COLLECTION AND ANALYSES OF PHYSICAL DATA FOR DEEP INJECTION WELLS IN FLORIDA

by

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A Thesis Submitted to the Faculty of

The College of Computer Science and Engineering

in Partial Fulfillment of the Requirements for the Degree of

Master of Science

Florida Atlantic University

Boca Raton, Florida

August 2010

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ACKNOWLEDGEMENTS

First and foremost, I would like to thank my advisor Dr. Fredrick Bloetscher, for providing me the opportunity to explore the interesting world of Deep Injection Wells. He shared his knowledge and spent numerous days and nights to proofread my paper.

Besides my advisor, I would like to thank the rest of my thesis committee: Dr. Daniel Meeroff, who offered valuable comments to challenge and better my work, Dr. Jarice Rodriguez-Seda, who helped me to brainstorm the statistical analyses part of the thesis, Dr. Khaled Sobhan, who always ensured my graduation paperwork go smoothly.

Finally, I would like to thank those closest to me, whose presence helped make the completion of my graduate work possible. My husband, Seneca House, thanks for providing love, patience, and understanding. I am grateful to my family, my dad He Ji Gao, my mom Xiao Yin Cheng, and my stepmom Shun Ji Han. To them I dedicate this thesis.

ABSTRACT

Author: Jie Gao

Title: Collection and Analyses of Physical Data for Deep Injection Wells in Florida

Institution: Florida Atlantic University

Thesis Advisor: Dr. Fredrick Bloetscher

Degree: Master of Science

Year: 2010

Deep injection wells (DIW) in Florida are regulated by the U.S. Environmental Protection Agency (USEPA) and the state of Florida through the Underground Injection Control regulations contained within the Safe Drinking Water Act. Underground injection is defined as the injection of hazardous waste, nonhazardous waste, or municipal waste below the lowermost formation containing an underground source of drinking water within one-quarter mile of the wellbore. Municipalities in Florida have been using underground injection as an alternative to surface disposal of treated domestic wastewater for nearly 40 years. The research involved collecting data as of September, 2007 on all the Class I DIWs in the state of Florida and evaluating the differences between them. The analysis found regional differences in deep well practice and canonical correlation analyses concluded that depth below the USDW is the most significant factor to prevent upward migration of the injected fluid.

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CHAPTER 1 BACKGROUND

1.1 Introduction

Florida is a groundwater-rich state. High quality groundwater underlies virtually all of the state. Over 90 percent of the 18 million residents and 42 million annual visitors rely on groundwater for their water supplies. In addition, 50 percent of all other water users, including agricultural, industry, mining, and electrical power generation, are also supplied by groundwater (FDEP, 2008).

When one envisions wells, they are equated with a means to withdraw drinking water supplies to serve human needs. As defined by Merriam Webster dictionary (2008), a "well" is a hole or shaft in the earth dug or drilled to tap an underground supply of water, gas, oil, etc. However, wells are also used to inject liquid underground. When fluid is placed thousands of feet below surface through a well, the system is called a Deep Injection Well (DIW). The DIW practice is also referred to as "subsurface disposal," "underground injection," and "deep disposal."

DIWs in Florida are regulated by the U.S. Environmental Protection Agency (USEPA) and the State of Florida through the Underground Injection Control regulations contained within the Safe Drinking Water Act. Underground Injection is defined as the injection of hazardous waste, nonhazardous waste, or municipal waste below the lowermost formation containing an underground source of drinking water (USDW) within one-quarter mile of the wellbore (USEPA, 2001). The USDW is defined as an aquifer or its portion which contains sufficient quantity of groundwater to supply a public water system and either currently supply drinking water for human consumption or contains a total dissolved solids (TDS) concentration of less than 10,000 milligrams per liter (mg/L) and is not an exempted aquifer from protection as a source of drinking water (40 CFR 144.3, 2007). Any USDW should be free from degradation in its quality through isolation from injection zones. The criterion is conservative because water at the 10,000 mg/L TDS threshold is much too saline to be acceptable as normal drinking water without substantial treatment (Keith *et al.*, 2005).

Florida is the only state in the country that disposes of treated domestic wastewater through DIWs (USEPA, 2000). Robert Maliva writes that, in the absence of deep well injection, the liquid wastes would require higher treatment levels, with associated greater costs, but could be disposed of more readily through surface discharges and ocean outfalls (Maliva *et al.*, 2007). All other states only utilize the DIWs for disposing of hazardous materials and liquids, while the majority of treated wastewater is discharged to rivers and streams, with a small portion reused in some manner (Bloetscher *et al.*, 2005). Over 100 municipalities in Florida have been using underground injection as an alternative to surface disposal of treated domestic wastewater, some for as many as nearly 40 years (USEPA, 2005). In 2000, statistics show that approximately 22 percent of Florida's domestic wastewater from centralized treatment systems is disposed through deep aquifer injection wells and 44 percent through surface water outfalls as shown in Figure 1. The remainder is managed through other groundwater disposal systems, such as percolation ponds, spray fields, and rapid infiltration basins (USEPA, 2005).

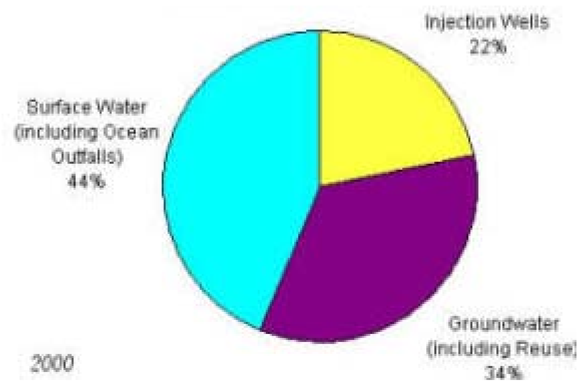


Figure 1 **Effluent Disposal of Municipal Wastewater in Florida (USEPA, 2005)**

There are reasons why Florida has implemented DWIs for injection disposal. First are its unique hydrogeologic conditions. The injection zone is highly permeable and located deep underground. Particularly in South Florida, the injection zone is located over 2,500 feet below the surface. In contrast, groundwater drinking source is much shallower, within a few hundred feet of the ground surface. Between the two is a confining layer that separates the two systems. In south Florida, this confining layer is dense clay that prevents negative impacts on USDW from migration of the injected wastewater. Even with reclaimed water systems, a back-up disposal mechanism is needed that has the same capacity as the plant. Injection wells solve this issue. Severe local restrictions on other types of wastewater disposal alternatives, such as limitations on water quality of discharges to surface water and land application have also increased the use of injection wells (USEPA, 2001).

1.2 History and Regulations

1.2.1 US UIC Program

History of underground injection can be traced back to China in A.D 300 and France in the 9th Century where water was injected into a cavity to extract salt (USEPA, 2008). According to the USEPA, the US has its first documented injection of fluid into wells to extract additional oil and gas in the early 1930s in Texas. Industrial waste injection started in the 1950 with Dow Chemical injecting industrial fluids in Michigan. In the mid 1960s and 1970s, injection began to increase sharply, growing at a rate of more than 20 new wells per year (USEPA, 2001).

In 1968, there was an episode of waste spilling out of an abandoned oil well with the Hammermill Paper Company in Erie, Pennsylvania, followed by several other cases of well failures for hazardous materials in 1974 and 1975, which occurred at the Velsicol Chemical Corporation in Beaumont, Texas (USEPA, 2001). An inspection revealed wastewater leaks in the well's casing into a USDW. This attracted attention of USEPA about the impact of deep-well disposal practices and Congress took immediate action. On December 16, 1974, President Ford signed the Safe Drinking Water Act (SDWA) into law, giving USEPA the authority to protect underground drinking water sources from unsafe injection practices (SDWA, Part C, Sections 1421-1426). After several years of studying and planning, USEPA promulgated the Underground Injection Control (UIC) regulations in 1980 (USEPA, 2008). This regulatory program stresses to ensure that injection activities are performed safely, protect USDW, and preserve future underground water resources.

To support this effort, USEPA developed the Statement of Basis and Purpose for the UIC program. Six pathways of contamination were identified as potential problems of jeopardizing USDW in the referenced document. These pathways described as following (USEPA, 1980):

1. Movement of fluids through a faulty injection well casing;

2. Movement of fluids through the annulus located between the casing and well bore;
3. Movement of fluids from an injection zone through the confining strata;
4. Vertical movement of fluids through improperly abandoned and improperly completed wells;
5. Lateral movement of fluids from within an injection zone into a protected portion of that stratum; and
6. Direction injection of fluids into or above an underground source of drinking water.

1.2.2 Florida UIC Program

The first recorded instance of deep well injection in Florida was in 1943. Brine produced as a by-product of oil extraction from the Sunniland oil field in Collier County was disposed of by pumping it back into the lower zones of the Floridan aquifer (Vernon, 1970; Meyer, 1989). The first injection of municipal effluent into brackish zones of the Upper Floridan aquifer began with a single injection well in Broward County just west of Lighthouse Point in 1959 (Meyer 1989, McKenzie and Irwin, 1984). Injection of treated municipal wastewater into the saltwater-filled Boulder Zone began in 1971 at a wastewater treatment plant in Miami-Dade County (Meyer, 1989, Meyer, 1974). The decade of the 1970's domestic injection wells were developed along the east coast of Florida, from Dade County to Brevard County, and on the west coast in Pinellas County. Also during the same period, several industrial injection wells were developed in the Florida panhandle, and in Polk, Indian River, and Palm Beach counties (Pitt, 1996).

From 1959 to 1970, the volume of municipal and industrial liquid wastes injected into the Floridan aquifer system increased gradually from 98 to 465.6 million gallons per year (Meyer, 1989). Permitting was handled on a case-by-case basis using unspecific federal and state rules to maximize the protection of the overlying aquifers (Pitt, 1996). Review agencies included Florida Department of Natural Resources, the State Board of Health, and the local water management districts in consultation with the U.S. Geological Survey (Meyer, 1989). In 1971, the volume of liquid wastes injected began to increase exponentially because of the discovery of Boulder Zone in South Florida, reaching 26.8 billion gallons per year in 1983 (Meyer, 1989).

Amendments to the SDWA in Part C added Sections 1422 and 1425, which provide an alternative means for States to acquire primary enforcement responsibility for the control of underground injection wells (GWPC, 2004). This approved delegation of UIC program to the states is called Primacy and the states that USEPA has determined have regulations, laws and resources in place that meet the federal requirements and are authorized to run the UIC program are referred to as Primacy States (GWPC, 2004). The state regulations have to be at least as stringent as the federal standards.

Shortly after the USEPA issued a guidance paper for granting primacy, the Florida Regulatory Commission reviewed the first draft of the proposed UIC regulations that would result in the granting of primacy to the state. The regulations thus drafted became Chapter 17-82 (now 62-528) of the Florida Administrative Code (FAC). Chapter 17-82 had been developed by the Florida Department of Environmental Protection (FDEP), in consultation with a group of advisors and representatives from industry, municipalities, consultants and environmentalists. The Florida Regulatory Commission adopted the UIC Chapter 17-28 in April 1982 (Pitt, 1996).

On February 7, 1983, the state of Florida was granted primacy (Federal Register Notice Reference 48FR5556) for deep injection wells. The Florida State UIC program is regulated by the FDEP, although FDEP still shares responsibilities with USEPA for Class II wells. Chapter 62-528 FAC sets minimum requirements on specifications for obtaining DIW permits, for well construction, for evaluation of geologic and hydrologic conditions relative to the site, for ensuring a safe mechanism for disposing of liquid waste, for proper well operation and monitoring, and for plugging and abandonment wells that pose a threat to SDWA. As described, the state's UIC program is tailored to the hydrogeology of Florida and consistent with the requirements of the federal program (Keith *et al*., 2005). After Florida's UIC program was approved, there was a rapid increase in total volume of injected wastewater and the number of deep injection wells (Keith *et al*., 2005).

1.2.3 Revisions of UIC Regulations

USEPA has revised and updated UIC regulations to conform to other federal laws. The Resources Conservation and Recovery Act (RCRA), as amended by the Hazardous and Solid Waste Amendments (HSWA) of 1984, requires USEPA to promulgate more stringent regulations of hazardous wastewater disposal via deep wells (USEPA, 1991). Thus in 1988, USEPA published a no-migration petition for deep wells injecting hazardous waste. The regulations require that each well operator provide a demonstration that the hazardous waste will not be released from the injection zone for at least 10,000 years, or will be rendered non-hazardous by natural processes (40 CFR 148, 2007).

Regulations of UIC program were also revised specifically to address any problems experienced by past injection well operations and concerns (Voorhess, 2001). Since the establishment of UIC program, there are only two recent studies to assess the risks and the safety practices of wastewater disposal via DIW.

In the early 1980's USEPA found that some municipal deep injection wells in Florida caused or may have caused fluid movement above the injection zone (Pitt, 1996). Where there appeared to be movement of the injected fluid into another zone, the well was deemed to be "leaking." The determination of leakage was made through elevated concentrations of ammonia and total Kjeldahl nitrogen, and depressed salinity, relative to native water in the Floridan Aquifer reported in monitoring wells in zones overlying the injection zone (Bloetscher *et al.*, 2001). At the initial stage of the migration detection, regulations required remedial action at the responsible wells as soon as any contamination was detected. However, while this appeared to fail to resolve the problem, FDEP declined to order a shutdown of any of the wells, because the contamination posed comparatively little risk to public health (Keith *et al*., 2005).

In 1991, Legal Environmental Assistance Foundation (LEAF), a local environmental group, filed a petition with USEPA for the withdrawal of Florida's primacy over the UIC program on the grounds that the program did not meet several of the federal UIC requirements (Keith *et al*., 2005). USEPA eventually denied the petition in 1995. Dissatisfied with this result, LEAF then filed a petition with the U.S. Court of Appeals to review USEPA's decision, arguing that Florida's UIC regulations were contrary to the SDWA because they were not protecting groundwater. In 1998, LEAF, USEPA, the U.S. Department of Justice, and FEDP reached a settlement involving modest revisions to the state's UIC program. However, LEAF continues to argue that the solution is not satisfactory and litigation still exists unresolved today (Keith *et al*., 2005).

In parallel with the legal action, the first risk assessment of the potential for health or environmental impacts of injection wells was completed in July 2001 by the University of Miami (UM) through a contract with the Florida Water Environment Association Utility Council. This study focused specifically on southeast Florida. It evaluated the comparative risk among injection wells, ocean outfalls and surface water discharges. The latter is not practiced in southeast Florida, so assumption of treatment levels was assumed with advanced wastewater treatment to remove nutrients. The UM study concluded that the risk to the environment and public health posed by class I injection wells was lower than ocean outfalls and surface water discharges. The risk driver was the potential for migration to aquifer storage recharge wells in the upper Floridan (Bloetscher *et al*., 2005).

USEPA entered into a contract with Cadmus group to conduct a second study (termed the "USEPA study". This study expanded the area of review beyond southeast Florida, although it utilized the data from the UM study, which was provided to Cadmus Group by the UM investigators. The complete study was published in April 2003 as the Relative Risk Assessment of Management Options for Treated Wastewater in South Florida, identified pathogens are the contaminant in municipal wastewater that presents the greatest risk to USDWs (USEPA, 2003). Despite including the Tampa Bay region, the USEPA study confirmed the UM results (USEPA, 2003).

In November 2005, as an attempt to settle the LEAF litigation, USEPA signed regulation entitled, “Alternative for Class I Municipal Disposal Wells in Specific Counties in Florida” to resolve the problem of potential contamination of USDW that is violating the no-fluid-movement federal regulations. The impacted counties as highlighted in Figure 2 consist of Brevard, Broward, Charlotte, Collier, Flagler, Glades, Hendry, Highlands, Hillsborough, Indian River, Lee, Manatee, Martin, Miami-Dade, Monroe, Okeechobee, Orange, Osceola, Palm Beach, Pinellas, St. Johns, St. Lucie, Sarasota, and Volusia. This rule (40 CFR 146.16, 2007) offers owners and operators of these municipal disposal wells the ability to continue to operate their wells, provided they meet additional wastewater treatment requirements designed to ensure an equivalent level of protection as required in the existing federal requirements.

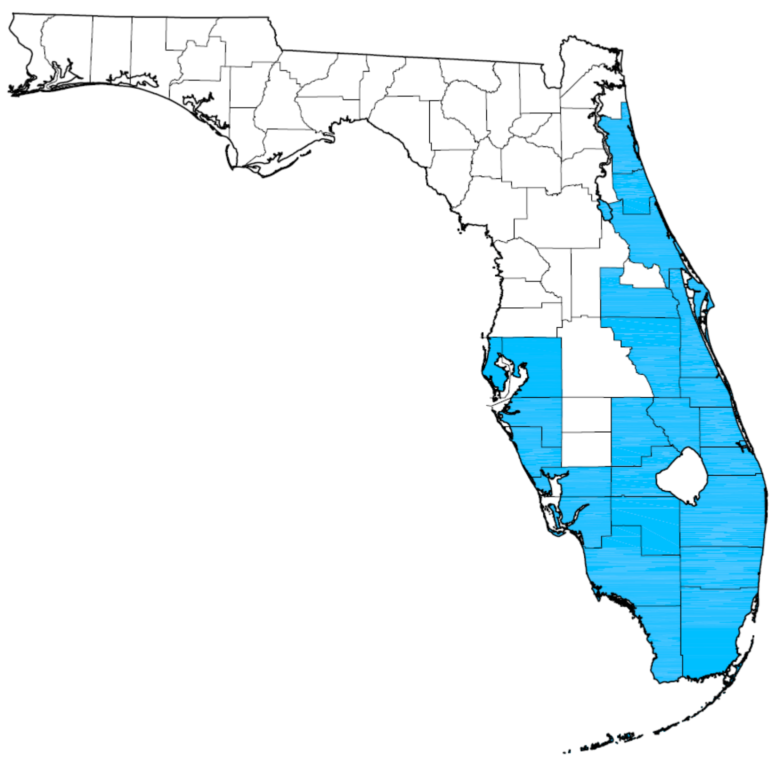


Figure 2 Counties Affected by Rule 40 CFR 146.16

40 CFR 146.16 recommended that where leakage was occurring, advanced secondary treatment with filtration and high-level disinfection (HLD), the level of treatment used for land application of reclaimed wastewater, is the minimum level of treatment. USEPA suggested that all new wells include the upgraded treatment levels. Typically the upstream filtration step uses media or cloth filters designed to achieve an effluent containing not more than 5 mg/L of total suspended solids (TSS) and 20 mg/L of 5-day carbonaceous biochemical oxygen demand (Bloetscher *et al*., 2005). By removing TSS before disinfection, filtration serves to increase the ability of the disinfection process to inactivate viruses and other pathogens. Filtration also serves as the primary barrier for removal of protozoan pathogens, such as *Cryptosporidium* and *Giardia* (FAC Chapter 62-610). USEPA believes this requirement will address viruses and bacteria, which represent the greatest risk to the USDW and public health (USEPA, 2005). This treatment method typically meets nearly all of the health-based United States and Florida primary drinking standards (Maliva *et al*., 2007; Bloetscher *et al*., 2005). It is also the required minimum treatment for producing reclaimed water for public access reuse in Florida, such as irrigation for golf courses, grassed medians, parks, lawns, etc.

A UIC historical timeline as shown in Figure 3, sums up the history described above:

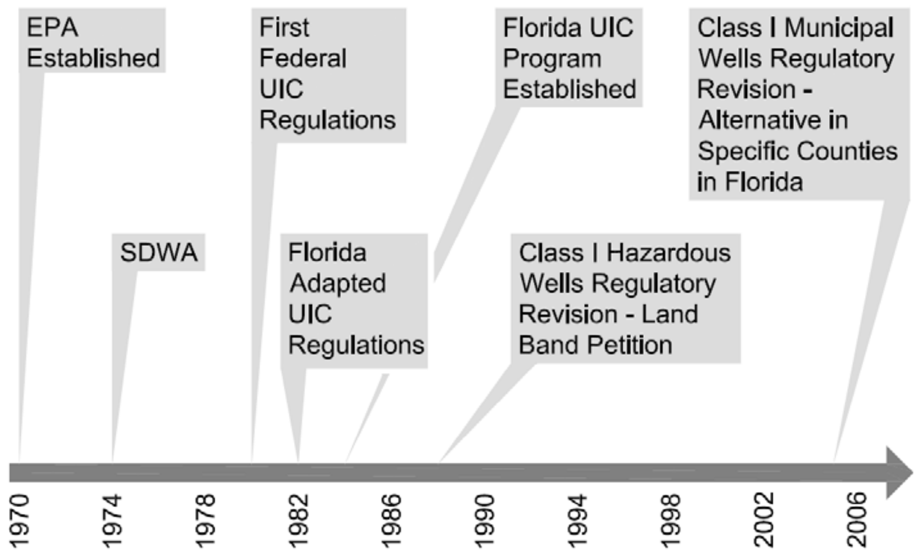


Figure 3 UIC Historical Timeline on Class I Wells

1.3 Well Classifications

Deep injection well is one of the underground injection options. For instance, injection can also be accomplished through shallow wells that are inserted above USDW. To distinguish variations of the nature of the fluid being injected and the depth of injection zone, wells can be categorized by USEPA's UIC regulations. Under Code of Federal Regulations (CFR) title 40 parts 144 and 146, deep well injection is recognized as a Class I well. There are a total of five classified injection well types that are defined in 40 CFR 146.5 (2002) and are described as follows:

- Class I

    (1) Wells used by generators of hazardous waste or owners or operators of hazardous waste management facilities to inject hazardous waste beneath the lowermost formation containing, within one-quarter mile of the well bore, an underground source of drinking water.

(2) Other industrial and municipal disposal wells which inject fluids beneath the lowermost formation containing, within one quarter mile of the well bore, an underground source of drinking water.

(3) Radioactive waste disposal wells which inject fluids below the lowermost formation containing an underground source of drinking water within one quarter mile of the well bore.

- Class II

(1) Wells which inject fluids which are brought to the surface in connection with natural gas storage operations, or conventional oil or natural gas production and may be commingled with waste waters from gas plants which are an integral part of production operations, unless those waters are classified as a hazardous waste at the time of injection.

(2) For enhanced recovery of oil or natural gas.

(3) For storage of hydrocarbons which are liquid at standard temperature and pressure.

- Class III

(1) Wells which inject for extraction of minerals including mining of sulfur by the Frasch process.

(2) In situ production of uranium or other metals; this category includes only in-situ production from ore bodies which have not been conventionally mined. Solution mining of conventional mines such as stops leaching is included in Class V.

(3) Solution mining of salts or potash.

- Class IV (banned in Florida)

(1) Wells used by generators of hazardous waste or of radioactive waste, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous waste or radioactive waste into a formation which within one-quarter (1/4) mile of the well contains an underground source of drinking water.

(2) Wells used by generators of hazardous waste or of radioactive waste, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous waste or radioactive waste above a formation which within one-quarter (1/4) mile of the well contains an underground source of drinking water.

(3) Wells used by generators of hazardous waste or owners or operators of hazardous waste management facilities to dispose of hazardous waste, which cannot be classified under paragraph (a)(1) or (d) (1) and (2) of this section (e.g., wells used to dispose of hazardous waste into or above a formation which contains an aquifer which has been exempted pursuant to § 146.04).

- Class V

(1) Injection wells not included in Class I, II, III, or IV.

More concisely, Class I wells as used to inject waste beneath the lowermost USDW; Class II wells as used to dispose of fluids associated with the production of oil and natural gas; Class III as wells used to inject fluids for the extraction of minerals; Class IV wells as used to dispose of hazardous of radioactive wastes into or above a USDW; and Class V wells are all wells not included in the other classes, and generally used to inject non-hazardous waste (GWPC, 2004). All wells are regulated by the FDEP and the USEPA. Only Class II injection wells are administered by the Florida Bureau of Geology, Florida Department of Natural Resources and USEPA (Meyer, 1989). In the state of Florida, the approximate inventory of injection wells as of September 2007 according to USEPA is 216 for Class I, 64 for Class II, none for Class III or Class IV (banned since 1983), and 54,700 for Class V. Figure 4 illustrates the variations among all five classified injection wells.

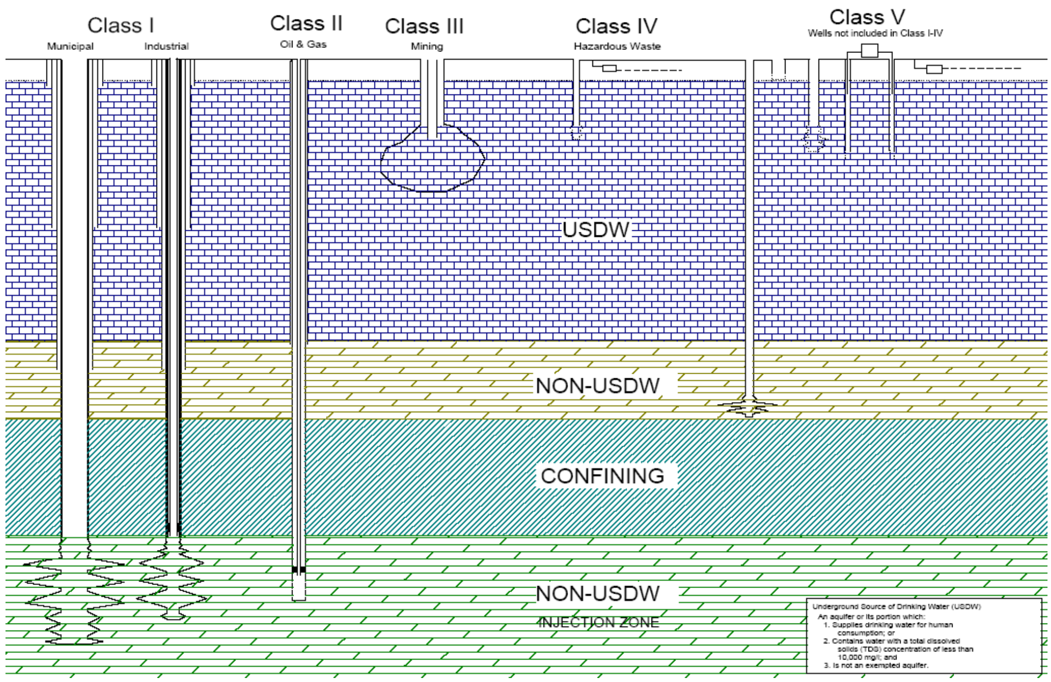


Figure 4 UIC Classified Injection Wells (FDEP, 2009)

1.4 Well Usages

There are four basic alternatives for the disposal of the effluent from wastewater treatment plants in Florida: 1) ocean outfalls, 2) surface discharges, 3) deep well injection, and 4) reuse (Bloetscher *et al.*, 2005). DIW remains one of the most attractive (both economically and environmentally) methods of treated effluent disposal and even with a strong emphasis on reuse, DIW will still be needed as the emergency disposal system for all other alternatives (Pitt, 1996). Thus, the majority of DIW or Class I Wells are passageways for discharging primarily two types of treated wastewater in Florida: non-hazardous domestic and non-hazardous industrial.

