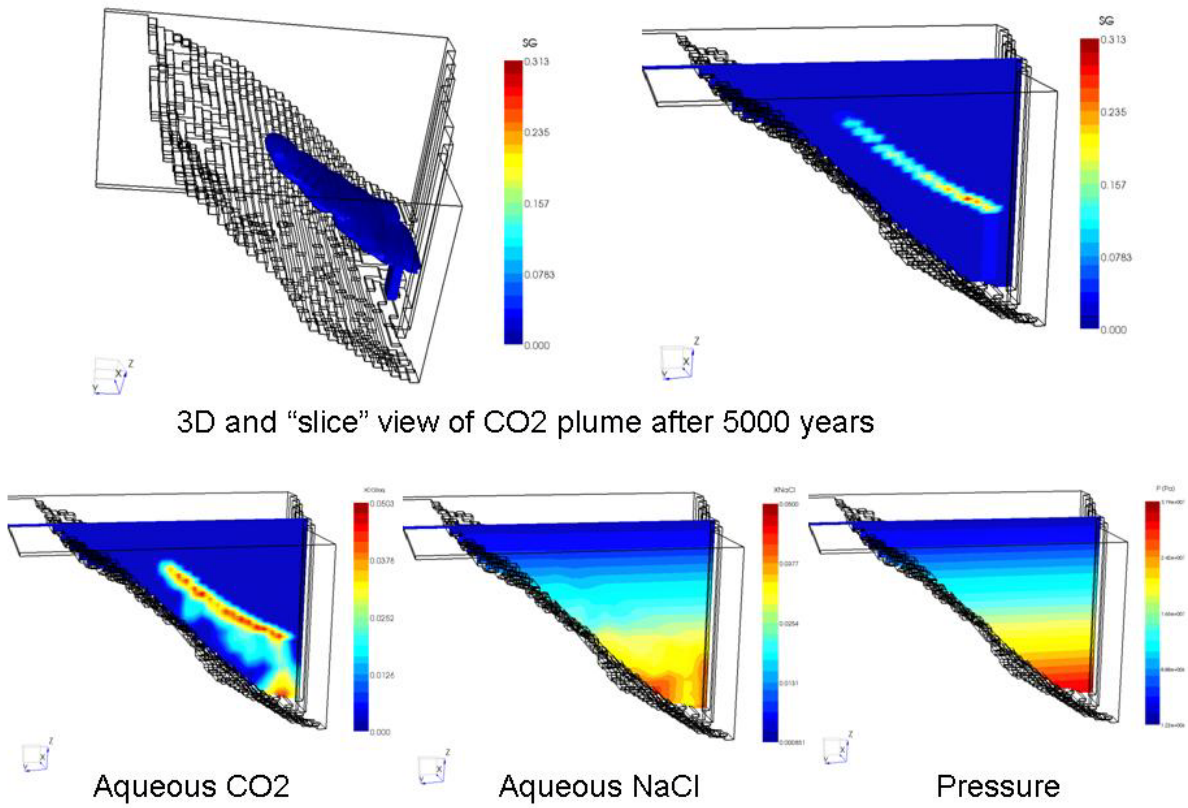


Figure B10: CO_2 Saturation, Aqueous CO_2, Aqueous NaCl, and Pressure (in Pa) in an Injection Scenario Where CO_2 Is Injected at a Rate of 1 MTonnes/Year. (The Reklaw seal in this case is taken to have a Kv/Kh ratio of 0.001, so the CO_2 is retained beneath the Reklaw and migrates updip through the Carrizo Formation.) After 5,000 years, there is a slight updip migration in salinity and a very slight pressure disturbance propagating updip. Figure shows 20x vertical exaggeration.