Non-hazardous domestic or municipal deep injection wells receive wastewater from domestic wastewater facilities that are those principally designed to collect and treat sanitary wastewater or sewage from dwellings or homes, business buildings, institutions, and recreational facilities (FDEP, 2008). Two treatment processes are required to remove physical, chemical and biological contaminants from raw sewage: primary treatment and secondary treatment. A secondary treatment municipal facility is directed principally toward the removal of biodegradable organics and total suspended solids through the use of activated sludge processes, fixed film reactors, extended aeration, or modifications or combinations of these processes. A conventional secondary treatment facility will typically have preliminary treatment (i.e. bar screens, grit removal, etc.) and it may have primary clarifiers ahead of a secondary biological treatment process (FDEP, 2008). The final disinfected effluent must meet secondary wastewater treatment standards and must be in compliance with FDEP regulations (Chapter 62.-528 FAC) before pumping into deep wells. This water quality is the same as treated wastewater discharged to rivers throughout the U.S. and Canada.

Non-hazardous industrial wastewater discharges are wastes that do not meet the legal definition of hazardous wastes defined under 40 CFR 261.3, Section of 3001, of Subtitle C of the SWDA, as amended by the 1976 RCRA (GWPC, 2004). These discharges are highly variable in the amount and types of pollutants they contain. Representative large industries that discharge wastes include North Florida's pulp and paper mills, Central Florida's phosphate mines, and many electrical power generation plants throughout the state (FDEP, 2008). Representative smaller industrial facilities include car washes and laundromats, which have distinctly different wastes. Agriculture is one of the biggest industries in Florida (FDEP, 2008). Many agricultural production and processing activities, such as citrus processing, dairies and aquaculture facilities, are regulated under the Department's Industrial Wastewater Program (FDEP, 2008).

Two other non-hazardous types of Class I wells include combined sewage disposal and reverse osmosis (RO). The combined sewage disposal is treated wastewater from both domestic and industrial sources. RO wells receive concentrate from reverse-osmosis desalination facilities. This type of Class I well has been increasingly popular in recent years due to more stringent drinking water standards for disinfection by-products, which have led more utilities to consider upgrading to membrane processes (Skehan and Kwiatkowski, 2005). Concentrate is deemed industrial due to toxicity concerns.

As defined by USEPA, wastewaters are considered to be hazardous wastes if they demonstrate a hazardous characteristic of ignitability, corrosive, reactivity, or toxicity, or are a listed waste as determined by EPA. Current FDEP inventory shows that there is only one active hazardous well operated at Keiser Industries in Polk County, which belongs to FDEP Southwest District. The injection well is for the disposal of the facility's waste stream produced from the manufacturer of sodium, potassium, ammonium, and magnesium fluorosilicate through a chemical reaction between fluorosilicic acid with a source of salt. The waste stream is classified as hazardous due to corrosivity with pH value less than 2 and/or arsenic toxicity.

1.5 Aquifer Formations

Understanding aquifer systems in Florida is necessary to reveal why such a geologic formation is an ideal setting for deep injection wells. Throughout the state of Florida, the aquifer systems are composed of varying formations based on rock composition and physical characteristics (Massox *et al.*, 1992). However, the hydrostratigraphic framework determined by various water management districts, the United States Geological Survey (USGS) and the Florida Geologic Survey (FGS), indicates that the Florida aquifer systems can be recognized as three vertical sequences from top to bottom as shown in Figure 5: uppermost aquifer system, intermediate confining unit/aquifer system, and Floridan aquifer system (Massox *et al.*, 1992).

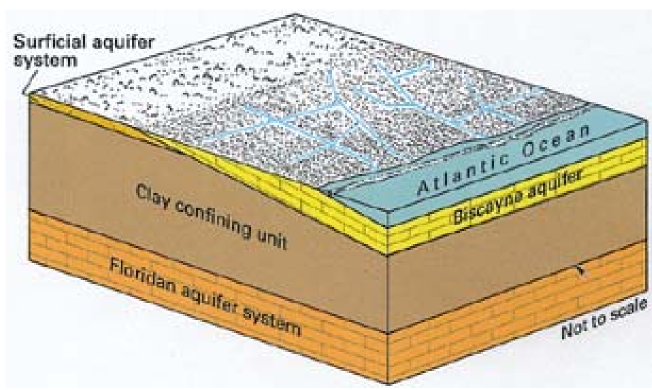


Figure 5 Cross Section of Florida Aquifer Systems (Miller, 1990)

As described by Massox *et al.* (1992), these three geologic units are composed of thick Cenozoic sediments, which vary widely from one area of the state to another. The Cenozoic sediments rang from latest Paleocene (55 million years ago) to Late Pleistocene (<100,000 years ago) in age. The deposition of these sediments was strongly influenced by fluctuations of sea level. Carbonate sediment deposition dominated the Florida Platform until the end of the Oligocene Epoch (24 million years ago). The resulting Cenozoic carbonate sediment accumulation ranges from nearly two thousand feet thick in northern Florida to more than five thousand feet in the southern part of the state (Massox *et al.*, 1992). Geological period of Paleogene is listed in Table 1 according to the International Union of Geological Sciences (IUGS), as of July 2009.

Table 1 Subdivision of the Paleogene Period (IUGS, 2009)

System	Series	Stage	Age (Ma)
Quaternary	Pleistocene	Gelasian	younger
Neogene	Pliocene	Piacenzian	2.588–3.600
		Zanclean	3.600–5.332
	Miocene	Messinian	5.332–7.246
		Tortonian	7.246–11.608
		Serravallian	11.608–13.65
		Langhian	13.65–15.97
		Burdigalian	15.97–20.43
		Aquitanian	20.43–23.03
Paleogene	Oligocene	Chattian	23.03–28.4
		Rupelian	28.4–33.9
	Eocene	Priabonian	33.9–37.2
		Bartonian	37.2–40.4
		Lutetian	40.4–48.6
		Ypresian	48.6–55.8
	Paleocene	Thanetian	55.8–58.7
		Selandian	58.7–61.7
		Danian	61.7–65.5
Cretaceous	Upper	Maastrichtian	older

1.5.1 Uppermost Aquifer System

In name, the uppermost aquifer system lies atop all other aquifer systems. It contains water mostly under unconfined conditions (Miller, 1990). Three main aquifers of the uppermost aquifer system to which names have been applied are sand and gravel aquifer, Biscayne aquifer, and surficial aquifer. Each aquifer system has its unique lithology and permeability, even though they all have the same geologic age, which is primarily Pleistocene and younger (Miller, 1990). The distribution of these aquifers is shown in Figure 6.

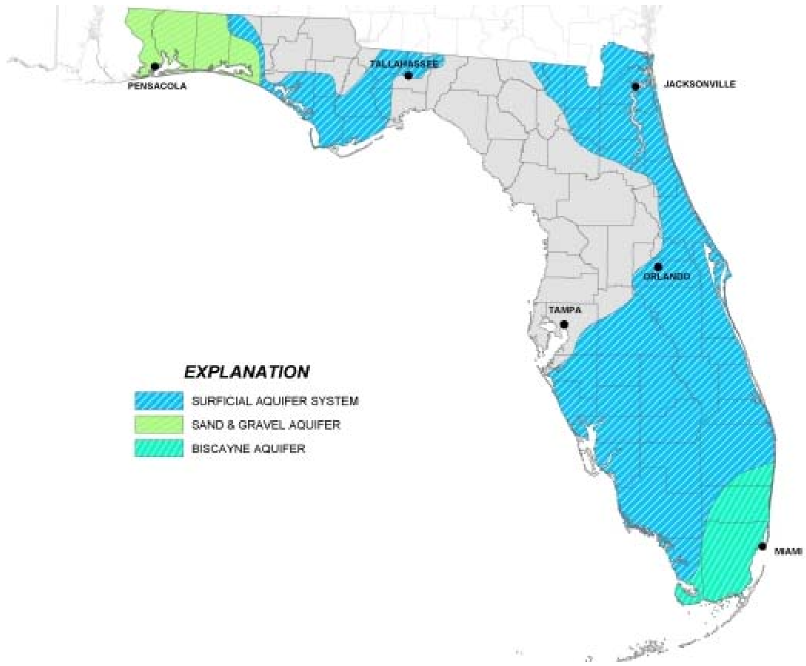


Figure 6 Distribution of Uppermost Aquifer System in Florida (FDEP, 2008)

1.5.1.1 Sand and Gravel Aquifer

The sand and gravel aquifer is limited to the westernmost part of panhandle Florida. As its name indicates, the sand and gravel aquifer consists largely of interbedded layers of sand and gravel (Miller, 1990). Water in the aquifer is under unconfined conditions where the clay beds are thin or absent, and is generally under artesian conditions where such beds are thick (Miller, 1990). Movement of ground water is generally coastward (Miller, 1990). The sand and gravel aquifer yields moderate volumes of water and is the primary source of drinking water for Santa Rosa and Escambia counties (Miller, 1990).

1.5.1.2 Biscayne Aquifer

The Biscayne aquifer underlies approximately 4,000 square miles of southeastern Florida (Miller, 1990). It contains highly permeable limestone and less-permeable sandstone and sand (FDEP, 2008). Most of the formations are thin and lens-like (Miller, 1990). In general, the entire aquifer is sandier in its northern and eastern parts, and contains more limestone and calcareous sandstone to the south and west (FDEP, 2008). The aquifer ranges in thickness from a few feet near its western limit to about 240 feet near the coast (USEPA, 2003; FDEP, 2008; Meyer, 1989; Reese, 1994). The Biscayne aquifer is unconfined and generally flows toward the ocean (FDEP, 2008). It is the principal source of potable water for all of Miami-Dade and Broward Counties and the southeastern part of Palm Beach County (FDEP, 2008).

1.5.1.3 Surficial Aquifer

Aside from the sand and gravel and the Biscayne aquifers, a surficial aquifer system that includes any otherwise undefined aquifers is widespread throughout the rest of state (FDEP, 2008). Unlike the sand and gravel and the Biscayne aquifers, in the remainder of the state, the surficial aquifer system is much less productive and therefore is principally used only for domestic, limited commercial, or small municipal supplies (FDEP, 2008). While the aquifer is still used by a large number of people, it generally yields small volumes of water due to its physical characteristics (FDEP, 2008). It is described as a thin layer of unconsolidated sand beds that commonly contains a few beds of shell and limestone (FDEP, 2008). Groundwater in the surficial aquifer generally flows from areas of higher elevation towards the coast or streams where it can discharge as base flow (FDEP, 2008).

1.5.2 Intermediate Confining Unit/Aquifer System

Intermediate confining unit or the intermediate aquifer system lies between the uppermost aquifer system and the Floridan aquifer system. The sediments compromising the intermediate confining unit/aquifer system exhibit wide variability over the state (FDEP, 2008).

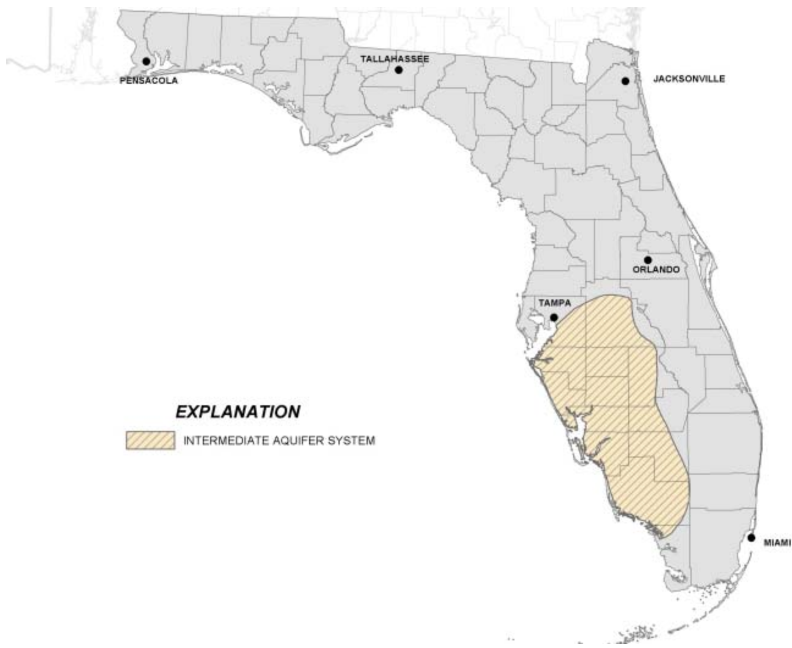


Figure 7 Distribution of Intermediate Aquifer System in Florida (FDEP, 2008)

1.5.2.1 Intermediate Aquifer System

The intermediate aquifer system is clearly defined in southwestern Florida, which starts in Hillsborough and Polk Counties and extends south through Collier County (FDEP, 2008), which is illustrated in Figure 7. The aquifers within this system contain water under confined conditions. It is mainly comprised of permeable layers of sand, shell and limestone separated by thin, clay confining units. The intermediate aquifer system is not extensively used, and its characteristics are not well known, especially where the Floridan is near the land surface and contains freshwater. However, it is the main source of water supply for Sarasota, Charlotte and Lee counties where the underlying Floridan aquifer contains brackish water. Much of the water pumped from this aquifer system is used for agriculture. In most places, water percolates down from the surficial aquifer system above to the intermediate aquifer system. Lateral flow is generally from a high area in Polk County towards major surface water features and the Gulf of Mexico.

In many places, the intermediate aquifer system can be divided into two aquifers, the Tamiami-upper Hawthorn and the lower Hawthorn-upper Tampa aquifer, separated in most places by an unnamed confining unit. The aquifer system thickens southward from Polk County into Charlotte County. Farther south, in Collier County, the aquifer system thins as the lower Hawthorn-upper Tampa aquifer becomes predominately clay with little permeability. The Tamiami-upper Hawthorn aquifer is the principle water-yielding part of the intermediate aquifer system in Glades, Hendry, Charlotte, Lee, and Collier Counties; elsewhere, the lower Hawthorn-upper Tampa aquifer is the major source of supply.

1.5.2.2 Intermediate Confining Unit

The intermediate confining unit is defined as in places where poorly-yielding to nonwater-yielding strata mainly occur. This system occurs widespread in the state and its thickness is highly variable. Thus, the unit retards the vertical movement of water between the uppermost aquifer system and the Floridan aquifer system to varying degrees. Where the confining unit is thick or where is contains much clay, leakage through the unit is much less than where the confining unit is thin, sandy or is interspersed limestone formations.

1.5.3 Floridan Aquifer System

The Floridan aquifer (Figure 8) is found throughout Florida and extends into the southern portions of Alabama, Georgia, and South Carolina (Miller, 1990). The Floridan is a multiple-use aquifer system. Where it contains freshwater as shown in Figure 8, it is the principal source of water supply. South of Lake Okeechobee in Florida, the aquifer contains saltwater. Some of this saltwater is withdrawn for cooling purposes and some withdrawn and converted to freshwater by desalinization plants. Desalinization of the Floridan is one of the water supplies in the Florida Keys, which have no other source of freshwater except that which is imported from their Florida City plant via pipeline (Miller, 1990). Thus, the areas that indicate no potable water actually indicate water that must undergo reverse osmosis treatment prior to usage.

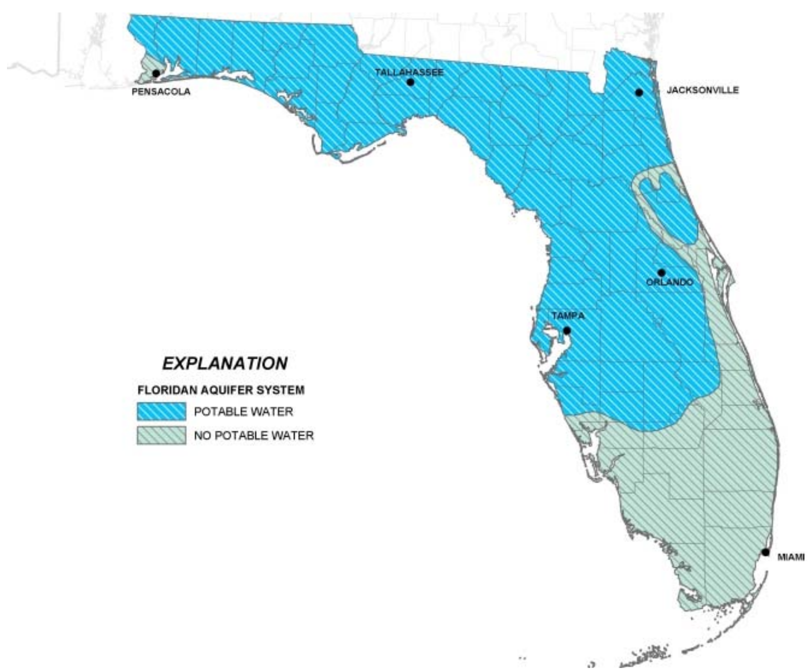


Figure 8 Distribution of Lower Floridan Aquifer in Florida (FDEP, 2008)

The Floridan aquifer system is comprised of a sequence of limestone and dolomite, which thickens from about 250 feet in Georgia to about 3000 feet in south

Florida. This aquifer system is divided into three distinct hydrogeologic units, based on the basis of geology, hydrochemistry, and hydraulics (Miller, 1990). These units are the Upper Floridan aquifer, the middle confining units, and the Lower Floridan aquifer. All Class I wells in Florida have their injection zones either within the Upper or the Lower Floridan Aquifer, which greatly depend on their locations and geologic formations (see further discussion in Section 3.2).

1.5.3.1 Upper Floridan Aquifer

The aquifer is highly permeable in most places and includes the Suwannee and Ocala Limestones, and the upper part of the Avon Park Formation (Miller 1990). The thickest and most productive formations of the system are the Avon Park Formation and the Ocala Limestone of Eocene age. The Suwannee Limestone (Oligocene age 23-37 million years ago) is a principal source of water, but it is thinner and much less extensive than the Eocene formations (Miller, 1990). Despite the huge volumes of water that are being withdrawn from the aquifer system, water levels have not declined greatly except locally where pumpage is concentrated or the yield from the system is minimal.

South of Lake Okeechobee, the Upper Floridan aquifer contains brackish ground water with specific conductance of the groundwater averaging 5,000 μS/cm (Meyer, 1989). The salinity of the groundwater generally increases with increasing depth and with distance downgradient and southward from central Florida (Meyer, 1989). The hydrogeology of the Upper Floridan Aquifer varies throughout the state (Reese, 1994). For instance, vertical hydraulic conductivity in the upper part of the aquifer may be higher in southeastern Florida, averaging 15 ft/day, because of unconformities present at formation contacts within the aquifer that may be better developed in this area (Reese, 1994). Groundwater movement is generally southward from the area of highest head near Polk City in central Florida to the Gulf of Mexico and to the Atlantic Ocean (Meyer, 1989).

1.5.3.2 Middle Confining Unit

The middle confining unit of the Floridan aquifer chiefly consists of the lower part of the Avon Park Formation but locally includes the upper part of the Oldsmar Formation (Meyer, 1989). These rocks consist of low-permeability clays, fine-grained limestones, and anhydrous dolomite, ranging in thickness across South Florida from 900 to 1,100 feet (Bush and Johnston, 1988; Duncan *et al*., 1994; Miller, 1997; Reese and Memburg, 1999). The confining unit actually consists of seven separate, discrete units that are idealized into a single layer (Miller, 1990). Regardless of rock type, wherever the middle confining unit is present, it generally restricts the movement of ground water between the Upper and Lower Floridan aquifers (Miller, 1990). Confinement between flow zones is better in southwestern Florida than in southeastern Florida (Reese, 2000).

1.5.3.3 Lower Floridan Aquifer

The hydraulic properties and geology of the Upper Floridan aquifer are better known than the properties of the Lower Floridan because less data from boreholes is available (USEPA, 2003). The Lower Floridan aquifer contains salty ground water that compares chemically to modern seawater (Meyer, 1989). It consists chiefly of the Oldsmar Formation and, to a lesser degree, the upper part of the Cedar Keys Formation (Meyer, 1989). In the Lower Floridan aquifer there are permeable dolostone layers of the Oldsmar Formation that are separated by less permeable limestones. The transmissivity of the lower dolostone ranges from about $3.2x10^6$ ft^2/d to $24.6x10^6$ ft^2/d, whereas that for the overlying dolostones is an order of magnitude less (Meyer, 1989).

1.5.3.4 Boulder Zone

In South Florida, its Lower Floridan aquifer contains an important and extremely peameable cavernous zone, which is known as the Boulder Zone (Figure 9). This name is applied to the zone not because it consists of boulders, but because it is difficult to drill into, having the same rough, shaking, grabbing effect on the drill stem and drilling rig as boulders do (Miller, 1990). The cavernous nature of the Boulder Zone was created by the vigorous circulation of ground water through the carbonate rocks in the geologic past, and does not result from the present ground-water flow system (Miller, 1990). The Boulder Zone is the thick section of dolostone in the lower Oldsmar Formation (Maliva, 1998). The distribution of the thick dolomite bed and high transmissivity cavernous zones within the Lower Floridan is difficult to determine because complex variations exist within the rock units (Maliva, 1998; Miller, 1986). The initial increase of the utilization of Class I deep injection wells resulted for the discovery of the Boulder Zone in 1969 (Meyer, 1989).

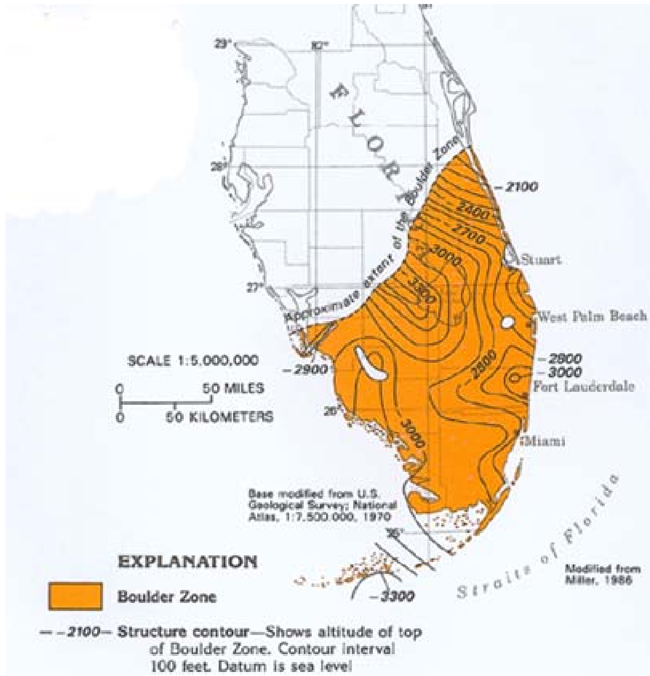


Figure 9 Boulder Zone in South Florida (Miller, 1990)

1.6 Hydrogeological Profiles of Deep Injection Wells

DIWs are largely concentrated in four regulatory District Offices of Florida Department of Environmental Protection (FDEP): Central, Southeast, South and Southwest Districts. The other two Districts (Northwest and Northeast) are not considered for this thesis because as of September, 2007, the Northwest District only regulates two non-hazardous industrial wells in Pensecola, and there is no Class I wells present in the Northeast District. Figure 10 illustrates the responsible counties for all six districts. Each district has its own unique hydrogeologic formations, which determine the appropriate depths of injection zone of the DIWs. Descriptions are provided in the following subsections to detail the hydrogeologic formations of each district.

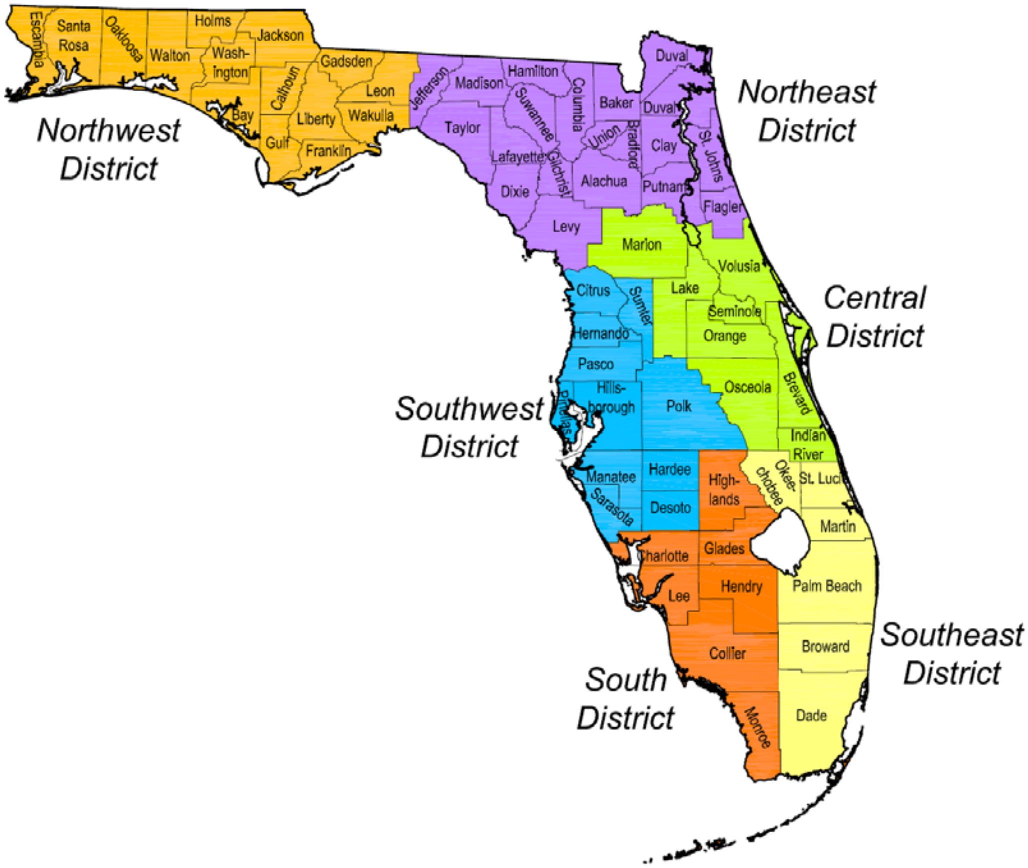


Figure 10 **FDEP District Map (FDEP, 2008)**

1.6.1 Central District

Deep well injection in Brevard County occurs within the Boulder Zone of Lower Floridan Aquifer as illustrated in Figure 11, approximately 2,500 feet below land surface. The base of the USDW is also located in the Lower Floridan Aquifer, approximately 1,500 feet below the land's surface and 950 feet above the injection zone (Duerr, 1995; USEPA, 2003). Thus, no clear confining layer is present between the injection zone and the base of the USDW. However, the middle confining unit (located between 556 and 1000 ft) acts as a hydrologic barrier that separates and hydrologically confines the Lower Floridan Aquifer from the Upper Floridan Aquifer (USEPA, 2003).

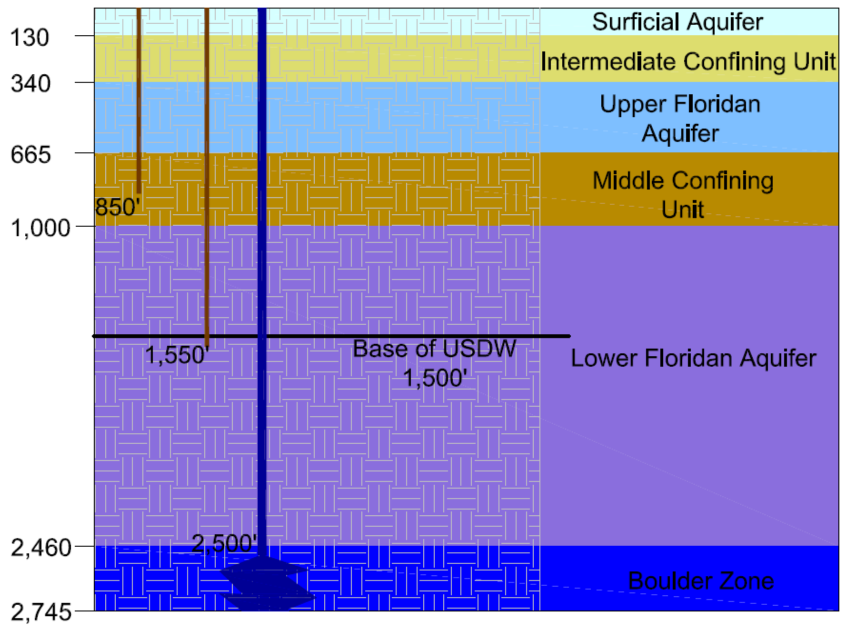


Figure 11 **Typical Class I Well in Central District (USEPA, 2003)**

1.6.2 Southeast District

In southeastern coastal Florida, where the Class I Wells (Figure 12) are concentrated, the base of the Floridan aquifer system occurs at an approximately of 3,500 feet (Bloetscher *et al*., 2001). In general, the Upper Floridan Aquifer occurs in the depth interval between approximately 900± feet and 2,000± feet (Bloetscher *et al*., 2001). Water in the Upper Floridan Aquifer is brackish with total dissolved solids (TDS) concentration generally less than 10,000 mg/L. The salinity increases with depth. The depth where salinity equals that of seawater is 2,000 ± feet. Below this depth the salinity is constant and equal to that of seawater (Bloetscher *et al*., 2001). The Middle Confining Unit is located at the approximate depth interval between 2,000 and 3,000 feet below land surface (Miller 1990, Bloetscher *et al*., 2001). For the most part, the salinity of water present in this section is equal to that of seawater, except perhaps in those portions of the unit above approximately 2,000 feet. The Boulder zone is essentially the lower Floridan

Aquifer in the Southeast District, with an approximate depth interval between 3,000 feet to 3,500 feet (Bloetscher *et al*., 2001). It is believed that water in the Boulder Zone is moving slowly west (Meyer, 1989; Bloetscher *et al*., 2001).

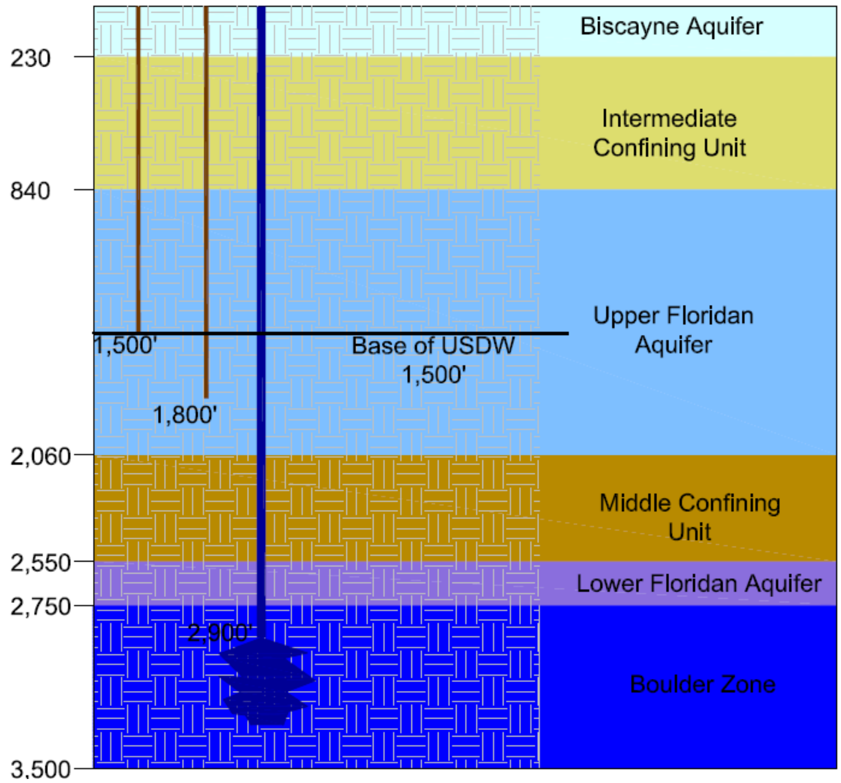


Figure 12 Typical Class I Well in Southeast District (USEPA, 2003)

All documented deep well injection in Southeast District of Florida occurs within the boulder zone (USEPA, 2003; Maliva 2007). Typically, injection wells discharge within the top 250 to 300 feet of the boulder zone (FDEP, 1999) or approximately 2,900 feet below land surface (Bloetscher *et al*., 2001). The base of the USDW is located more than 1,000 feet above the injection zone, within the Upper Floridan Aquifer (Duerr, 1995).

The USDW layer is the Upper Floridan Aquifer. It is currently used for water supply and aquifer storage and recovery wells, which receive and store treated water that is extracted for public water supply during high-demand seasons. The brackish aquifer is also being developed for public water supply, which is treated by reverse osmosis (Bloetscher *et al*., 2001). As the demand for water grows in the future, the level of development of the Upper Floridan as a source of drinking water will likely grow (Bloetscher *et al*., 2001).

1.6.3 South District

In southwestern Florida, the surficial aquifer system includes the water-table aquifer and the lower Tamiami aquifer. The intermediate aquifer system lies within the Hawthorn Group and includes, in descending order, the sandstone aquifer and the mid-Hawthorn aquifer. The sandstone aquifer is present in Lee County and in western Hendry and Collier Counties (Reese, 2000; Merritt, 2004). The mid-Hawthorn aquifer is absent in most of Hendry County (Merritt, 2004).

In southern Florida, the Floridan aquifer system includes the lower part of the Arcadia Formation of the Hawthorn Group (Miocene-Late Oligocene), Suwannee Limestone (Oligocenen), Ocala Limestone (Late Eocene), Avon Park Formation (Middle Eocene), Oldsmar Formation (Early Eocene) and the upper part of the Cedar Keys Formation (Paleocene; Miller 1986). An overall trend in southwestern Florida is for dolomite in the Floridan aquifer system to occur at stratigraphically lower positions and greater depths from northwest to southeast (Maliva, 1998). However, in large parts of South District, limestones within the Floridan aquifer system are absent due to erosion (Guertin *et al*., 2000). All of the water in the Floridan aquifer system in southern Florida is brackish to marine in chemical quality.

The Upper Floridan aquifer includes the lower part of the Hawthorn Group, the Suwannee Limestone, the Ocala Limestone, and the upper part of the Avon Park Formation (Merrit, 2004). Dolomite is abundant in the Avon Park Formation, in the Charlotte County East Port and West Port wells, whereas it constitutes only a small percentage of the Avon Park Formation in southern Collier County wells. Generally, the Upper Floridan aquifer in southwestern Florida consists of several thin water-bearing zones of relatively high permeability interlayered with thick zones of much lower permeability (Reese, 2000; Merritt, 2004). The Upper Floridan water-bearing zones usually are composed of limestone or limestone with interbedded dolomite, and are characterized by secondary porosity (Reese, 2000; Merritt, 2004).

The thick sequences of dolomite in the Avon Park Formation and Oldsmar Formation pinch out laterally to the south and north, respectively, in southern Charlotte County rather than merging into a single continuous dolomite sequence that cross cuts formation boundaries. High-transmissivity zones in the lower Floridan aquifer are usually associated with dolomite beds. The stratigraphic position and depths of high-transmissivity injection zones are highly variable, and cannot be predicted with any confidence, except in the general sense that they are present in the lower Floridan aquifer.

The Lower Floridan aquifer includes the dolomite-evaporate unit that may be within the lower part of the Avon Park Formation or the upper part of the Oldsmar Formation, and extends down into the Cedar Keys Formation (Reese, 2000; Merritt, 2004). The Lower Floridan aquifer also is characterized by thin water-bearing zones of high permeability interlayered with thick zones of low permeability (Reese, 2000; Merritt, 2004). The zones of high permeability commonly are composed of sucrostic dolomite that collapses when drilled into. Some of the collapsed dolomitic zones used for waste injection have remarkably high permeability (Reese, 2000; Merritt, 2004).

Class I Wells in the South District as illustrated in Figure 13 discharge into the Boulder Zone that is 2,500 feet to 3,250 feet deep underground (Maliva, 1998). Three main aquifer systems identified in the South District include: the surficial aquifer system, the intermediate aquifer system, and the Floridan aquifer system (Maliva, 1998). The surficial aquifer system contains the water table aquifer and one or more semi-confined aquifers. The intermediate aquifer system, which is also referred to as the intermediate confining unit, contains several limestone aquifers that are separated by clay or marl confining units. The water in the intermediate aquifer system is brackish throughout south Florida (Maliva, 1998).

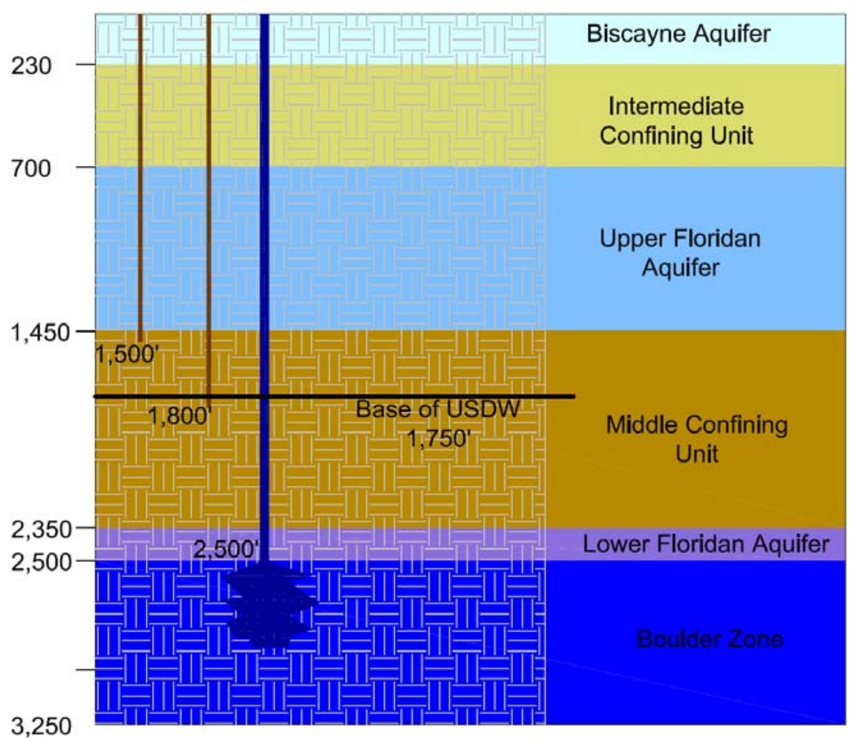


Figure 13 Typical Class I Well in South District (USEPA, 2003)

The conceptualization of the Floridan aquifer system as upper and lower aquifers separated by a middle confining unit is a somewhat inadequate generalization. Thin, water-bearing zones can be found anywhere within the carbonate sequence extending downward from the lower part of the Hawthorn Group to the Cedar Keys Formation. Thus, it is difficult to select upper and lower elevations for such a confining unit at individual well sites, and also difficult to generalize confining unit boundaries on a regionally extensive scale (Reese, 2000; Merritt, 2004).

1.6.4 Southwest District

Deep well injection in Pinellas County as illustrated in Figure 14 is conducted in the Upper Floridan Aquifer, within the most permeable upper portion of the Avon Park Formation (Hickey, 1982; Hutchinson, 1991; USEPA, 2003). This is unique in a sense that the other three district all have deep wells within their Lower Floridian Aquifer. Typically for Southwest District, injection wells discharge within the uppermost 100 to 300 feet of the Avon Park Formation (USEPA, 2003), approximately 1,250 feet below land surface. The Boulder Zone is absent in this region of the state.

Wastewater is injected below the base of the USDW into brackish to salty groundwater that has TDS concentrations of 20,000 mg/L (Hickey, 1982; Hutchinson, 1991; USEPA, 2003). The base of the USDW is located approximately 570 feet above the injection zone, which is still within the Upper Floridan Aquifer (Duerr, 1995; USEPA, 2003). These shallower wells in Pinellas County were the first identified to have vertical migration (USEPA, 2003).

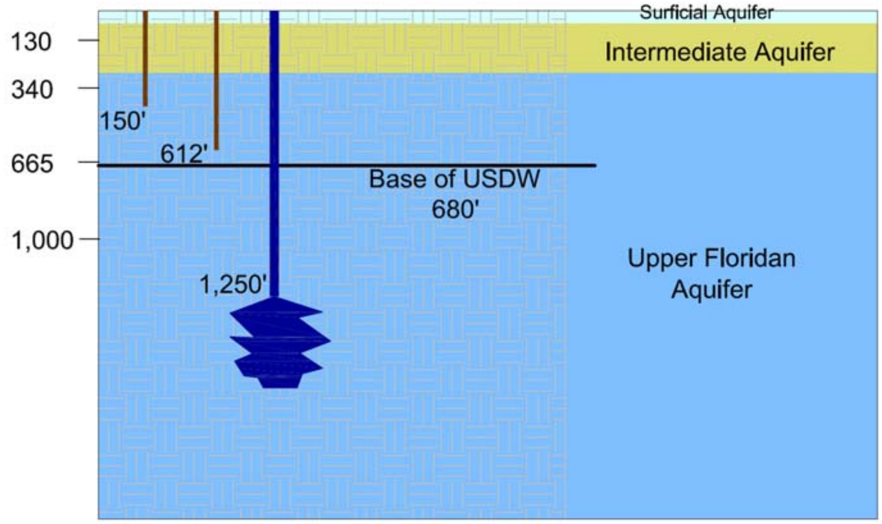


Figure 14 Typical Class I Well in Southwest District (USEPA, 2003)

1.7 Construction Requirements

Construction standards for non-harzardous industrial and municipal DIW are set forth in 40 CFR 146.12 and FAC 62-528.410. These criteria require a multilayer protection design for all Class I wells with proper casing and cementing to prevent the movement of fluids into or between USDW [FAC 62-528.410 (1)(a)].

As specified in FAC 62-528.410, in designing for casing, cementing, tubing, packer, or other alternatives to a packer, the following factors shall be considered: depth of setting; characteristics of the injection fluid; injection and annular pressure; rate, temperature and volume of injected fluid; size and grade of casing; life expectancy of the well; lithology of injection and confining zone; and type or grade of cement. Design specifications must be submitted to the permitting authority for review and approval prior to installation of any new well. The permitting authorities include FDEP as the administering agency and other agencies where necessary, such as water management districts, or local programs [FAC 62.528.440 (1)].

In addition to the design specifications, there are also several other materials required to be submitted for review and approval: a step-by-step drilling plan includes proposed drilling program, sampling, coring, and testing procedures that must be followed during construction phase [FAC 62-528.410 (3)]; a cement testing program entails temperature and cement evaluation survey to ensure that the cement seal is adequate to prevent migration of fluids in channels, microannular space, or voids in the cement [FAC 62-528.410 (5)(g)]; a centralized cementing program for the purpose of centralizing the casing, to provide adequate annular space around the casing for proper cementing [FAC 62-528.410 (5)(i)(3)].

After the permitting process, a multi-stage construction can begin for installation of a new Class I well with each stage constructed to protect a specific portion of the aquifer being penetrated (FWEA, 2008). Drilling and installation of the casing seals off a different aquifer zone. As a result, the well telescopes to ever smaller diameter, cemented within the prior casing (or stage of construction). This type of construction is typically accomplished by first drilling a constant diameter hole to a desired depth, then inserting a steel pipe with a smaller diameter into the cavity, cement is immediately pumped down to encase the entire length of the pipe and seal it to the surrounding rock. All but one of the DIWs were constructed with steel casing. The same routine is repeated as each successive wellbore is smaller in diameter and extends farther down until the deep injection zone is reached.

The number of stages is determined by the size, location and type of the well. For example, five stages and four casings are usually required for installing a 24” diameter municipal deep well in Southeast Florida as shown in Figure 15 and Table 2. The final stage is not shown in the table, which consists of drilling an open bore hole down into the injection zone. The well usually has a minimum injection capacity of 15 million gallons per day (Meyer 1989).

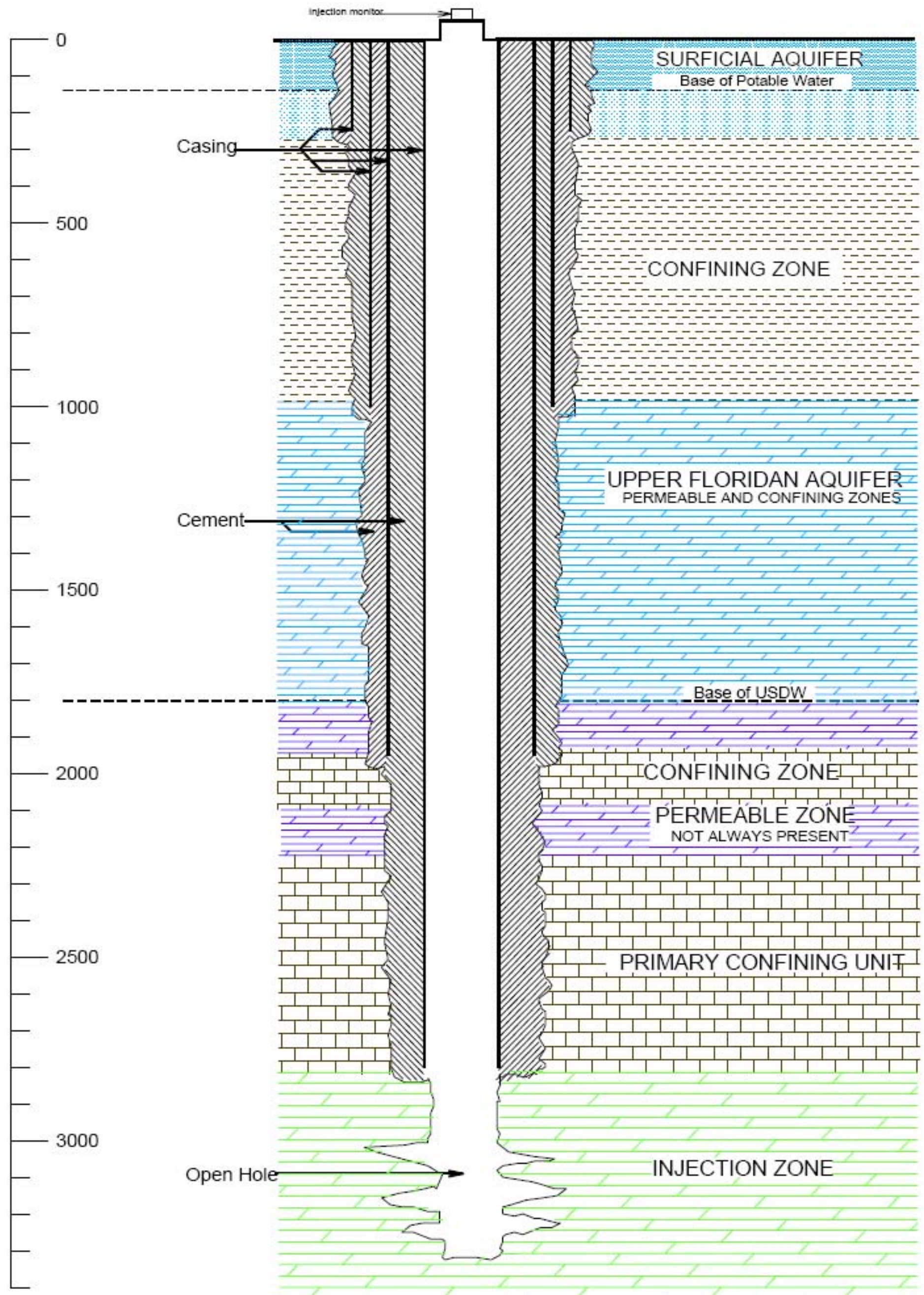


Figure 15 **Typical Class I Well Construction in Southeast Florida (USEPA, 2007)**

Table 2 Typical Municipal Class I Well Design in Southeast Florida

Casing	Outside Diameter (inch)	Wall Thickness (inch)	Typical Length** (foot)	Material
Surface	52	3/8	100-250	Steel
Shallow Intermediate	42	3/8	900-1000	Steel
Deep Intermediate*	34	3/8	1500-2100	Steel
Injection	24	1/2	2400-3000	Seamless Steel

*The deep intermediate casing is set below the base of the lowermost underground source of drinking water

**Casing depths apply only to Southeast Florida

During drilling and construction of a new Class I well, deviation checks shall be conducted to assure that vertical avenues for fluid migration in the form of diverging holes are not created during drilling [FAC 62-528.410 (6)(a)(1)]. After completion of construction, a list of testing is required for final submittal to demonstrate it will function as built, this list includes: cement evaluation surveys; temperature survey; pressuring tests; video television surveys; injection tests; withdrawal tests; caliper surveys; and radioactive tracer surveys [FAC 62-528.410 (7)].

1.8 Monitoring and Testing Requirements

Class I injection wells are monitored so that if migration of injection fluids were to occur it would be detected before reaching the USDW. Monitoring requirements include characteristics, flow rate and volume of injected fluid, injection pressure, annulus pressure, and background water quality of the injection zone [FAC 62-528.425(1). Dataloggers are utilized to generate thousands of data points for this monitoring program. The collected data has to be submitted for review by regulators, who also inspect the well site to make sure everything is operating according to the requirements put in place to protect drinking water source. Frequency of monitoring is usually specified in the permit.

Other than monitoring, periodic testing is conducted on all Class I injection wells at a minimum of every five years to determine that the well structure has integrity [FAC 62-528.425(d)]. The mechanical integrity tests are conducted by inserting packers into the well and pressure testing the casing to determine if it leaks. If the casing leaks, the well cannot be placed back into service until such time as the leak is fixed.

Monitoring wells are required to be permitted and constructed to collect data in two monitoring zones, which are above the injection zone at a sufficient distance from the well [FAC 62-528.425(1)(g)]. A distance of less than 150 feet is recommended by FAC 62-528.425(1)(g)(3). The wells are required to monitor the absence of fluid movement adjacent to the well bore and the long-term effectiveness of the confining zone [FAC 62-528.4259(1)(g)(1)]. Types of monitoring wells include single-zone, dual-zone and multi-zone.

All Class I injection well systems are required by the Florida Department of Environmental Protection to have a monitoring system that consists of a zone open below the deepest USDW and a second zone located near or above the deepest USDW (Maliva 2007). The monitoring zones are sampled monthly or weekly. The presence of wastewater in a monitoring zone may be indicated by a decrease in salinity and an increase in nutrient parameters such as total Kjeldahl nitrogen (TKN), over time. In some instances, vertically migrating fluids may push more saline native waters upwards before injected fluid are detected in the monitoring zone (Maliva 2007). Stable water chemistry is evidence that a monitoring zone has not been impacted by injected fluids (Maliva 2007). This type of leaking is migration of the injected water and is the suspected problem in all leaking wells (Maliva, 2007).

1.9 Risk Assessment

Migration of injected fluid into USDWs as mentioned in the previous subsections has been documented at Florida injection well sites including, but not limited to: Melbourne D.B. Lee in the Central District (USEPA, 2003); Seacoast Utilities, Miami-Dade North and South District Regional Wastewater Treatment Plant in Southeast District (USEPA, 2003; Maliva, 2007); and Northwest Pinellas County, Clearwater East, McKay Creek, and South Cross Bayou in the Southwest District. Some of the above wells located in the Southeast District are currently under investigation, while the majority of the above wells located in the Southwest District have been abandoned. It is worth noting that injected fluid has not been detected in a monitoring zone at any of the South District injection well systems as of September 2007 (Maliva, 2007).

Injected fluid movement may be present in injection well systems at Sykes Creek and Intercil Corporation Facilities in the Central District; and Palm Beach County South Regional Wastewater Treatment Plant, Broward North Central, Margate, Plantation NW, and G.T. Lohmeyer in the Southeast District, as detected in deep monitor wells completed below the deepest USDW (USEPA, 2003; Maliva, 2007). All of these instances require further investigation. Dating of the first detection of wastewater in a monitoring zone is not exact because of variations in analytical methods for nutrients and salinity leading to confounding in the monitoring data (Maliva, 2007). Statistically significant changes in multiple parameters are necessary for a conclusive determination of wastewater presence in a monitoring zone (Maliva, 2007).

It was concluded by USEPA (2003) that there are two main reasons why upward migration occurred at the well sites mentioned above. First, the differences in fluid temperature and density between native and injected water affects relative buoyancy. Injected wastewater has fluid densities that are roughly equivalent to those of fresh water. This wastewater is injected at depths where the native groundwater is saline or hypersaline. The comparatively lighter, less-dense wastewater responds to a buoyancy force component that promotes vertical movement. (USEPA, 2003) Another factor influencing fluid movement in subsurface geology is injection pressure. In many settings where underground injection is practiced, increases in pressure head (resulting from injection pressure) play a crucial role in determining the movement of fluids. In parts of South Florida, where injection zones demonstrate a great capacity to accept injected fluid (for example, the Boulder Zone), this force component may be less significant.

The risk driver was defined as the potential for migration to the upper Floridan, provided that significant vertical fluid movement does not occur (Bloetscher *et al.*, 2005). Identified pathogens are the contaminant in municipal wastewater that presents the greatest risk to USDWs (USEPA, 2003). Despite the occurrence of upward migration within the deep injection wells, the USEPA (2003) and UM (Bloetscher *et al.*, 2005) risk assessments, discussed in Section 1.2.3, confirmed that the risk to the environment and public heath posed by Class I injection wells was lower than the other disposal methods including ocean outfalls and surface water discharges.

1.10 Goals and Objectives

The goal of this project is to determine if there are any statistically significant differences between the DIWs in different parts of the state of Florida and if differences can be found in the physical parameters that might impact the long-term use of the wells. To this end, the permits for all of the Class I deep injection wells in the state of Florida as of September, 2007 were obtained. The differences will provide useful information to the regulators and should be considered when regulating current and future Class I injection wells. It is worth noting that a comprehensive collection and analysis of the physical data of the DIWs has never been performed. To accomplish this goal the following were performed:

- Collect copies of all permits for all wells in Florida, as of September, 2007,
- Collect construction documents and stratigraphy data from all available well completion reports,
- Develop a database of physical and permit parameters for all the DIWs in the state,
- Analyze the physical parameters and permit information to discern any differences that might impact long-term use,

Ultimately the goal is determine if there is a means to predict which wells are most likely to experience upward migration that would violate the current UIC regulations and to determine if any of the physical parameters might increase the likelihood of vertical fluid migration (leakage) into a USDW.

CHAPTER 2 DATA COLLECTION AND METHODOLOGY

2.1 Data Collection

The Florida State UIC program is regulated by FDEP. An effort of collecting data from each of the regulatory District Offices, including Central, Southeast, South, and Southwest, was performed. As a part of the process, a hard copy of the UIC permit for every Class I Well issued by FDEP was obtained. In addition, the files were scanned to collect construction and stratigraphy data from all the well completion reports. All permit files were scanned and are attached in Appendix I. Copies of the relevant well completion report data is included in Appendix I. The next step was to develop a database of physical and permit parameters for all the DIWs in the state.

Variables of interest were first identified as they may provide the reasoning for regional differences and frequent occurrences of upward migration in certain regions. Then the identified parameters were carefully extracted from each of the well permit documents and systematically compiled in a tabular form. The table is listed in Appendix II, which is sorted by FDEP map reference number as listed in Figure 16. This set of collected data is a representation of the deep injection well inventory in September, 2007. Descriptions of the collected data set are provided as follows:

- District: District in which the DIW resides
- County: County in which the DIW resides

- Usage: Classification of wells including hazardous or non-hazardous. Non-hazardous wells include municipal, reverse osmosis, combined, and industrial.
- Leaking Status: A leaking well indicates confirmed or possibly detected upward migration into or below the USDW base; it does not include leaking caused by any physical damage of the well itself.
- Operational Status: Operational status is either active, pending, abandoned, or converted.
- Number of DIW: The number of individual Class I Wells onsite to accommodate the designed injection capacity.
- DIW Depth: A measure of depth in feet of the deepest point of the DIW opening.
- DIW Final Casing Depth: A measure of depth in feet of the most interior and deepest well casing that is installed at the final construction stage.
- DIW Injection Horizon: A distance in feet measuring the difference between the well and its final casing depth.
- DIW Final Casing Diameter: A measure of diameter in inches of the most interior and deepest well casing that is installed at the final construction stage.
- DIW Peak Flow: A measure of injection capacity in million gallons per day at peak flow.
- Number of Monitoring Wells: The number of wells onsite for monitoring Class I wells.
- Depth of Lower Monitoring Zone: A depth measurement of the lower opening of the monitoring well in feet. If more than two monitoring zones present at any given site, the lowest monitoring zone is considered.

- Depth of Upper Monitoring Zone: A depth measurement of upper opening of the monitoring well in feet. If more than two monitoring zones present at any given site, the upper most monitoring zone is considered.
- Distance from Injection Zone to Lower Monitoring Well: A distance in feet measuring the difference between final casing depth and lower monitoring zone depth.
- Distance from Injection Zone to USDW: A distance in feet measuring the difference between final casing depth and the base of USDW zone.
- Clay Zone Boundary: Indicates whether a clay zone is present above the injection point. The clay zone boundary is categorized as solid, interspersed, or none.
- Clay Zone Thickness: A thickness measurement in feet of the clay zone above the injection point. Zero indicates an absence of the clay zone.
- Boulder Zone: Indicates whether the injection of the Class I Well is in boulder zone.
- Tubing and Packer: Indicates whether the Class I Well uses tubing and packer.

Collecting the following variables was attempted. However, limited data was available from the UIC permit.

- Vertical and Horizontal Hydraulic Conductivity (K): The measure of waters ability to maneuver through a porous media. It is the rate of flow per unit time per unit cross-sectional area.
- Porosity: A measure of how densely materials are packed within a media. It is the ratio of pore volume to total volume.

2.2 Methods of Data Analysis

In order to better understand the differences between the regions, the collected data was managed, summarized, and analyzed. Statistical methods were utilized to gain some sense of the parameters by presenting them in graphical and numerical forms.

2.2.1 Graphical Methods

Graphical techniques are utilized to summarize the important data by presenting pie charts, interval plots, and histograms. A pie chart was developed to describe possible result for each variable within each category. It should be noted that some of these variables are by site and some by well. For example, upward migration can only be evaluated at a site, not at a well if more than one well is present on a site. This technique is simple yet provides an overview of the data classification. An interval plot not only illustrates the range of the data, and also shows the mean value of the data. However, such graphs eliminate the outliners that are defined. A histogram represents a relative percentage of the data within each category. The x-axis is labeled by categories, and y-axis is labeled by percentages.

2.2.2 Analytical Methods

By using an analysis of variance (ANOVA) table, the means of treatments are tested for significance and interaction terms. A regression model is employed to fit an empirical equation to the experiment, which quantifies the contributed factors. The ANOVA table generates sum of squares, degree of freedom, mean square values, F values, and P values. These values test the means of each variable. A confidence level of 95 percent was used for the analysis.

Relating a response variable (y) to a single quantitative independent variable (x) is given by the equation of a straight line is called a linear regression. The equation can be expressed as follow:

$y = \beta_o + \beta_1 x$

where β_o is the y-intercept

β_1 is the slope of the straight line

2.2.3 Canonical Correlation Analysis

Canonical correlation analysis (CCA) is a means of determining the importance of a given independent variable on a depend value, introduced by Harold Hotelling. CCA will find roots for a dependent variable that are optimal with respect to correlations and corresponding correlations. For example, if we have two sets of variables, x and z, and there are correlations among the variables, then canonical correlation analysis will enable us to find linear combinations of the x's and the z's which have maximum correlation with each other. SAS will be used to evaluate this parameter. The dependent variable will be “leakage”.

2.3 Analytical Tools

The availability of statistical software has allowed us to analyze data in an efficient and accurate manner. The software used for this thesis is Microsoft Excel and Minitab.

2.3.1 Microsoft Excel

Microsoft Excel 2007 was used to compile and manage the collected data in a tabular format. It is a spreadsheet application written and distributed by Microsoft for

Microsoft Windows. Each row represents each well while each column represents each variable. The sort function is used to separate the data into regions for analysis. It is an excellent tool for importing data into any statistical software for further data evaluation.

2.3.2 Minitab

Minitab 16 Statistical Software was developed at the Pennsylvania State University by researchers Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner in 1972. It is a general purpose statistical software that combines data management and analyses. The data files are formatted like a spreadsheet and simple to manipulate and arrange data as necessary. It takes input data from Microsoft Excel and provides basic statistics, graph generations, regression analysis, to variance analysis and design of experiments.

Minitab 16 is used to convert parameters into useful data prior to conducting analyses. For instance, the leaking status (yes or no response) was converted to a numerical score (1 or 2). After data conversion, the software is utilized to construct graphs for summarizing the variables of interest and for comparing the differences between the regions.

2.3.3 SAS

SAS 9.2 is a popular statistical software developed by SAS Institute. It has been on the market for more than 30 years. It can be programmed to perform data entry and management, report writing and graphics, statistical analysis, and many more. The program was used to generate canonical correlation distinguish the significance of key variables. A confidence level of 95 percent was used for the analysis.

2.3.4 Groundwater Vistas

Groundwater Vistas (GV), developed by Environmental Stimulations Incorporated, was utilized to model the movement of the treated wastewater within the DIWs. GV is a three dimensional groundwater flow and transport modeling software that couples with Microsoft Windows to generate comprehensive graphical analysis. It supports multiple design models including, but not limited to, MODFLOW, MODPATH, MT3DMS, SEAWAT, GFLOW, PEST-ASP, RT3D, SWIFT. The modeling results can be displayed in both plan and cross-sectional views and be presented with contours, velocity vectors, detailed mass balance analyses, and so on.

For the purpose of the modeling exercise, MODFLOW, MODPAT, MT3DMS, and SEAWAT were utilized to model and calibrate Class I Wells. MODFLOW is a numerical modeling program that uses block-center finite difference approximation to analyze groundwater flow rate and volume balance for each block. MODPAT is a three-dimensional particle-tracking model that works with MODFLOW. MT3DMS is the capacity of simulating variations in fluid density. SEAWAT models variable-density groundwater flow and solute transport.

The author attempted to use Groundwater Vistas to model injection wells as two sites in each district, but this effort was not successful. After considerable efforts, it was determined that two problems existed: the Groundwater Vistas software does not properly interface with SEAWAT to provide useful solutions and the lack of data on deep aquifers is also a limiting factor. Thus, the modeling effort is excluded.

CHAPTER 3 RESULTS AND DISCUSSIONS

3.1 Overview

This section is broken into three parts. Section 3.2 outlines descriptive statistics, which are designed to provide the basic information with Class I injection wells in Florida. Section 3.3 outlines discretized data between wells and practices in the four FDEP Districts of interest. Section 3.4 outlines comparative statistics between districts to determine differences in the well construction and practices to evaluate whether these differences may impact injection well reliability and operation.

3.2 Descriptive Statistics

For providing quantitative summaries of the collected data, pie charts and interval plots were generated by Minitab and are provided with descriptive summaries. The intent of this section is to evaluate data for a single variable across all DIWs in the state.

In order to provide an overview of the Class I deep injection wells for this study, a table was created to summarize Florida's well inventory at the time of data collection (September, 2007). Table 3 below shows the breakdown of the total number of wells for each FDEP District Office: Central, Southeast, South and Southwest.

The wells were categorized and counted by usage and permitting status. Well usages are defined in Section 1.3 as either hazardous or non-hazardous. Municipal, combined, RO, and industrial further divide the non-hazardous wells. The permitting status of the wells is categorized as any one of the following:

- Pending: permit has been filed but currently under review within the FDEP.
- Non-active: wells were no longer permitted by plugging or abandoning, or were converted by classifying as a different type of wells, or standby as being under investigation or evaluation, or were classified as an exploratory well that was used for testing only
- Active: permit has been awarded or renewed and the wells are in service

As of September 2007, there was a total of 129 Class I well sites and 216 wells in Florida (GWPC, 2007 and USEPA, 2007). The operational status of the wells includes 22 pending, 20 non-active, and 174 active. Among the 174 active wells, only 1 was classified as a hazardous well and the rest (173) were non-hazardous wells, including 105 municipal, 15 industrial, 16 domestic and industrial combined, and 37 reverse osmosis (RO). Figure 16 shows locations of DIWs in Florida.

Table 3 Class I Well Program in Florida

Location	Pending	Non-Active	Active					Total
			Hazardous	Non-Hazardous				
				Municipal	Combined	RO	Industrial	
Central	0	2	0	8	0	1	3	**14**
Southeast	12	4	0	66	9	18	6	**115**
South	7	1	0	14	6	15	2	**45**
Southwest	3	12	1	17	1	3	0	**37**
Northwest	0	1	0	0	0	0	4	**5**
Florida	*22*	*20*	*1*	*105*	*16*	*37*	*15*	***216***

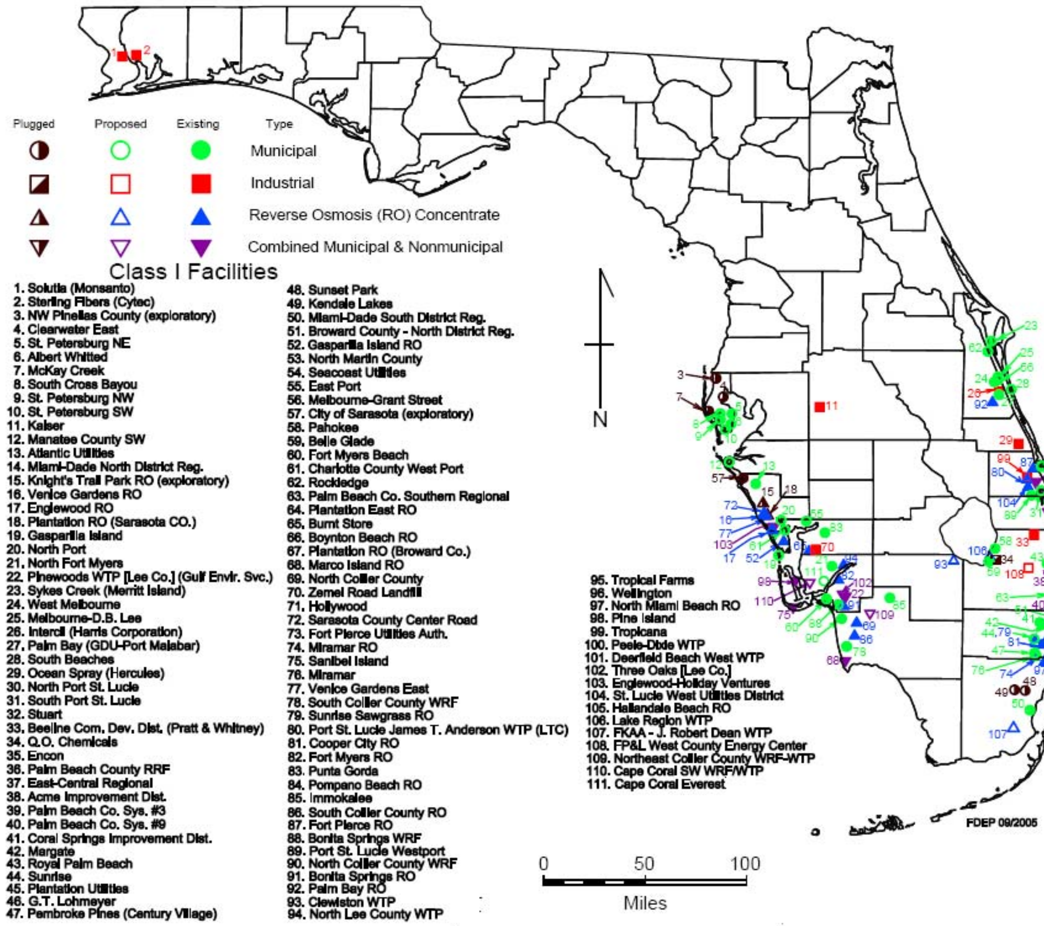


Figure 16 **Class I Well Program in Florida (USEPA, 2007)**

3.2.1 Well Distribution

Figure 17 shows the statewide distribution of DIWs based on usage, in percent and number (using the number of well sites). Wells utilized for disposal of treated municipal wastewater use 50 percent of the entire DIW well inventory. This is reflected in the statistical analysis of wastewater facilities in Florida that was conducted by FDEP in 2006. There were approximately 3,400 FDEP permitted wastewater facilities, not including onsite systems permitted by the Florida Department of Health. 39 percent of these facilities were classified as industrial wastewater and 61 percent were domestic wastewater (FDEP, 2008). The popularity of using reverse osmosis for treatment to comply with disinfection by-products rules is reflected in the 30 percent of DIWs used for the injection of concentrate. The only active hazardous well resides in Polk County, which has been carefully monitored to ensure its performance.

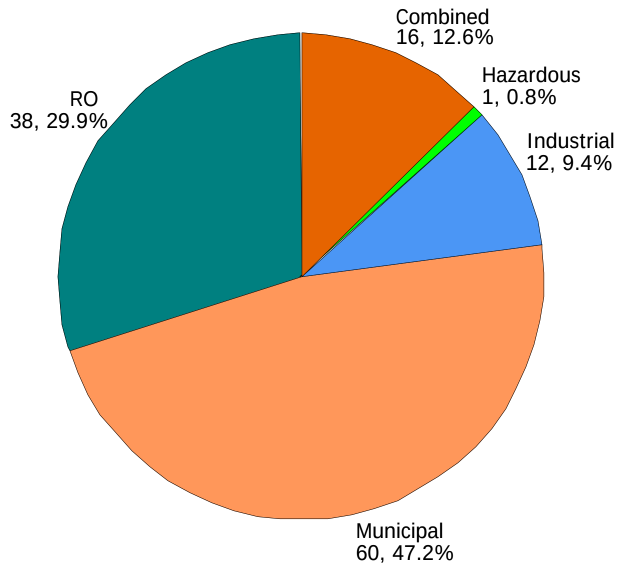


Figure 17 DIW Sites Distributed by Usage Pie Chart

Figure 18 shows both the number and thepercent of DIW sites that are, or are suspected of leaking (defined as vertical migration of injectate and not caused by physical damage of well). 19 percent of well sites have been detected or possibly detected upward migration into or below the base of USDW level, which is an important consideration from comparative statistics. Whether these wells may “leak” will be explored in Sections 3.3 and 3.4 based on variables such as depth and type of well. 81 percent of the sites do not have any leakage or upward migration issues. The relatively low percentage of leaking well sites (19 percent) indicates the DIW system is a fairly successful disposal method. It will be discussed in a later section that the leaking wells are concentrated in certain regions of Florida.

Within the 19 percent of leaking well sites, only 17 percent have been abandoned. For the four abandoned leaking well sites, there was an average of two well per site. This indicates a success of the implementation of the new regulation, Alternative for Class I Municipal Disposal Wells in Specific Counties in Florida as discussed in Section 1.2.3. The leaking wells were allowed continuing operation due to its upgraded treatment level met High Level Disinfection.

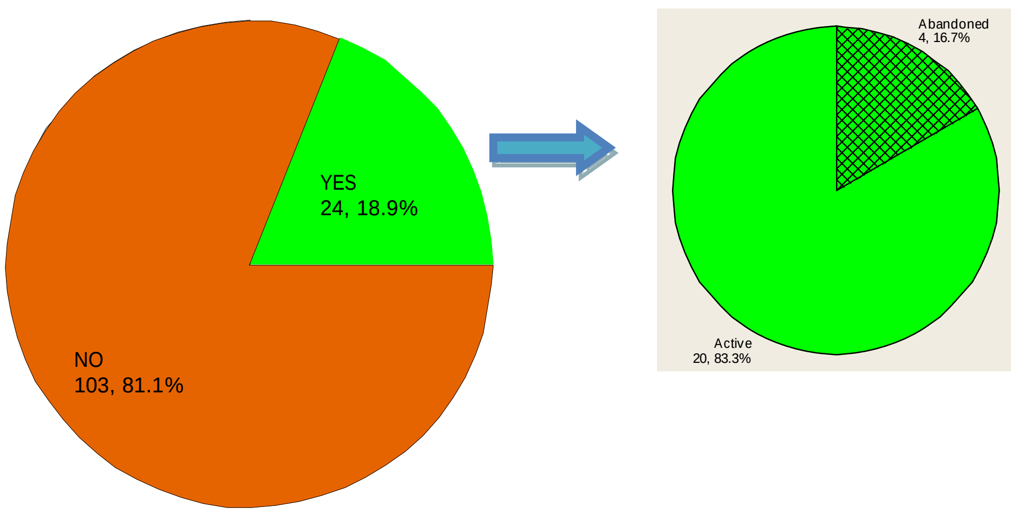


Figure 18 DIW Sites Distributed by Leaking Status Pie Chart

Figure 19 illustrates the distribution of DIW sites by operational status in both number and percentage. Almost 80 percent of wells are active or in operation, 14 percent are under review by FDEP for new construction, 5.5 percent are abandoned, and 2 percent have been converted to either a monitoring well or a different classified well. Due to the implementation of Alternative for Class I Municipal Disposal Wells in Specific Counties in Florida as specified in Section 1.2.3 Revisions of UIC Regulations, some of the municipal treatment plants upgraded their treatment levels to meet high level disinfection requirements. The improvements have allowed continuing operation of the wells that might be defined as "leaking" by accepting more highly treated wastewater.

Some were converted to Class V wells. Thus, Figure 18 shows that while 18.9 percent of the well sites were defined as leaking, only 5.5 percent of all wells are abandoned. Determination of whether the leaking and abandoned wells coincide will be studied in Section 3.3.

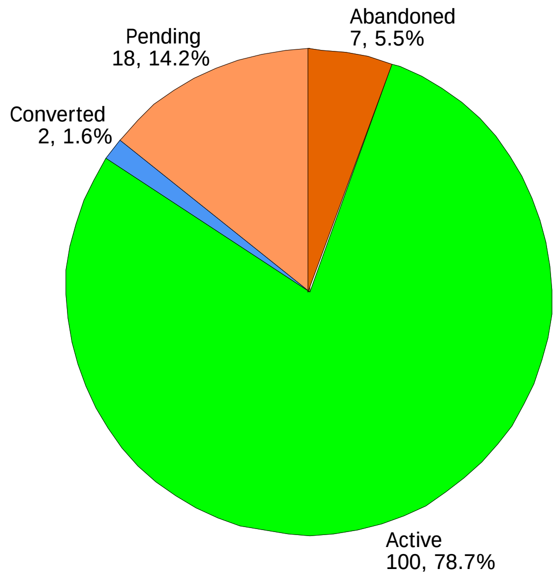


Figure 19 DIW Sites Distributed by Operational Status Pie Chart

Figure 20 indicates that the majority of sites with DIWs have only one or two DIWs on site. This reflects the fact that that majority of the wells have a low capacity or they are used for back-up disposal only, requiring fewer wells for disposing treated wastewater. Only 32 facilities in 2006 (around 1 percent of the total number of facilities) have permitted capacities of 15 million gallons per day or more (the capacity of one, 24 inch DIW). However, 32 facilities represent more than 50 percent of the total permitted wastewater capacity in Florida (FDEP, 2008). In addition, RO plants do not produce much brine for injection daily (under 3 MGD).

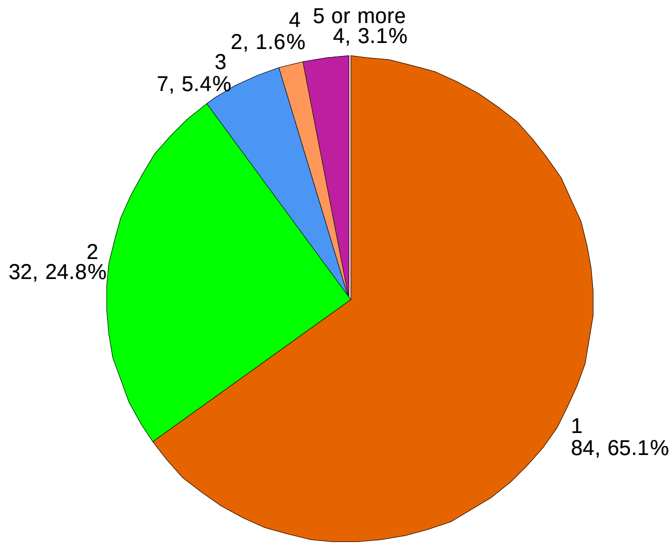


Figure 20 Number of DIW at Site Pie Chart

3.2.2 Well Depth

Figure 21 illustrates that 50 percent of the well depths range from –3500 feet to –3000 feet. Nearly 15 percent of wells have a depth ranging from –5000 feet to –3500 feet, while another 10.9 percent are –3000 to –2500 feet deep. 18 percent are shallower than -2000 ft. Figure 22 illustrates approximately 50 percent the final casing depths are in the range of –3000 feet and –2500 feet. The differences yield an average injection zone of 500 feet thick. As one can recall, the injection zone is defined by FDEP as below the lowermost formation containing an USDW within one-quarter mile of the wellbore. Since both figures illustrate a wide range of well depths that are determined based upon specific hydrogeological settings at each site, this shows USDW depths vary greatly throughout the state.

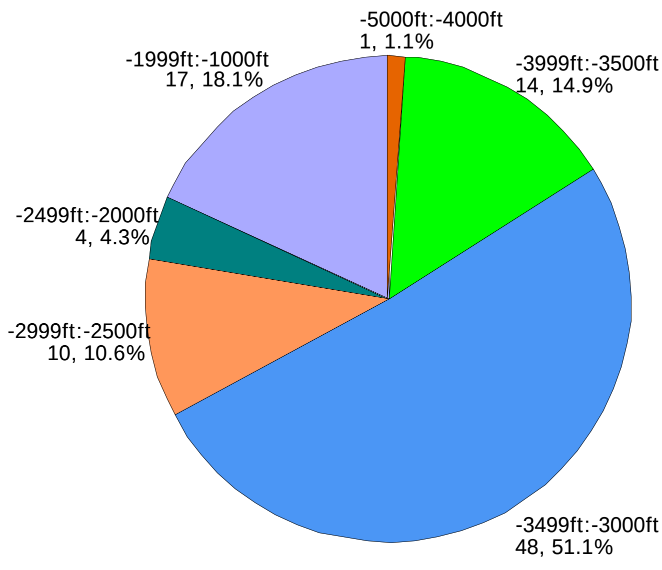


Figure 21 DIW Depth Pie Chart

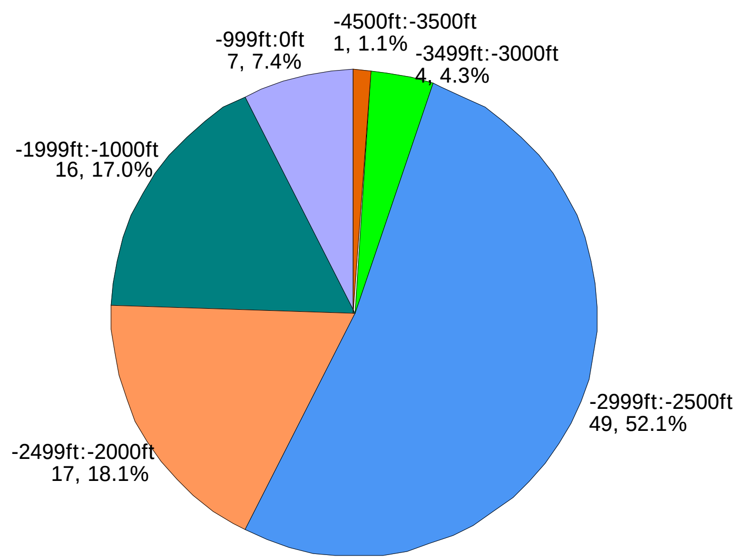


Figure 22 DIW Final Casing Depth Pie Chart

Figure 23 shows the abandoned wells are in a wide depth range of –4000 feet to –800 feet with a mean value of –2,400 feet. The active wells are in a depth range of –3,100 feet to –2,800 feet with a higher mean value of –2,900 feet. The active wells have a mean depth that is 500 feet deeper than the abandoned wells. It should also be noted that the pending wells that are in the review process for construction are even deeper, approximately 400 feet, than the active well. It appears to be a trend to deepen the wells perhaps to ensure less negative impact of the USDW.

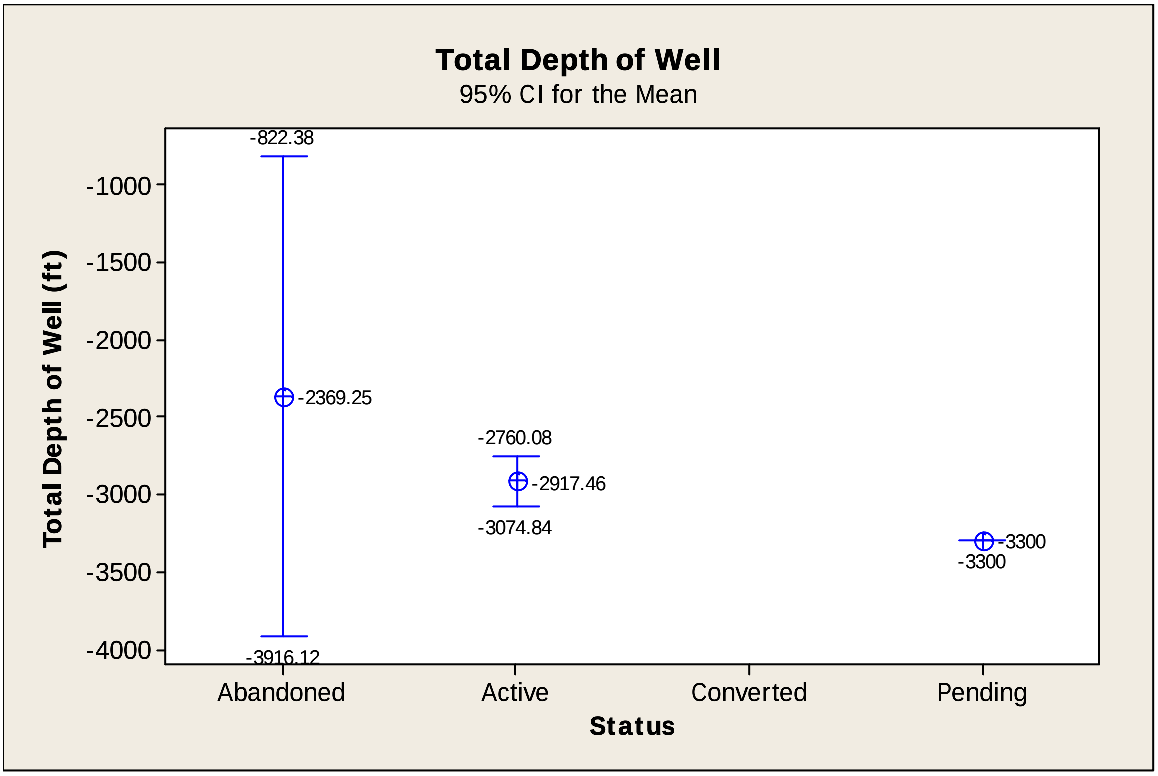


Figure 23 Total Well Depth Versus Well Status Interval Plot

Figure 24 shows that the only hazardous well in Florida has the deepest injection point at –5,000 feet below ground surface. The rest of the wells have comparable well depths anywhere from –3,500 feet to –2,000 feet with a slightly lower mean value of -2,750 feet for non-hazardous industrial wells.

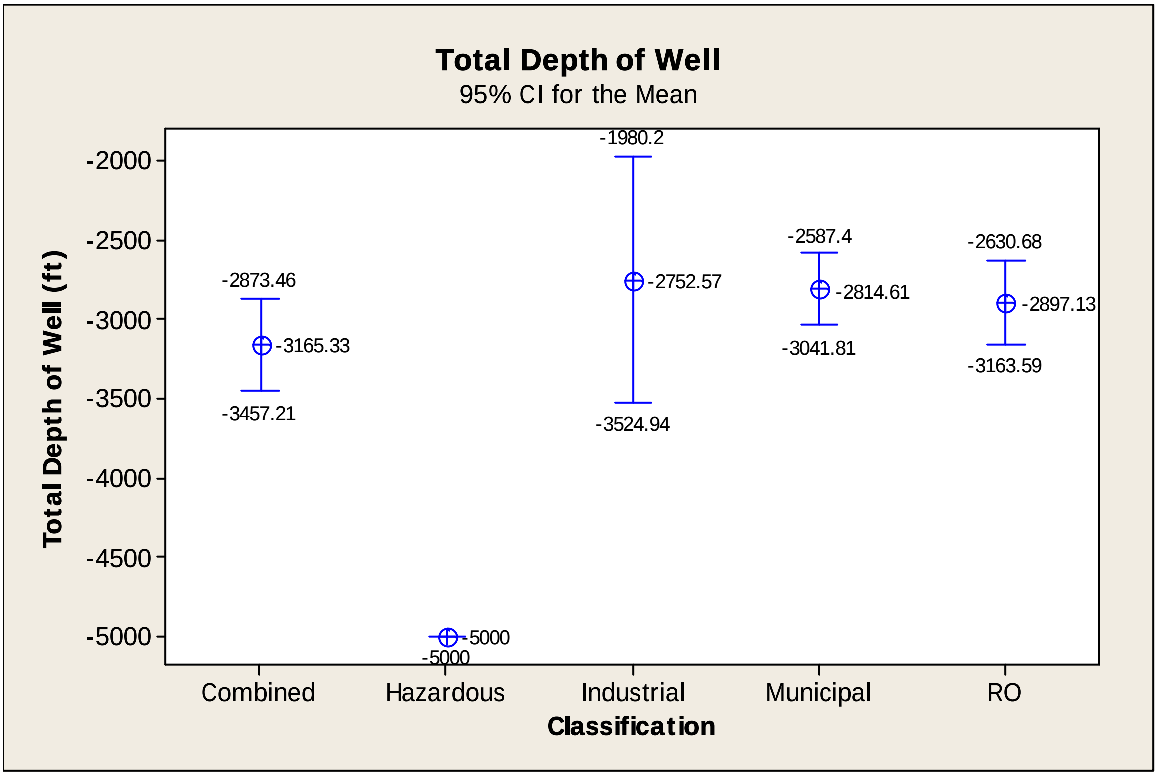


Figure 24 Total Well Depth Versus Well Type Interval Plot

3.2.3 Well Diameter

Final casing diameters are generally one incremental larger than the injection capacity. The common well diameter ranges from 22 inches to 25 inches as shown in Figure 25. These wells have a capacity on or about 15 MGD. This range is typical of the municipal injection well systems in the southeast region as discussed in Section 1.7 describing typical well construction. A wide range of well diameters have been implemented anywhere from 7 inches at the low end and 28 inches at the high end. Given the majority of wells have a small diameter, it confirms the low injection capacity for existing Class I wells.

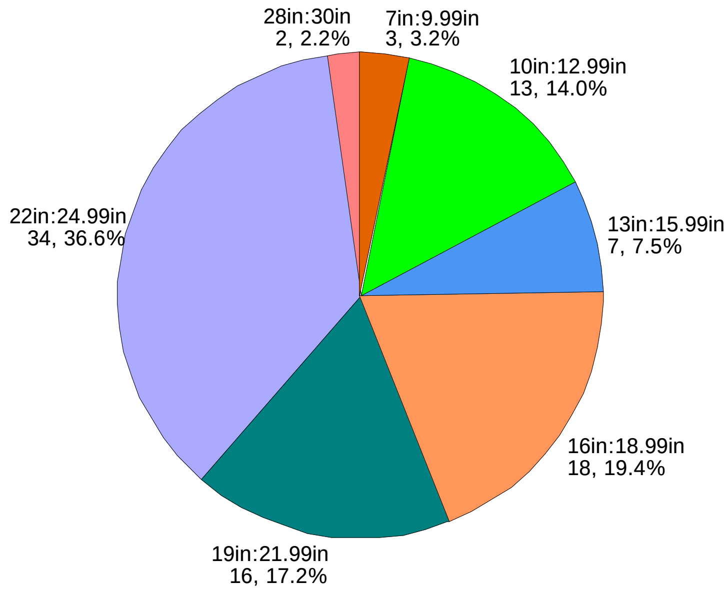


Figure 25 DIW Final Casing Diameter Pie Chart

Unlike the fact that well depths are common to all well types, well casing diameters are considerably varied depending on the type of the wells. Figure 26 shows that the deepest hazardous well has the smallest well diameter of 7 inches. The non-hazardous industrial wells have a casing diameter less than 11 inches, while the municipal wells casing diameter is above 19 inches. The diameters of RO and combined wells are in between the mean values of industrial and municipal well. Municipal wells are the largest user of Class I wells in terms have a bigger diameter for accepting higher quantities.

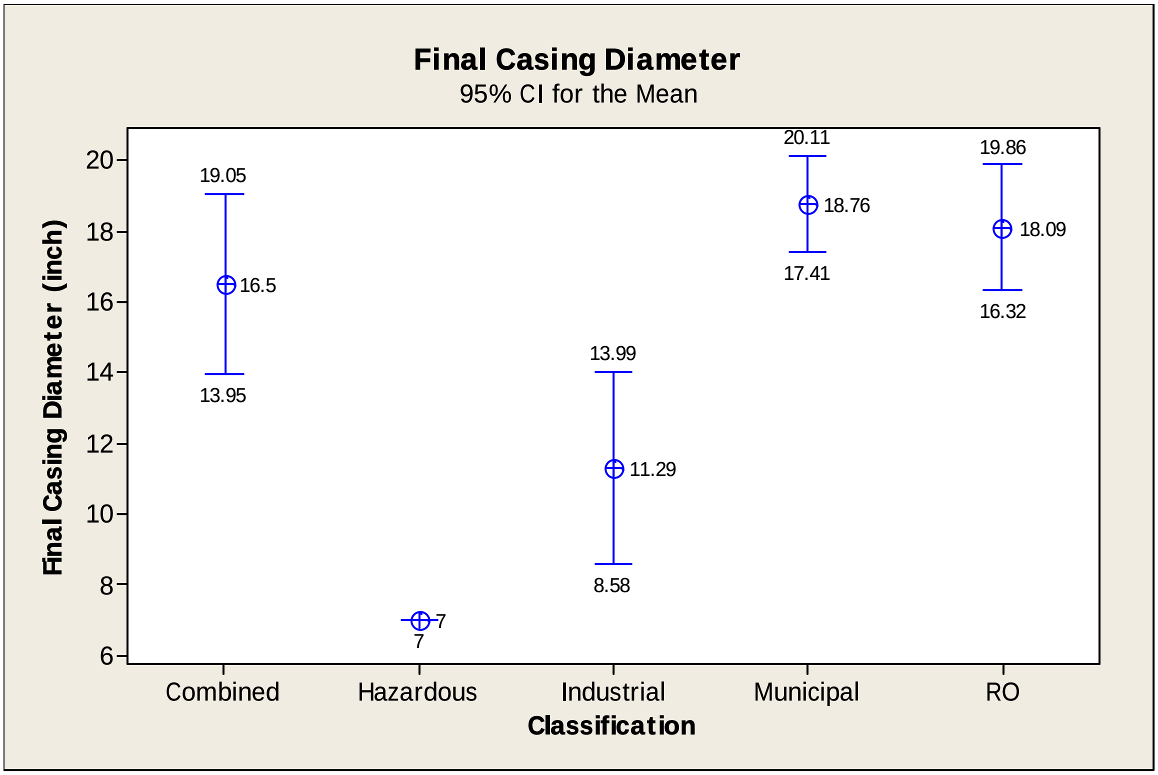


Figure 26 Final Casing Diameter Versus Well Type

Figure 27 shows that abandoned wells have a smaller casing diameter in comparison to the active wells. The abandoned well diameters have a mean value of 16 inches versus 18 inches for active wells. However, the pending wells have a mean value of 13 inches, which is smaller than anticipated. It is worth nothing that many data of pending wells are missing at the time of application. Thus, the graph does not reflect true range of wells in review for construction. It should be noted that two of the abandoned wells were in Miami-Dade County. They were abandoned when the county acquired smaller utilities and incorporated them into the regional county system.

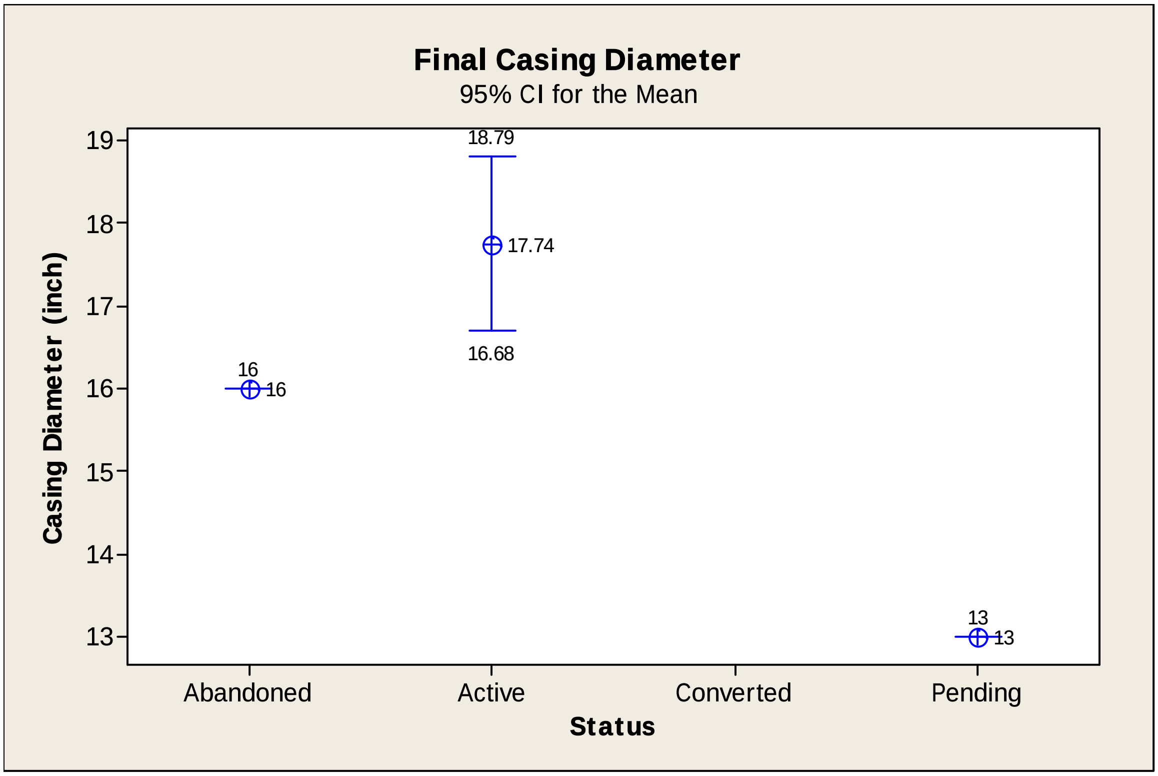


Figure 27 **Final Casing Diameter Versus Well Status Interval Plot**

3.2.4 Monitoring Wells

Monitoring wells are required to be permitted and constructed to collect data in two monitoring zones at a distance of less than 150 feet from the wells. These are the essential mechanisms to monitor the absence of fluid movement adjacent to the well bore and the long-term effectiveness of the confining zone. There are three types of monitoring wells including single-zone, dual-zone and multi-zone. Since two monitoring zones are required by FDEP and 57 percent of the sites contain a single well as shown in Figure 28, the majority of the monitoring wells are either dual- or multi-zone. Dual zone wells are more cost effective and warrant a faster construction schedule than single-zones. In addition, 65 percent of injection facilities only have one deep injection well on site as shown in Figure 20. Having only one DIW on site requires only one dual-zone monitoring well to meet FDEP monitoring standards.

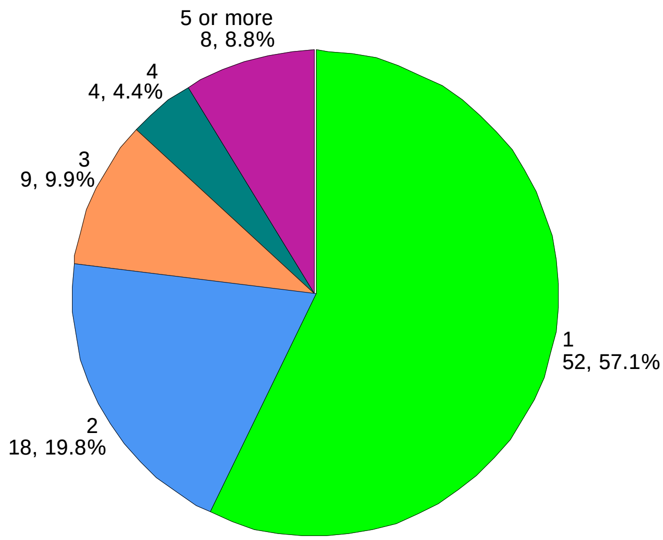


Figure 28 Number of Monitoring Wells Pie Chart

Lower zone monitoring wells are designed to monitor the aquifer zone immediately above the injection horizon. They are also required to be below the base of the USDW. Figure 29 illustrates that 64 percent of lower monitoring wells have depths ranging from –2,000 feet to –1,000 feet. In comparison to Figure 22 showing the distribution of final casing depths, lower monitoring wells are approximately 1,000 feet above the final casing depths. This trend indicates the USDW resides about 1,000 feet above the injection zone.

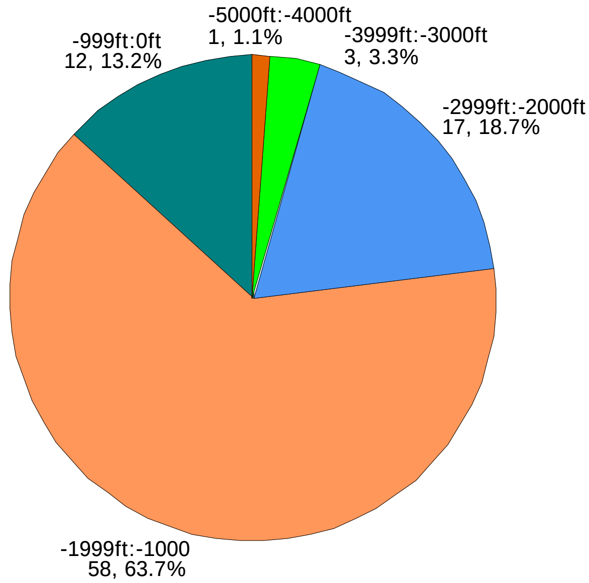


Figure 29 Depth of Lower Monitoring Zone Wells Pie Chart

Upper monitoring zone wells are required to be within or above the USDW zone. Figure 30 shows somewhat evenly distribution depths between –2,000 feet and 0 feet deep. The largest distribution is 34 percent at depths ranging from –1,500 feet to –1,000 feet, which is 500 feet or more above the lower monitoring zone wells.

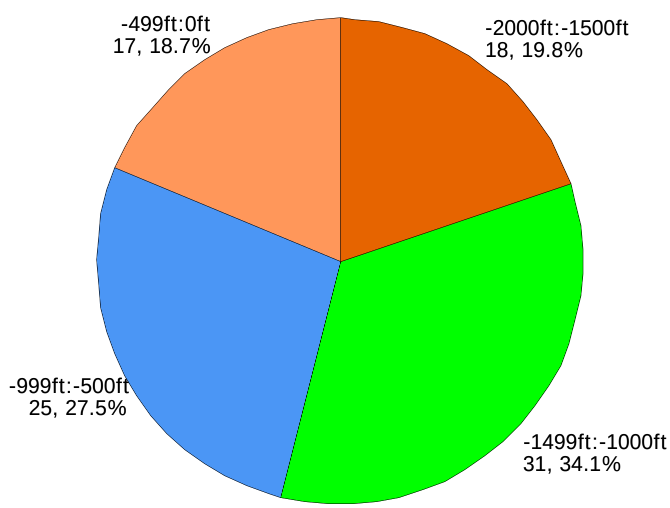


Figure 30 Depth of Upper Monitoring Zone Wells Pie Chart

3.3 Discretized Statistics

The collected data can be broken down into four FDEP Districts. The intent of this section is to determine where there may be differences in the construction and operation of injection wells between the districts. Discretized statistics will permit a comparison of single variables among different locations. The first four subsections provide a breakdown of the well inventory by counties within each district office. Follow by pie charts, histograms, and interval plots, which were generated by Minitab. Discussions are carried out to interprete and summarize the graphs.

3.3.1 Central District

For Central District, Class I Wells can be found in two counties, Brevard and Indian River, both are located at the south end of the coastal line. As of September 2007, there were a total of 14 DIWs with 2 non-active and 12 active. No new wells were proposed at the time. 12 active wells were all classified as non-hazardous including 8 municipal, 1 RO and 3 industrial. Numbers of wells for Brevard and Indian River are listed in Table 4.

Table 4 Class I Well Program in the Central District

			Active				
				Non-Hazardous			
Location	**Pending**	**Non-Active**	**Hazardous**	Municipal	Combined	RO	Industrial
Brevard	0	2	0	8	0	1	2
Indian River	0	0	0	0	0	0	1
Central District Total	*0*	*2*	*0*	*8*	*0*	*1*	*3*

The two non-active DIWs in Brevard County include one exploratory well at Palm Bay RO and one exploratory well that has been converted to a monitoring well at Sykes Creek Regional Water Reclamation Facility (WRF). Both facilities have active

Class I wells onsite for deep injection. Based on collected data, upward migration of injected wastewater into a USDW has been documented by the FDEP at Melbourne D.B. Lee. Also, injected fluid movement may be present in injection well systems at Sykes Creek and Intercil Corporation Facilities (USEPA, 2003; Maliva, 2007). The geologic formations in the Central District have an absence of a clear confined layer between the USDW and the injection zone as described in Subsection 1.6.1. However, the wells do have the Boulder zone available (northmost end).

3.3.2 Southeast District

The most popular district for Class I wells in Florida is the Southeast District, which contains more than half of all such wells in the state. Class I wells are found in each county within the district. At the time of data collection, there were a total of 115 DIWs with 12 pending, 4 non-active and 99 active. Among 99 active non-hazardous wells, 66 are municipal, 9 are domestic and industrial combined, 18 are reverse osmosis and 6 are industrial. Based on Table 5, Palm Beach, Broward, and Miami-Dade have the most DIWs.

Table 5 Class I Well Program in the Southeast District

			Active				
				Non-Hazardous			
Location	**Pending**	**Non-Active**	**Hazardous**	Municipal	Combined	RO	Industrial
St. Lucie	3	0	0	3	1	5	1
Martin	0	0	0	2	4	0	0
Palm Beach	2	2	0	14	4	3	5
Broward	2	0	0	26	0	9	0
Miami-Dade	3	2	0	21	0	1	0
Okeechobee	2	0	0	0	0	0	0
Southeast District Total	*12*	*4*	*0*	*66*	*9*	*18*	*6*

As of September 2007, four industrial DIWs at QC Chemicals were permanently abandoned in Palm Beach County. One municipal DIW at both Sunset Park and Kendale Lakes were also permanently abandoned in Miami-Dade County because of acquired utility ownership and took both injection well systems offline. Upward migration of injected wastewater into a USDW has been documented by the FDEP as having occurred at three injection well facilities: Seacoast Utilities and the Miami-Dade North and South District Regional Wastewater Treatment Plants (Maliva 2007). Upward migration of treated municipal wastewater into a monitor zone open below the base of the USDW was suspected to have occurred at another six injection well facilities in Broward and Palm Beach counties (Maliva 2007). The six well sites include Palm Beach County South Regional Wastewater Treatment Plant, Broward North Central, Margate, Plantation NW, and G.T. Lohmeyer. However, in the majority of injection well systems, no vertical movement of injected fluids has been detected in the monitoring zones (Maliva 2007). At the Palm Beach County site mentioned above, wastewater has been detected in monitoring zone, but not in monitoring zones open immediately above the main confining zone (Maliva 2007). Despite the occurrences of several upward migration cases, the number of problematic wells is minimal in comparison to the total wells currently in operation within this district.

3.3.3 South District

A total of 45 DIW systems were operational in the South District. As of September 2007, there were 7 pending, 1 non-active and 37 active wells. 37 non-hazardous active wells include 14 municipal, 6 domestic and industrial combined, 15 RO and 2 industrial. Table 6 shows the numbers and status of DIWs in each county of the South District.

Table 6 Class I Well Program in the South District

			Active				
				Non-Hazardous			
Location	**Pending**	**Non-Active**	**Hazardous**	Municipal	Combined	RO	Industrial
Hendry	0	0	0	0	0	1	0
Charlotte	0	1	0	4	0	4	2
Lee	2	0	0	5	4	6	0
Collier	4	0	0	5	2	4	0
Glades	1	0	0	0	0	0	0
South District Total	*7*	*1*	*0*	*14*	*6*	*15*	*2*

One exploratory well has been converted to a monitoring well at North Fort Myers Utilities that was indicated as a non-active well in Lee County. Another exploratory well has been converted to a monitoring well in Punta Gorda that was indicated as a non-active well in Charlotte County. Furthermore, injected fluid has not been detected in a monitoring zone at any of the South District injection well systems (Maliva 2007). It was concluded that hydrogeological conditions are considered to be generally suitable for safe deep-well disposal of waste liquids in the South District (Maliva 2007).

3.3.4 Southwest District

Most of the Class I wells in this district are concentrated along the coastline. The only well that is located away from the coast is at K.C. Industries in Polk County. It is also the only active hazardous DIW in the entire state of Florida. 37 wells were listed in the Southwest District at the time of collecting data with 3 pending, 12 non-active and 22 active. The 21 active non-hazardous wells include 17 municipal, 1 domestic and industrial combined and 3 RO. Table 7 illustrates the numbers and status of wells in each county of the Southwest District.

Table 7 Class I Well Program in the Southwest District

Location	Pending	Non-Active	Active				
			Hazardous	Non-Hazardous			
				Municipal	Combined	RO	Industrial
Polk	0	0	1	0	0	0	0
Pinellas	1	7	0	13	0	0	0
Manatee	0	1	0	1	0	0	0
Sarasota	1	4	0	3	1	3	0
Hillsborough	1	0	0	0	0	0	0
Southwest District Total	*3*	*12*	*1*	*17*	*1*	*3*	*0*

All seven wells have been permanently abandoned in Pinellas County due to the detection of upward migration of the injected fluid. They were located in Northwest Pinellas County, Clearwater East, McKay Creek and South Cross Bayou. One well at Manatee County Southwest has been converted from an exploratory well to a monitoring well. In Sarasota County, three exploratory wells at Ocean Spray Plant have been converted to monitoring wells and one well at Plantation RO was temporarily abandoned. As indicated in Table 7, one third of the Class I wells in the Southwest District were non-active.

3.3.5 Well Distribution

As mentioned in Section 3.2 Descriptive Statistics, a total of 129 well sites obtained construction permits in the state of Florida as of September 2007. Figure 31 illustrates the number of the well sites that each of the District Offices regulates. It also presents a percentage distribution among the regulatory offices. It clearly shows a large presence of Class I wells in Southeast region, followed by South, Southwest, and Central.

The Southeast District encompasses the three most populous counties in Florida: Miami-Dade, Broward, and Palm Beach, which are commonly referred to as the Tri-County area. The Southeast District is also where the Boulder zone was first discovered and has been studied extensively. In southeast Florida, the Boulder zone is viewed as an ideal site for accepting large amount of injected fluid, which coincides with having a large quantity of wastewater generated by the population of 6 million residents (Wikipedia, 2010). AS a result, since 1971, DIWs have become the accepted disposal method and/or a major emergency backup system of treated wastewater in Southeast District.

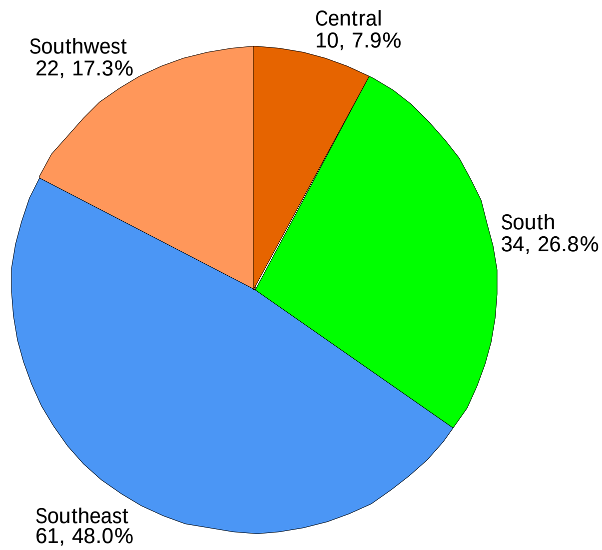


Figure 31 DIW Sites Distribution by District Pie Chart

Figure 32 shows well type distribution within each district office in percentage. Municipal wells are not only the most numerous wells in Florida as shown in Figure 17, but also they outnumber other types in every single district office. RO concentrate wells are the second most common well type. They are found mostly in the South, Southwest, and Southeast Districts. In the Central District, the industrial wells are twice the amount of the RO wells. As mentioned, there is only one hazardous well that is currently operated in Southwest region.

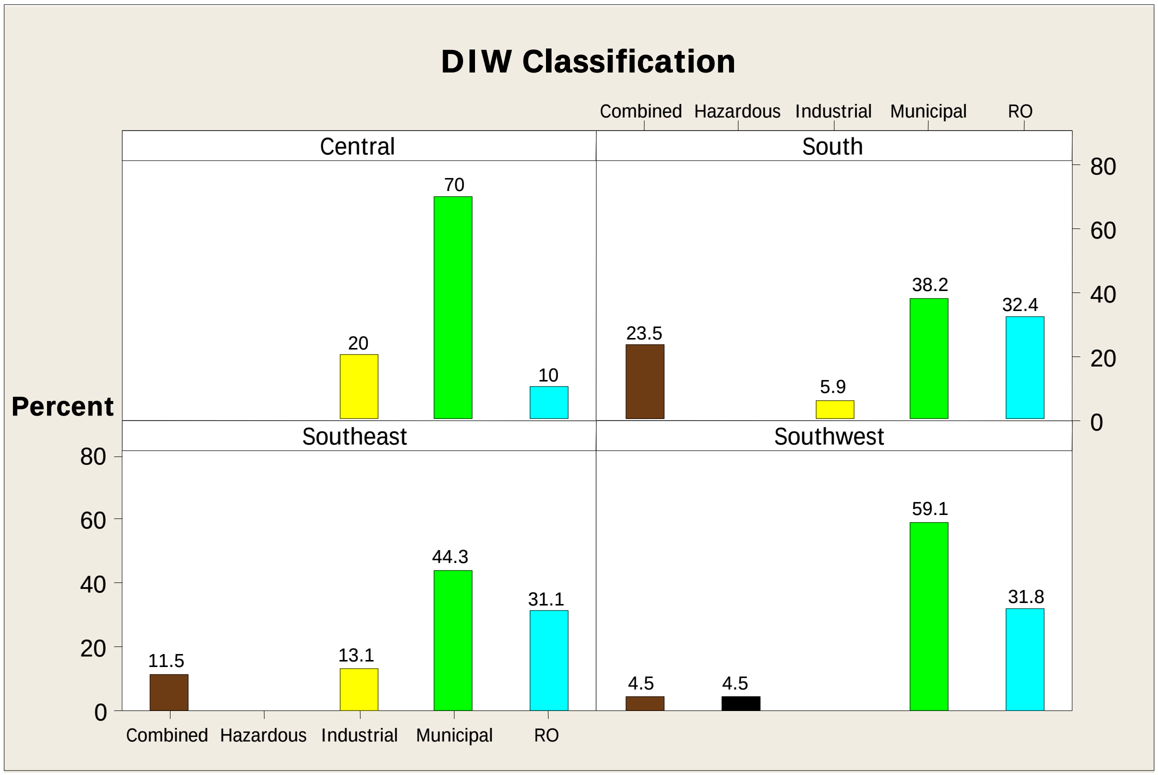


Figure 32 DIW Usages by District Histogram

Leaking wells are indicated where there is possible or confirmed detection of the injected fluid movement. Figure 33 shows the percent of DIWs that are or are suspected of leaking within each district. The Central District has the least number of wells as shown in Figure 31; however, it has the most leaking well sites: 40 percent of its total well sites, followed by 36 percent for the Southwest District and 20 percent for the Southeast District. No leaking wells have been documented in the South District prior to September 2007.

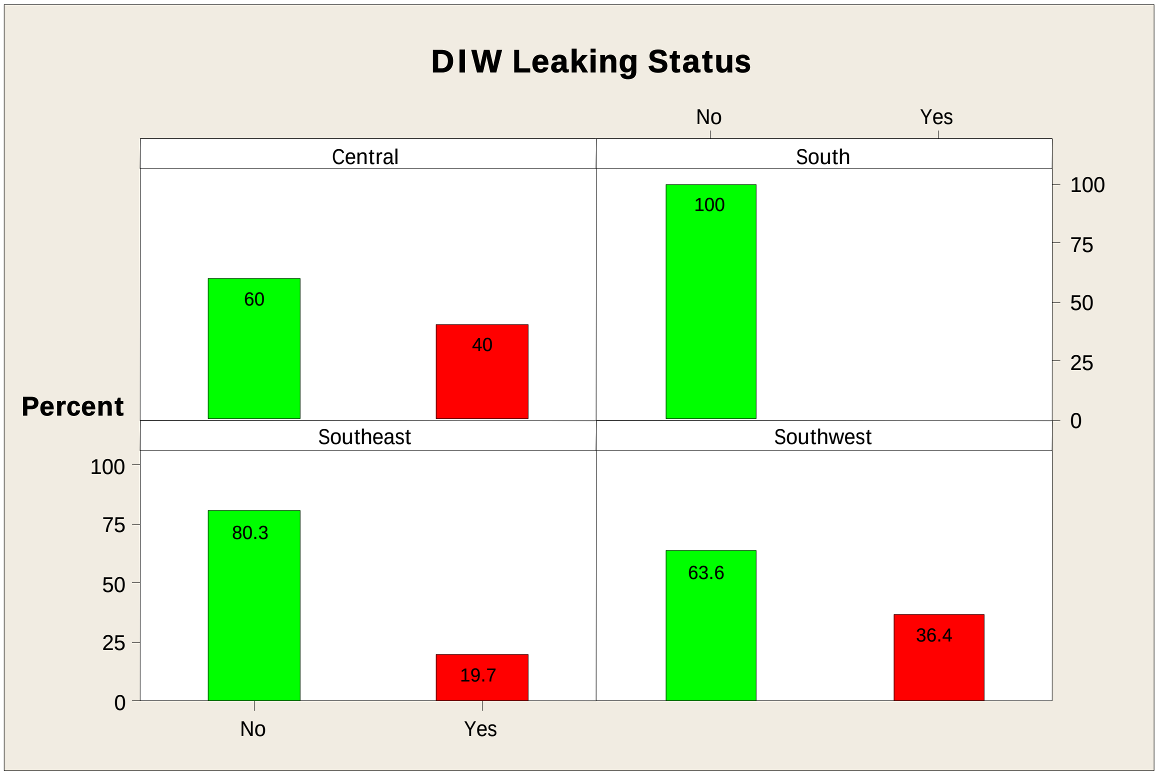


Figure 33 DIW Leaking Status by District Histogram

Operational status of the wells in percentages is shown in Figure 34. Even though the Central has 40 percent of its well sites that have detected upward migration, all the wells are still in operation. Their treatment levels have been upgraded to meet Alternative for Class I Municipal Disposal Wells in Specific Counties in Florida that is detailed in Section 1.2.3. Utilities that upgrade are allowed to continue operation. The upgraded treatment is equivalent to reclaimed water programs. The South District has 85 percent of active and 15 percent pending wells. This district has demonstrated successful DIW practice and more well sites are being added. On the other hand, the Southwest District has 36 percent of leaking well sites, and a majority of these wells are either abandoned or converted to other types. However, it appears there is a continued interest in DIWs in the Southwest District, as 14 percent of total well sites are in the review process for construction. Southeast has almost 20 percent of its total wells leaking and only ¼ of the leaking wells are abandoned. 16 percent of well sites in the Southeast District are pending for construction.

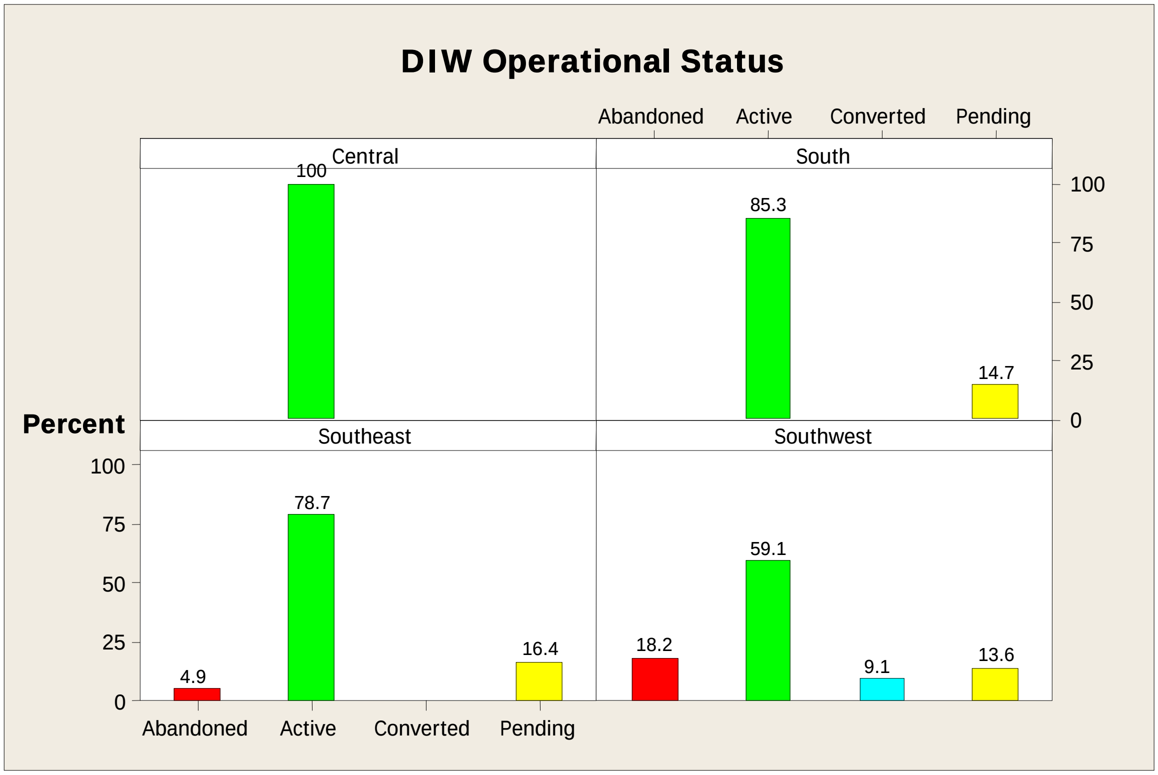


Figure 34 DIW Operational Status by District Histogram

Figure 35 shows status (active versus abandoned) of leaking well sites in each district as of September, 2007. As mentioned in the previous discussion, the Central District had all leaking wells in operation. Followed by the Southeast District in which 8.3 percent of leaking well sites has been abandoned. The Southwest District had almost 40 percent of the leaking wells sites abandoned. The reason of abandoning the leaking wells in the latter two districts was because of the change in utility ownerships and the wells were taken offline.

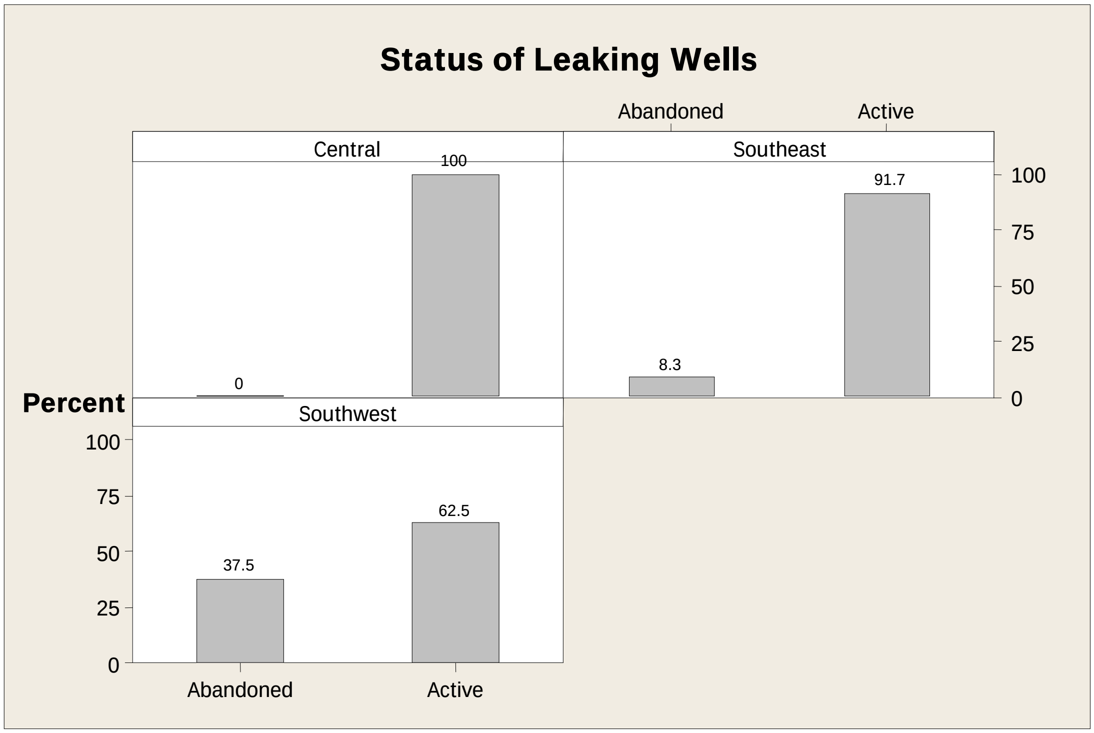


Figure 35 Status of Leaking Wells by District Histogram

35 percent of total deep injection well sites have more than one well onsite to accommodate adequate injection capacity, as illustrated in Figure 20. Figure 36 shows a descending order in the number of onsite wells for the Southeast, Southwest, Central, and South Districts. Miami-Dade South District Wastewater Treatment Plant in the Southeast District has the most onsite wells (17) for a rated capacity of 250 MGD.

Total peak flow at site in Figure 37 corresponds to number of wells in Figure 36. Similarly, DIW systems in the Southeast District have a mean value of 47 MGD injection capacity, followed by the Southwest District at 24 MGD, the South District at 9 MGD, and the Central District at 8 MGD.

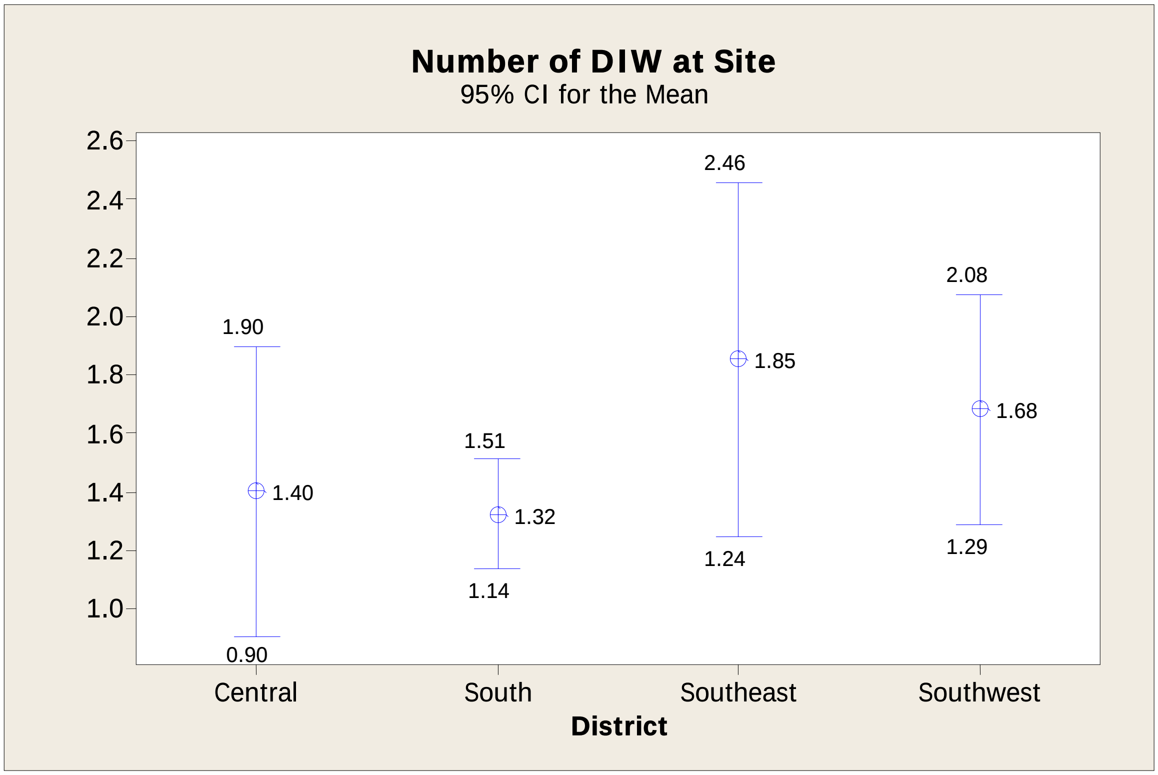


Figure 36 **Number of DIW at Site by District Interval Plot**

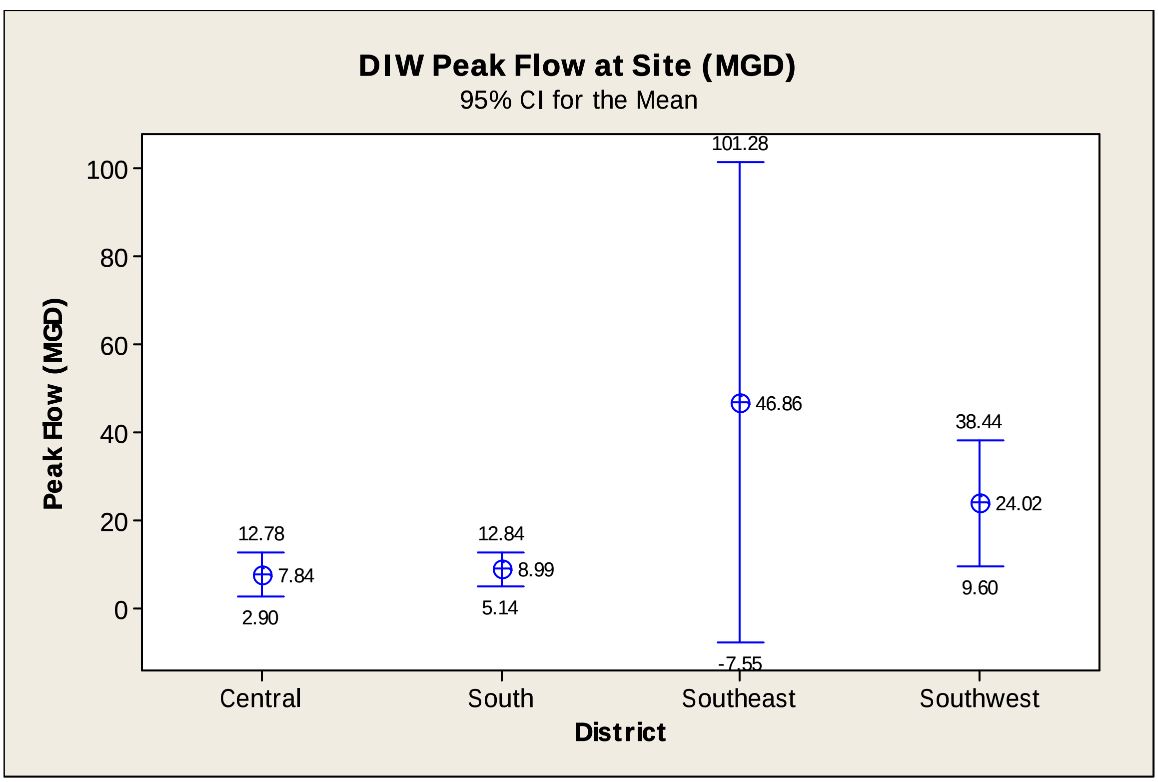


Figure 37 **DIW Peak Flow at Site by District Interval Plot**

3.3.6 Well Depth

Well depths are unique, which are determined to conform to its site specific hydrogeological formations. Figure 38 and Figure 39 provide well depths and final casing depths, respectively. Both interval plots show an identical descending order from the deepest to the shallowest: Southwest, Central, South, and Southeast.

Klein (1972) described the Lower Floridan Aquifer to be at or near the land surface in central Florida but dipping deeply beneath the surface to the southeast (Klein, 1972; McPherson 2000). As illustrated in Figure 38, the Central District well depths are in the range of –2,500 feet to –2,900 feet below ground surface with a mean value of –2,700 feet. The same figure shows that the Southeast wells are in the range of –3,150 feet to –3,400 feet with a mean value of –3,300 feet. This comparison confirms Klein's description as illustrated in Figure 40.

The South District offers the second deepest set of Class I wells anywhere from –2,700 feet to –3,100 feet with a mean value of –2,900 feet. This confirms the illustration in Figure 40 (Klein, 1972; McPherson 2000) that the Floridan Aquifer System dips deeper as it moves from the west coast (South District) to the east coast (Southeast District).

As expected, the shallowest Class I wells are in the Southwest District, where the majority of the wells are located in the Upper Floridan Aquifer zone. Depths range from –1,200 feet to –2,500 feet with a mean value of –1,800 feet.

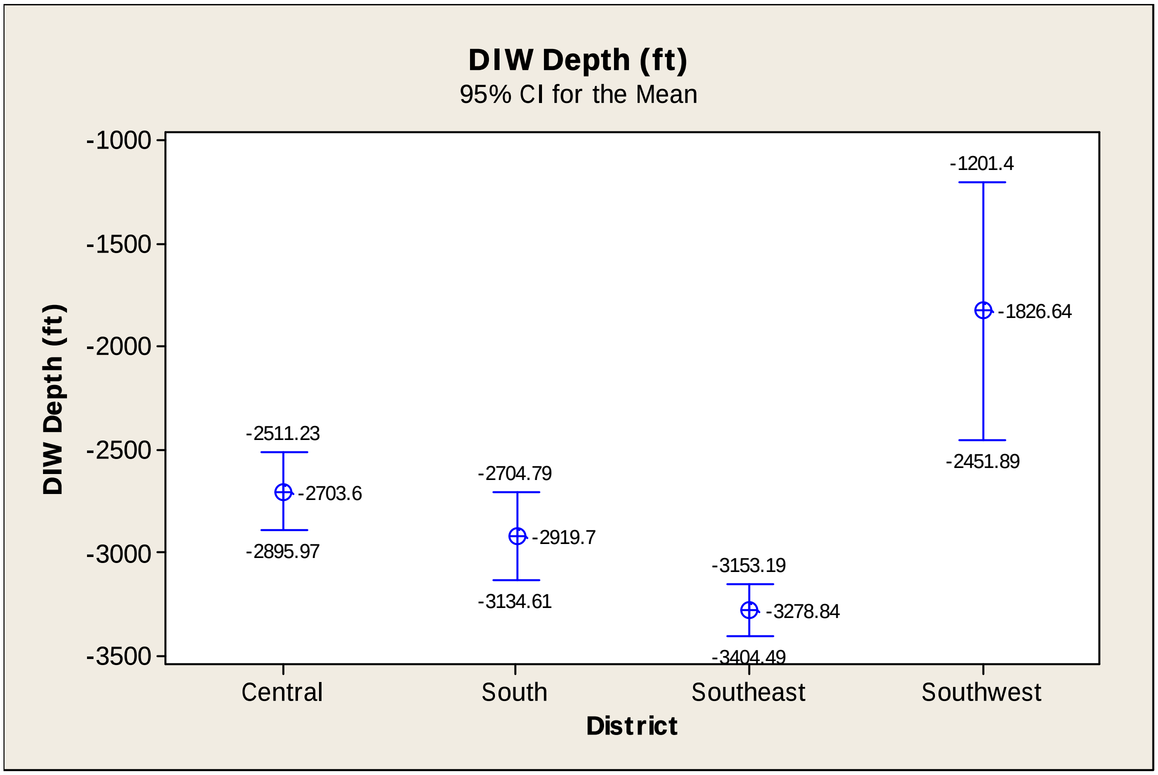


Figure 38 **DIW Depth by District Interval Plot**

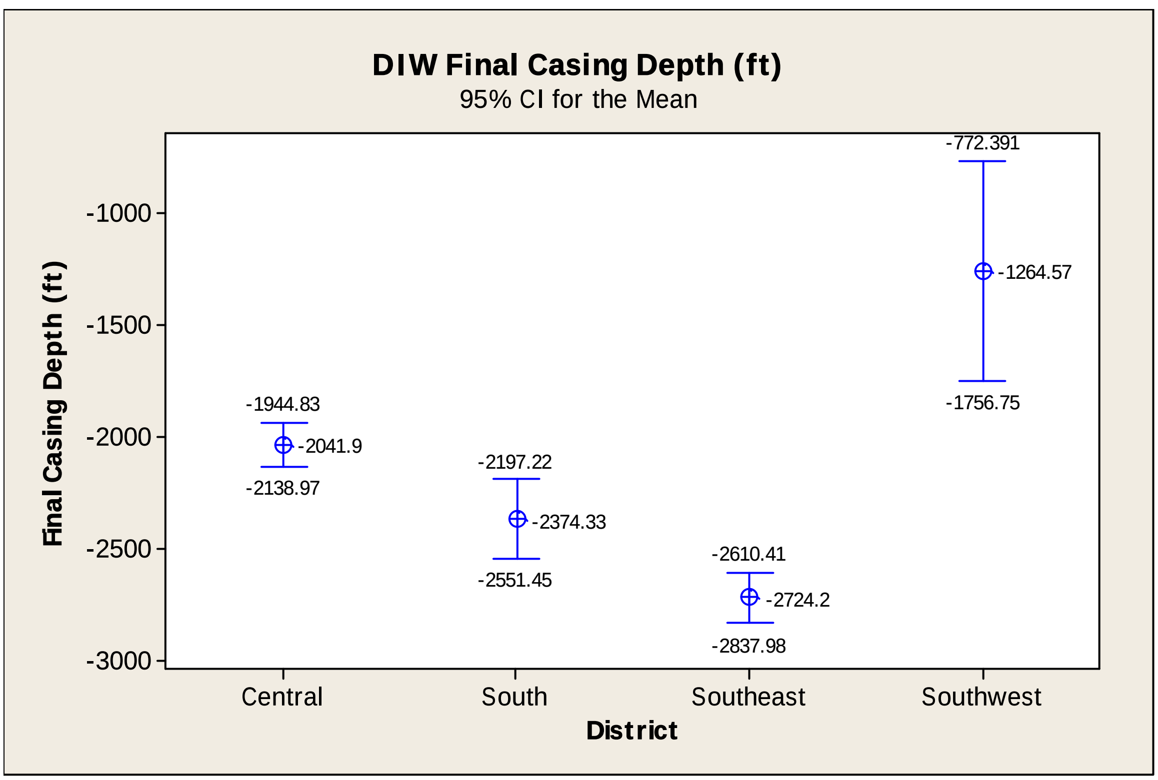


Figure 39 **DIW Final Casing Depth by District Interval Plot**

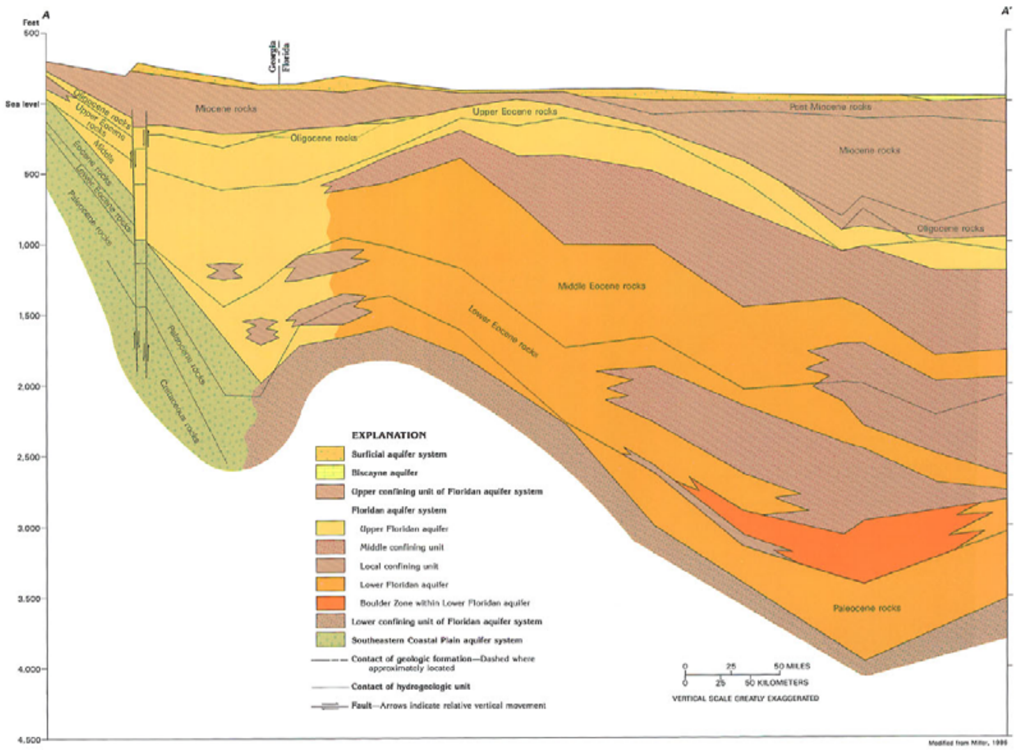
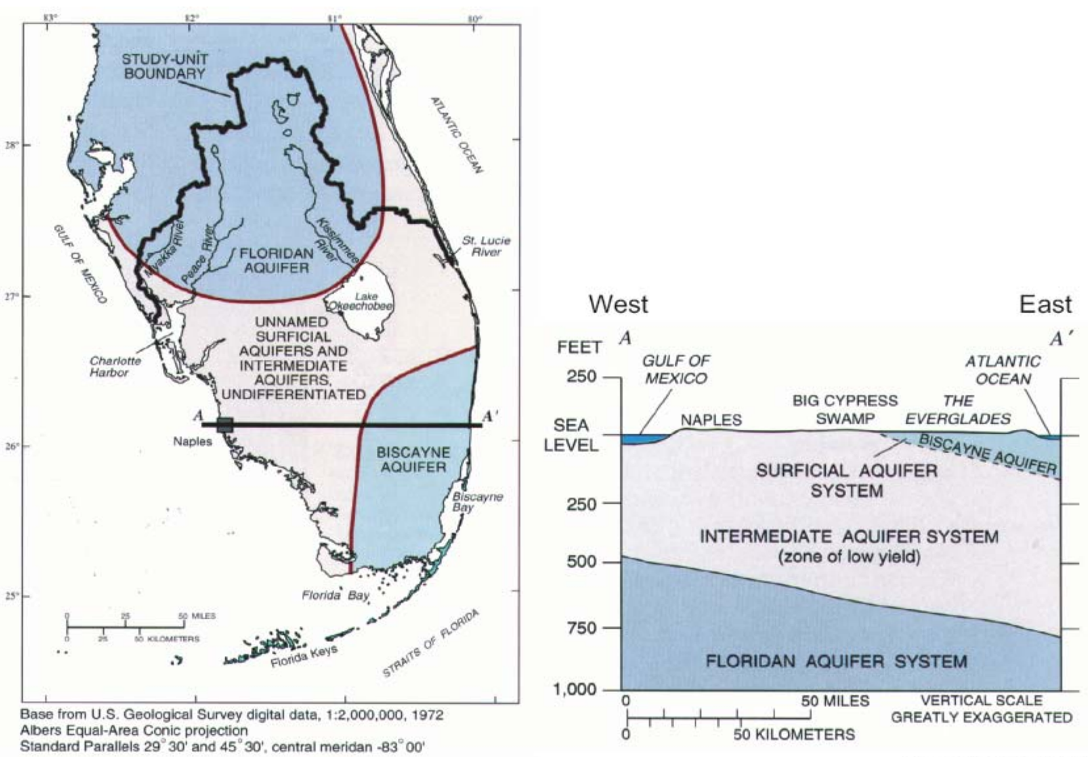


Figure 40 Hydrogelogic Formations from from North to South



Source: McPherson et al (2000)

Figure 41 Hydrogelogic Formations from West to East

DIW injection horizon is the difference between the final casing depth and the final well depth. There is no clear correlation between the injection horizon in Figure 42 and the depths. Central Florida (Central and Southwest Districts) has a wider injection horizon compared to South Florida (Southeast and South Districts).

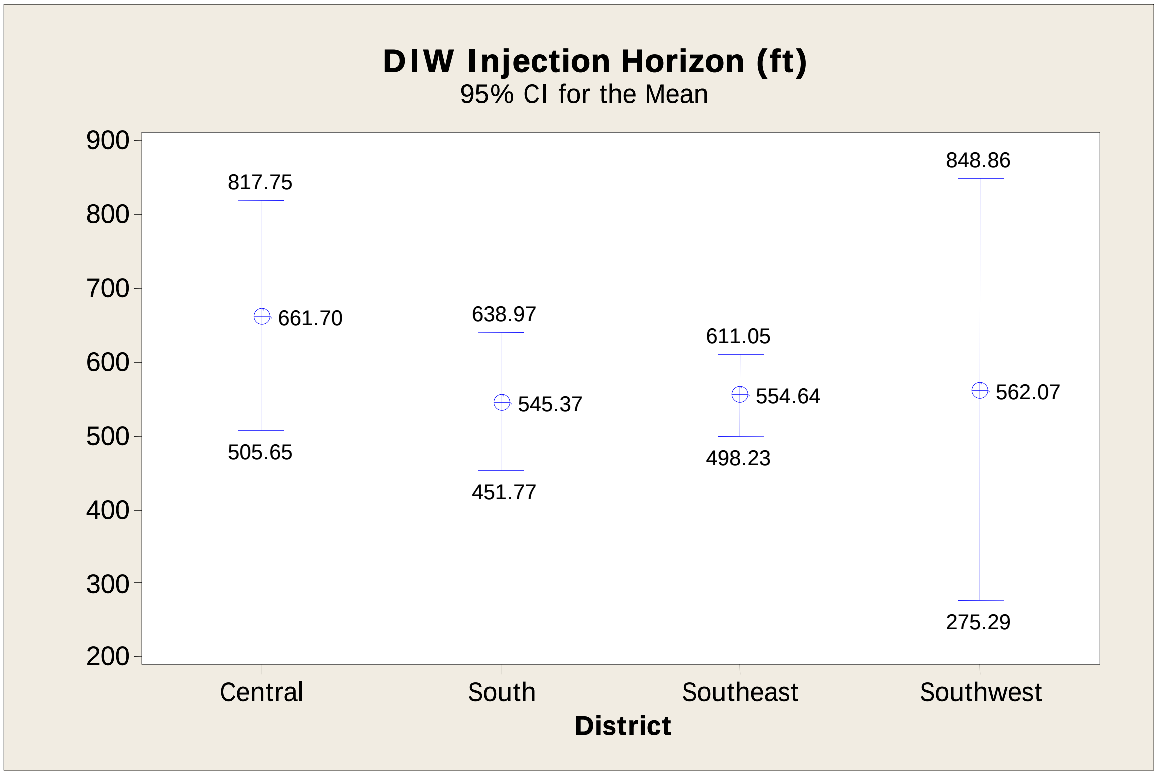


Figure 42 **DIW Injection Horizon by District Interval Plot**

3.3.7 Well Diameter

Figure 43 does not show a clear relationship between the well diameter and the hydrogeologic setting. However, previous discussions revealed that the Southeast District has deepest wells and the most number of wells with the largest casing diameter. Again, Central Florida (Central and Southwest Districts) has a wider range in casing diameter compared to South Florida (Southeast and South Districts).

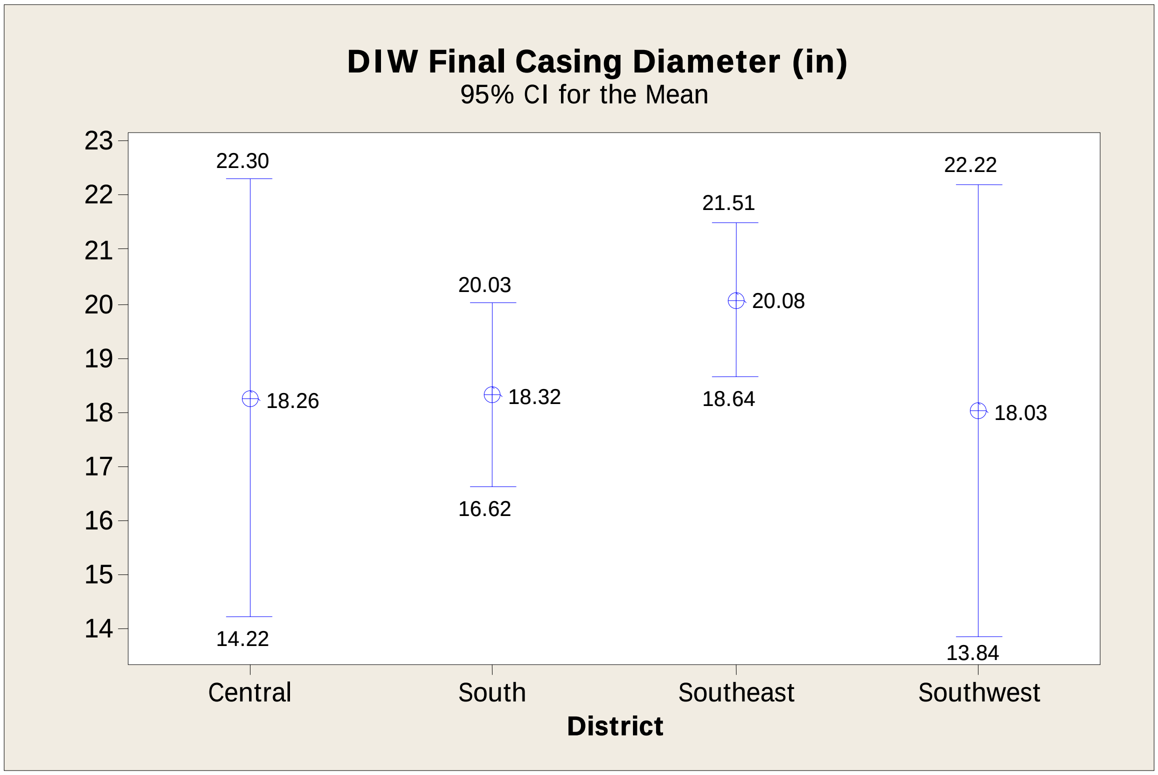


Figure 43 Final Casing Diameter Versus Well Location

3.3.8 Monitoring Wells

Figure 36 shows that the Southeast District has the highest number of wells onsite, but has the second fewest monitoring wells. In part this is because they have the most wells per site, and proper configuration of the DIWs and monitoring wells can permit one monitoring well to serve multiple DIWs. In addition, dual zone wells are common in this district. The remaining districts are shown in the descending order for number of wells versus number of monitoring wells comparing to their mean values: the Southwest, Central, and South Districts. This arrangement corresponds somewhat to the leaking wells percentage as illustrated in Figure 32.

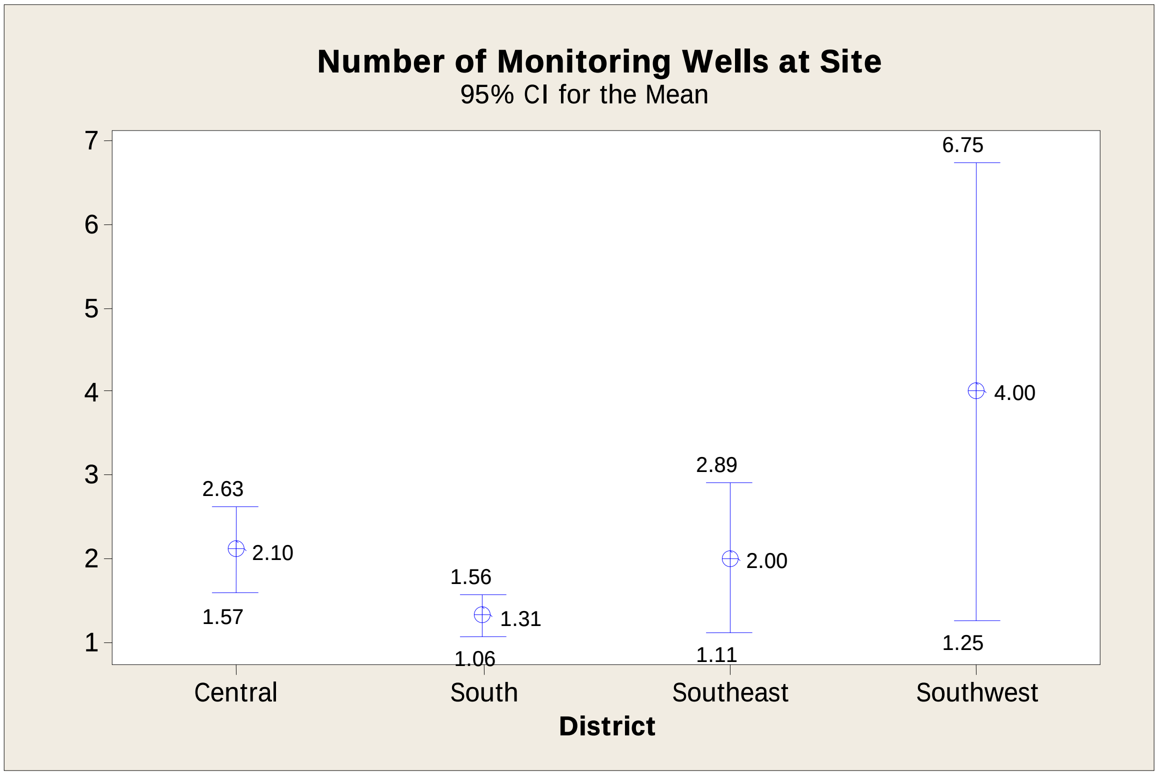


Figure 44 Number of Monitoring Wells by District Interval Plot

As expected, the depths of both lower and upper monitoring wells have a strong correlation with well depths. As detailed in both Figure 45 and Figure 46, the Southeast District implements the deepest set of the monitoring wells, followed by the South, Central, and Southwest Districts. Monitoring wells usually reside below and within the USDW base. The graphs demonstrate the USDW varies throughout the state, and the depths correspond to hydrogeological formations.

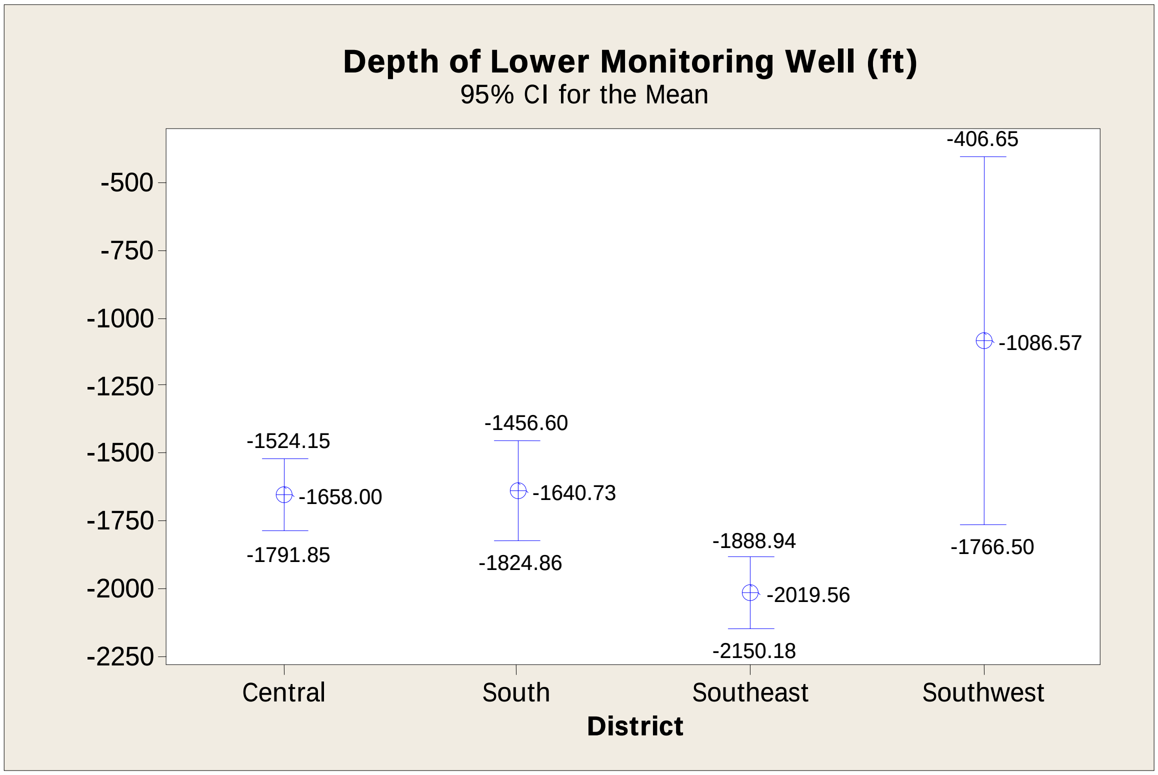


Figure 45 Depth of Lower Monitoring Well by District Interval Plot

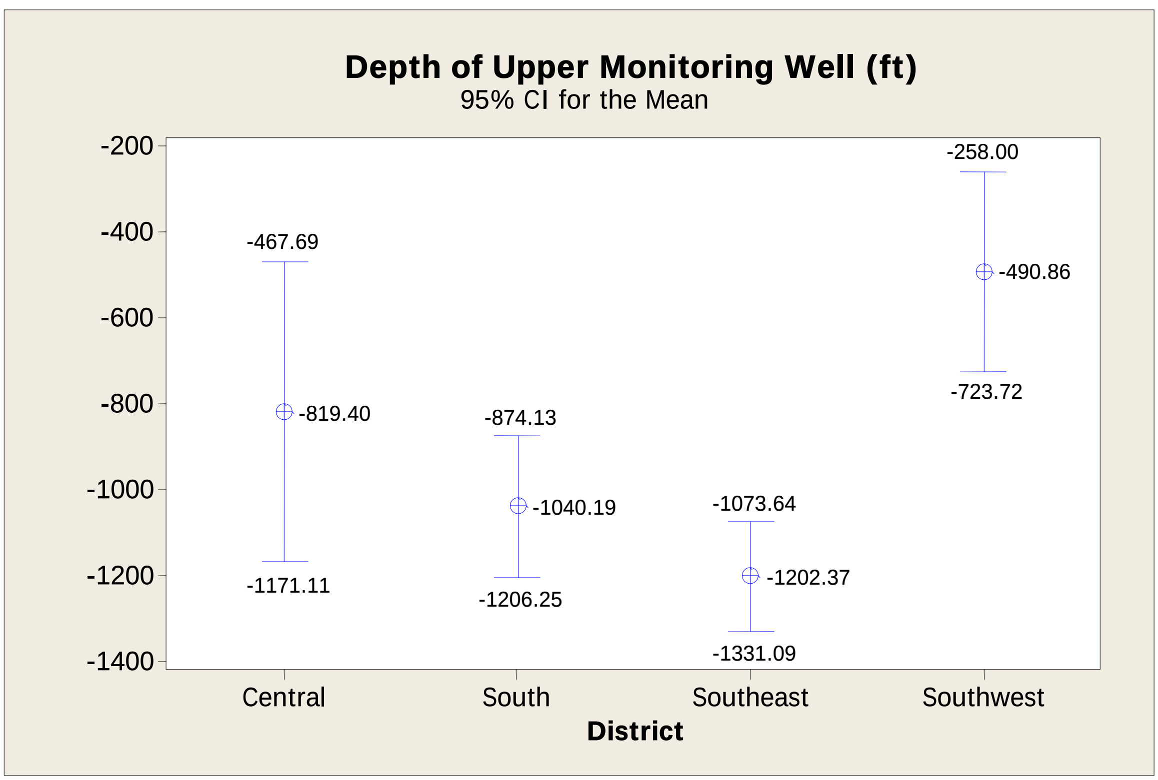


Figure 46 Depth of Upper Monitoring Well by District Interval Plot

The distance from the injection zone to the lower monitoring wells can be understood to demonstrate the distance from the injection zone to just below the base of USDW. One-quarter mile or 1,320 feet minimum is required according to 62-528 FAC. The Southwest District has the least distance among the four regions, but has the most identified abandoned leaking wells. In contrary, the South District has the most distance, and no leaking wells documented to as of September, 2007. The Central District has 40 percent of sites leaking and also has the second shortest distance as shown in Figure 47. Thus, the distance from injection zone to lower monitoring wells appears to have a strong relationship to the percentage of leaking wells at each district. This graph also confirms the importance of keeping the injection zone a safe distance from the USDW base as required by FDEP.

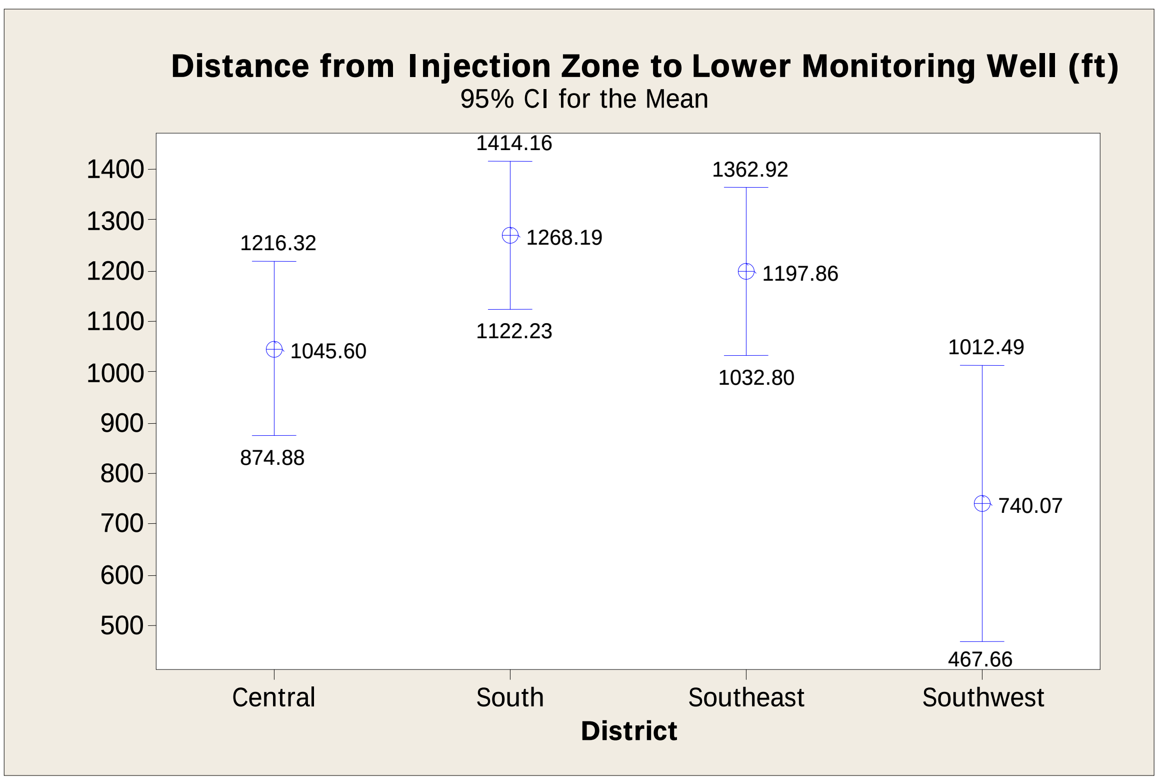


Figure 47 **Distance from Injection Zone to LMW by District Interval Plot**

3.4 Correlation analysis methods

Canonical correlation analyses were performed for the state well inventory and for each individual district. The missing data were eliminated from the set and a confidence level of 95% was used for the analyses. Eight independent variables that were identified to be the possible causes of upward migration including: 1) total depth of DIWs, 2) distance from final casing to the base of USDW, 3) distance from final casing to the lower monitoring zone, 4) district, 5) confining boundary, 6) injecting to the Boulder Zone, 7) meeting UIC's vertical requirement of one-quarter mile or 1,330 feet, and 8) tubing and packer. The canonical correlation analyses will provide the order of significance of the eight variables.

In order to perform canonical correlation analyses, the response and independent variables were converted as follows:

- Leaking: 1=Yes; 2=No
- Total depth of DIWs: 1=<2000; 2=2000 to 2500; 3=2500-3000; 4=>3000
- Distance from final casing to the base of USDW: 1=<500; 2=500 to 1000; 3=1000 to 1500; 4=>1500
- Distance from final casing to the lower monitoring zone: 1=<500; 2=500 to 1000; 3=1000 to 1500; 4=>1500
- District: 1=Central; 2=South; 3=Southwest; 4=Southeast
- Confining boundary: 1=Solid; 2= Interspersed; 3=None
- Injecting to the Boulder Zone: 1=Yes; 2=No
- Meeting UIC's vertical requirement of one-quarter mile or 1,330 feet: 1=Yes; 2=No

- Tubing and packer: 1=Yes; 2=No

Total depth of well measures the bottom of the injection horizon, which is also the deepest point of the DIW. Figure 48 is an interval plot of the total depths of leaking versus non-leaking wells. The figure shows the leaking wells have a mean value and a range shallower than non-leaking wells.

Distance from final casing to the base of USDW represents the vertical distance between the injection and USDW zones. The separation isolates USDW from contamination of the injected fluid in case of upward migration. Figure 49 shows the leaking wells have a mean value of 770 feet of vertical distance compared to 850 feet for non-leaking wells. The comparison depicts a safer practice for keeping the two zones further apart. In figures, Y means leakage, and N means no leakage detected.

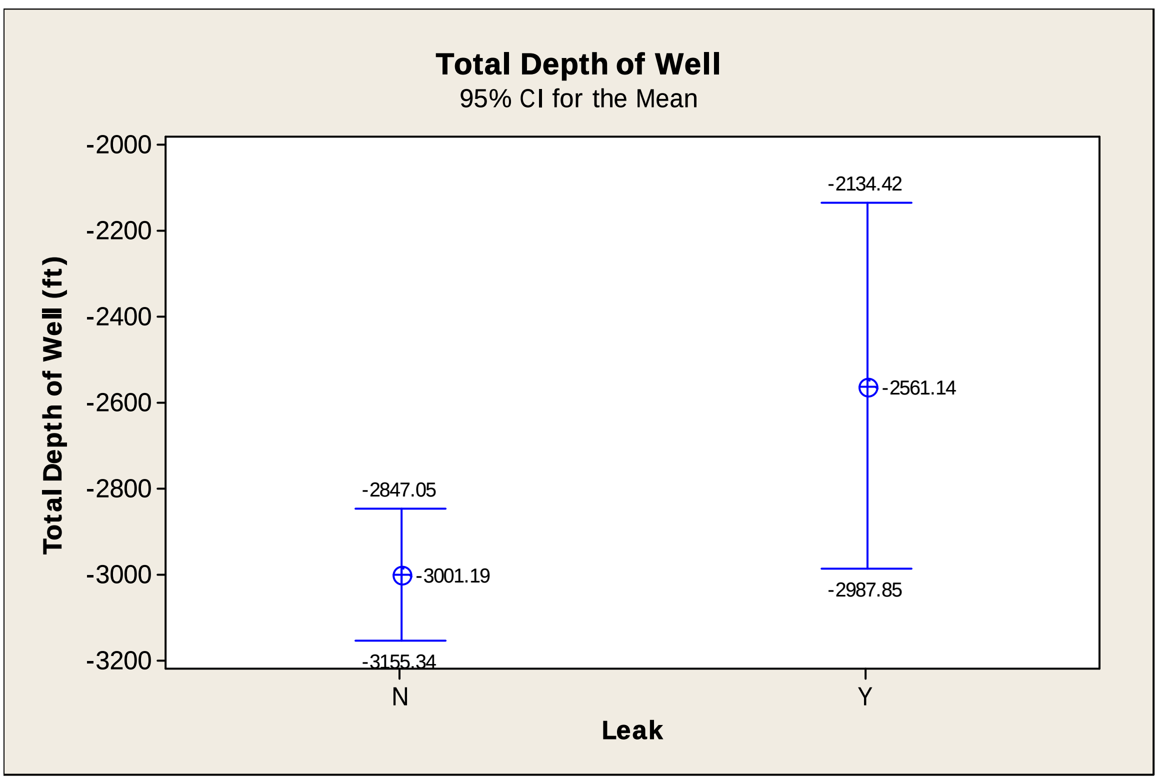


Figure 48 Total Depth of Leaking vs. Non-leaking Wells

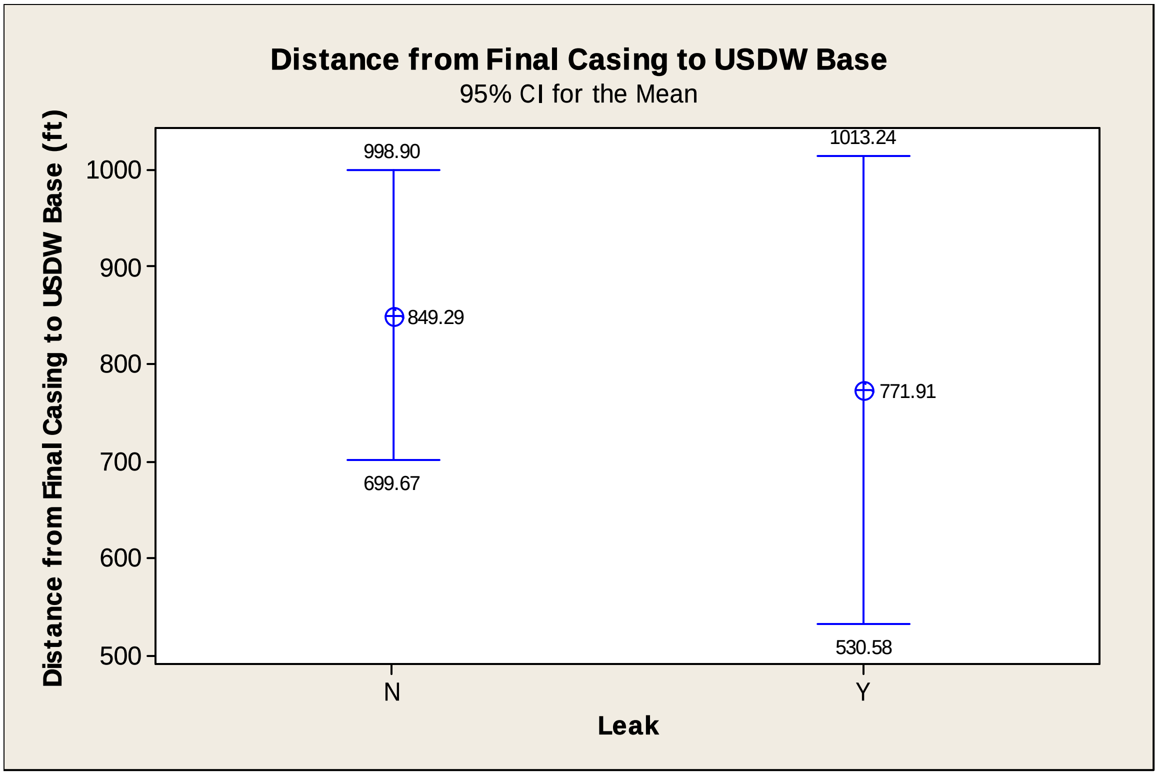


Figure 49 **Distance from Final Casing to USDW of Leaking vs. Non-leaking Wells**

Lower monitoring zone is required to be below the base of USDW. Vertical distance from final casing to lower monitoring zone is similar to vertical distance from final casing to USDW. Figure 50 shows the leaking wells has a shorter distance similar to Figure 49.

The confining boundary above the injection zone is categorized as solid, interspersed, or none (S, I, or N in the figure). Figure 51 shows the leaking wells appear to have less confining units present (more N=none) than the solid or interspersed values. Where some confining is present, there are fewer leaking wells. With the absence of the confining boundary, the injectate appears to move upwards more freely.

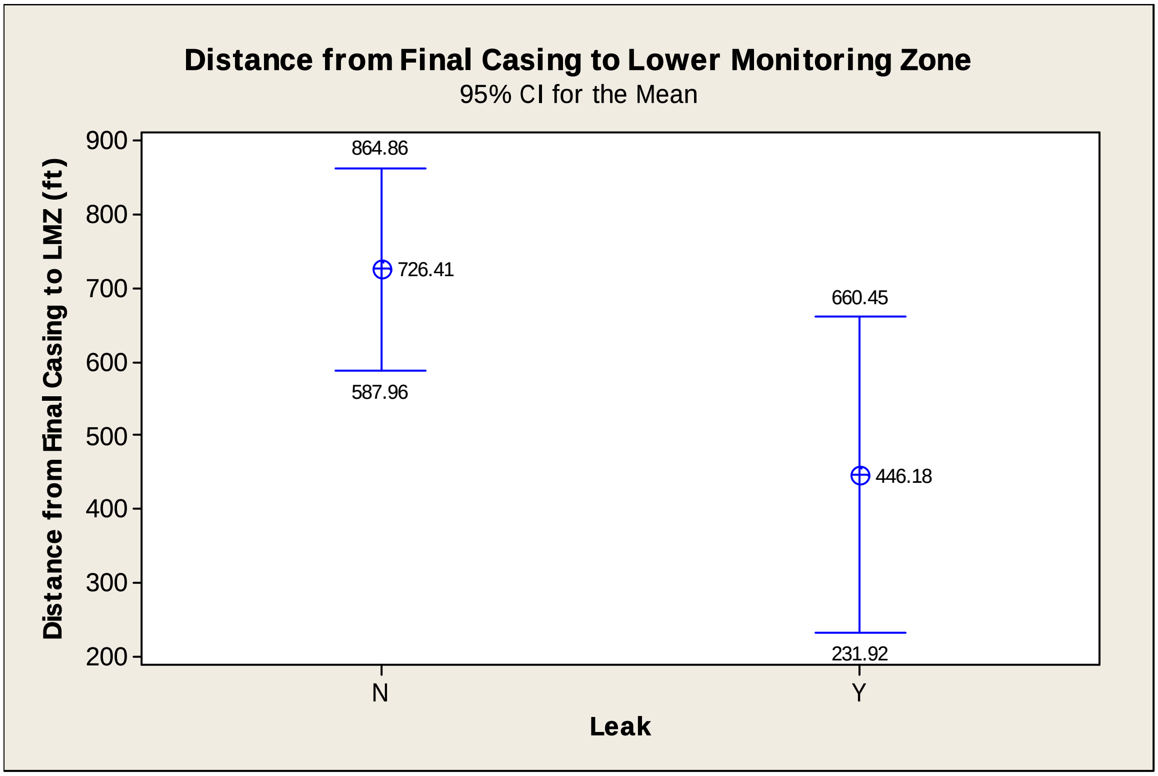


Figure 50 Distance from Final Casing to LMZ of Leaking vs. Non-leaking Wells

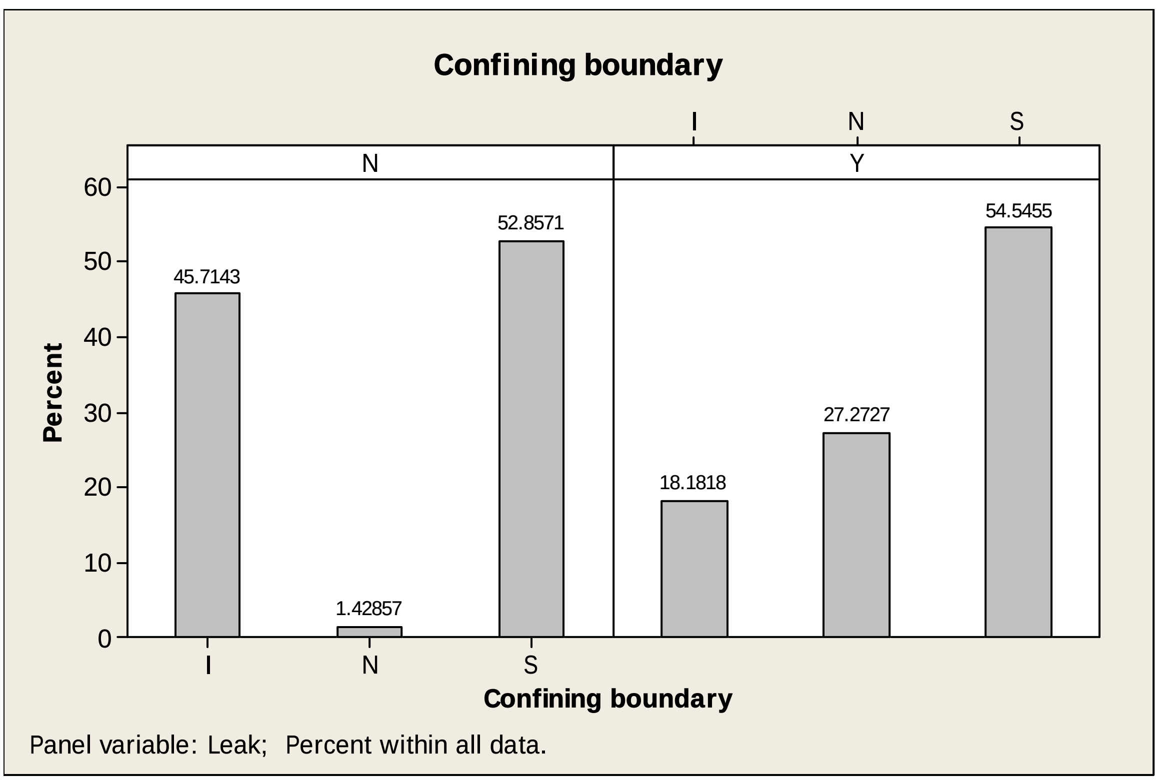


Figure 51 Confining Boundary of Leaking vs. Non-leaking Wells

Boulder zone is the most permeable and deepest aquifer system in Florida. As shown in Figure 52, 50 percent of leaking wells versus 28 percent of non-leaking wells are not in the boulder zone (bottom axis on left, top axis on right). It confirms the boulder zone is the better geological formation for accepting treated wastewater with less upward migration issues.

UIC requires the injection to be one-quarter mile or approximately 1,330 feet below the base of USDW. Meeting this requirement was examined for all the wells. Figure 53 shows 87 percent of leaking wells do not meet the requirement compared to 78 percent of non-leaking wells (bottom axis on left, top axis on right).

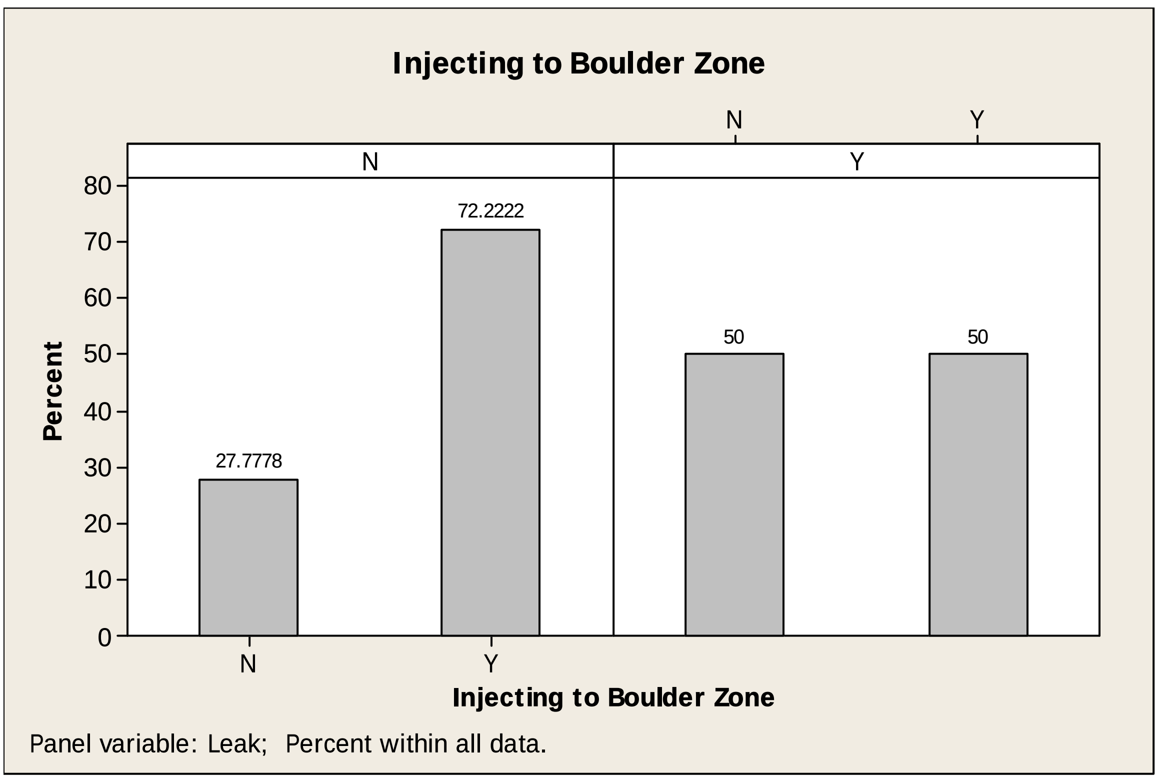


Figure 52 Injecting to Boulder Zone of Leaking vs. Non-leaking Wells

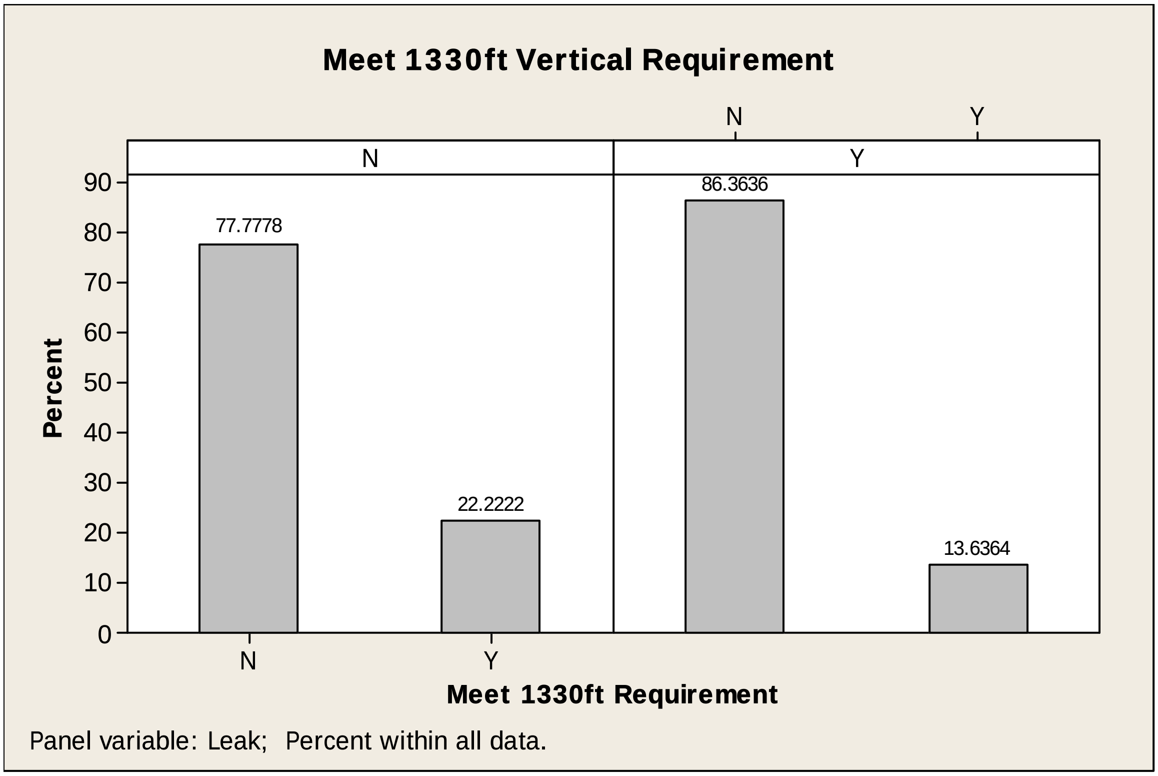


Figure 53 Meet Vertical Requirement of Leaking vs. Non-leaking Wells

A packer is used to seal off the bottom of tubing. A tubing and packer system is a preferred construction method for DIWs. Figure 54 shows over 80 percent of leaking wells do not have a tubing and packer system versus 50 percent of non-leaking wells (bottom axis on left, top axis on right). The system is proven to be a safe feature to prevent upward migration.

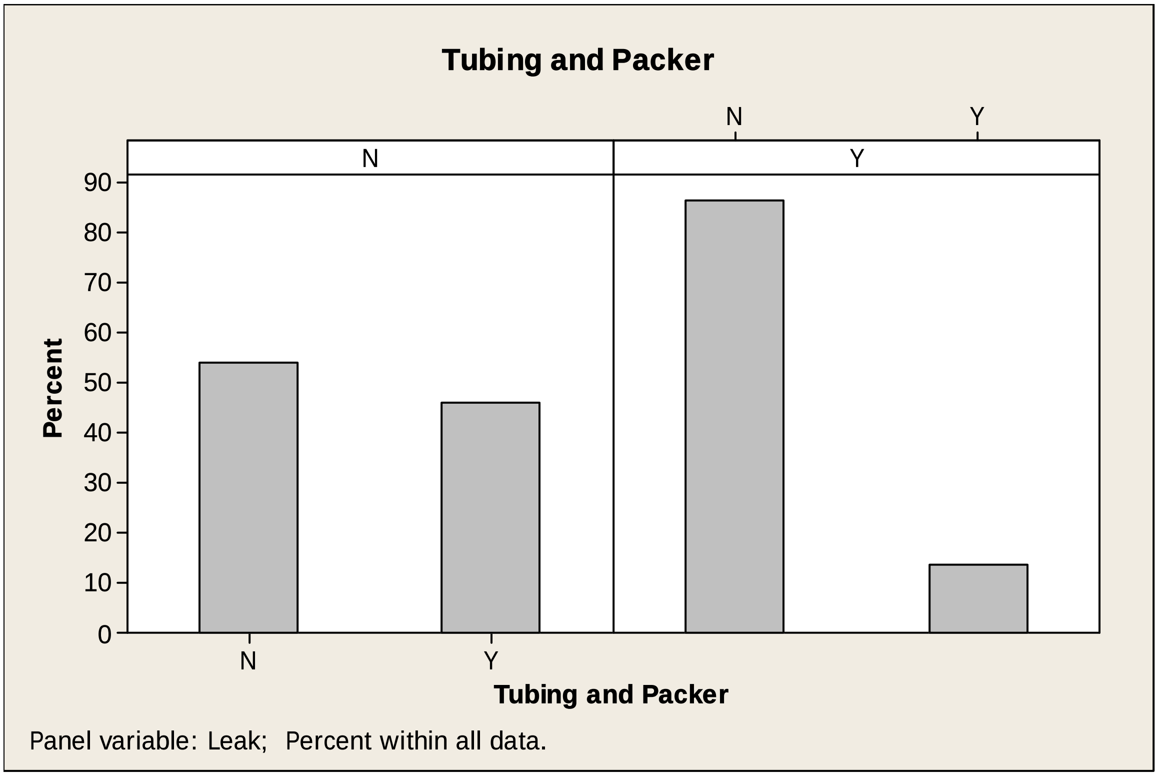


Figure 54 Tubing and Package of Leaking vs. Non-leaking Wells

The results of canonical correlation analyses are listed in Table 8. Well data were analyzed not only for the state, but also for each individual district. The analysis could not be performed successfully for the South District since this district does not have any leaking wells.

This summary matrix shows the vertical distance between the final casing to USDW is the most significant variable for Florida and the Central District. Such variable is also the second most significant variable for the Southwest District follow by the confining boundary condition. The Southeast District has total well depth to be the most significant variable following by confining boundary condition and meeting vertical requirement.

Table 8 Canonical Correlation Analyses Summary Matrix

Response = Leaking Well	**FL**	**Central**	**South**	**Southeast**	**Southwest**
District	-0.1580	N/A	N/A	N/A	N/A
Final Casing to LMZ	0.3364	-0.1992	N/A	0.4714	-0.2411
Tubing and Packer	-0.5475	-0.1328	N/A	0.0050	-0.2053
Final Casing to USDW	-0.8998	-0.8622	N/A	0.2608	-0.7346
Meet Vertical Requirement	-0.3183	0	N/A	-0.4569	0
Total Well Depth	0.2575	0.6858	N/A	-0.7962	0.2984
Injecting to Boulder Zone	-0.5200	-0.4980	N/A	0.0321	0
Confining Boundary	-0.2929	-0.8133	N/A	0.7876	-0.9986

CHAPTER 4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

DIWs in Florida are regulated by the USEPA and the state of Florida through the UIC regulations contained within the Safe Drinking Water Act. Underground injection is defined as the injection of hazardous waste, nonhazardous waste, or municipal waste below the lowermost formation containing an USDW within one-quarter miles of the wellbore. Municipalities in Florida have been using underground injection as an alternative to surface disposal of treated domestic wastewater for nearly 40 years. The research involved collecting data as of September 27, 2007 on all the Class I DIWs in the state of Florida and evaluating the differences between them.

The majority of DIWs are municipal and RO type; small in capacity; -3000 feet and deeper; and 16 to 22 inches in diameter. The majority of the monitoring wells have dual or multi monitoring zones to save construction cost and time. The only hazardous well has the smallest diameter (7 inches) and the deepest distance beneath ground (-5000 feet). Currently there are instances where the well appear to have upward fluid migration, deems to be "leaking" by FDEP. Regional differences have been suggested since the perception is the well leak more readily in the southwest district than the others. The goal of this investigation was to determine if there is a mean to predict which deep injection wells are most likely to experience upward migration that would violate the current UIC regulations and to determine if any of the physical parameters might increase the likelihood of vertical fluid migration (leakage) into a USDW.

The statistical analyses of the collected well data yield regional differences. The Southeast District has the most number and the deepest well sites in Florida due to the discovery of boulder zone and high demand of waste disposal from tri-counties. The Southwest District has the shallowest well sites and has the most abandoned leaking wells. Its injection zone is present in the Upper Floridan Aquifer, while the other three districts inject into the Lower Florida Aquifer or Boulder Zone. Comparison of the well depths and USDW depths confirm the differences in hydrogeological formations between the regions. The differences in regions can provide useful information to the regulators and should be considered when regulating Class I Injection wells. The canonical correlation analyses concluded the importance of keeping the USDW from the injection zone at the required distance (one-quarter mile). It is most significant factor that leads to upward migration of the injected fluid. As a result, absence of the Boulder Zone in the Southwest District and the differences between regions can provide useful information to the regulators and should be considered when regulation current and future Class I injection wells.

4.2 Recommendations

Groundwater modeling is a useful mathematical tool to predict the possibility of upward migration of the injected fluid within the deep injection wells for a defined period of time or to mimic such occurrence at a particular well site by calibrating wellhead pressure and monitored well water quality. It was described in Section 1.9 Risk Assessment that differences in fluid temperature and density between native and injected water affects relative buoyancy as well as the injection pressure in subsurface geology. The anticipated goal of the modeling is to confirm the causes of the migration, which can be used for design improvements and modeling for existing and new wells.

Bloetscher (2008) attempted to model the injection wells at the Southern Regional Wastewater Treatment Plant. The plant has been operated and maintained by City of Hollywood Public Utilities Department since the 1940s, but the wells were not unstalled until 2003. The plant provides a minimum of secondary treatment for the wastewater, plus filtered wastewater from the Towns of Davie and Cooper City. The plant has a treatment capacity of 50 MGD that utilizes ocean outfall (permitted at 46.3 MGD) and reclaimed water (production rate at 4 MGD) for treated effluent disposal. Filtered and disinfected reuse effluent is currently used to irrigate six public golf courses in the City of Hollywood (CHUD, 2009).

Two deep injection wells exist on site. Both municipal wells have been in operation since 2003 and capacity of each well is rated at 15 MGD. Both wells also shared the same design with a final casing diameter of 24 inches at a depth of 2,880 feet below land surface. Their open holes have an interval from 2,880 to 3,500 feet. A dual-zone monitoring well is located between the two wells. The shallow monitoring zone is completed from 1,250 to 1,300 feet at Upper Floridan Aquifer and the deep monitoring zone is completed from 1,750 to 1,800 feet at Middle Confining Unit. The lowermost USDW is at near 1,300 feet below land surface, which is just below the shallow monitoring zone.

Preliminary modeling by using collected field data was performed to determine the real likelihood of upward migration of the injected fluid within the wells. What was determined in this model as that the aquifer parameters for vertical conductivity and leakance in the vertical direction were several magnitudes greater than measured or estimated in the field. Modeling results showed no possible migration (Bloetscher *et al*., 2008).

The author attempted to use Groundwater Vistas and SEAWAT to modeling injection wells as two sites in each district, but this effort was not successful. After considerable efforts, it was determined that two problems existed: the Groundwater Vistas software does not properly interface with SEAWAT to provide useful solutions and the lack of data on deep aquifers is a limiting factor. It would be useful to gather this information in the future.

4.3 Additional work

It is recommended to consider the following for additional work on Class I wells in Florida:

- Additional data is needed to provide a more complete data analysis, particularly aquifer data such as hydraulic conductivity, porosity, etc.
- The data frequency does not respond to changes in water quality, pressure or injection rates quickly enough to determine if an event occurs.
- Construction defects are difficult to determine without modeling, meaning that aquifer parameters must be significantly different to encourage leakage at the deeper wells. Leakage due to construction issues should also be considered.
- More monitoring wells would help define the bubble geometry and direction of movement.
- Monitoring in the injection zone would help define buoyancy.

- Lack of far-field monitoring wells. 150 ft may be too close to measure anything.
- DEP database is difficult to use.
- Each well needs to be modeled.
- Stochastic and/or Bayesian evaluation of leak potential could be evaluated in a future thesis.

APPENDIXES

Appendix I FDEP UIC Permit for Deep Injection Wells (included in the attached CD)

Appendix II FDEP UIC Program Data (included in the attached CD)

REFERENCES

40 CFR 144.3. “Title 40 – Protection of Environment, Chapter I – Environmental Protection Agency, Part 144_Underground Injection Control Program,” Code of Federal Regulations. Washington: GPO, July 1, 2007.

40 CFR 146.16. “Title 40 – Protection of Environment, Chapter I – Environmental Protection Agency, Part 146_Underground Injection Control Program: Criteria and Standards, Subpart B_Criteria and Standards Applicable to Class I Wells, Sec. 146.16 Requirements for New Class I Municipal Wells in Certain Parts of Florida,” Washington: GPO, July 1, 2007.

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