Results of Preliminary Class I Injection Well Modeling in Southeast Florida

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Regulatory, political, and economic constraints have shaped wastewater management strategies in Southeast Florida. Until the 1960s, South Florida was somewhat undeveloped and wastewater was often emptied into canals and other water bodies. The degradation caused by this practice became obvious in the late 1960s, and with passage of the Clean Water Act, other options were pursued.

Currently three wastewater disposal options are available: Class I injection wells, ocean outfalls, and reclaimed water. Ocean outfalls were constructed in the early 1970s, with deep well construction starting after 1977. In contrast to most of the rest of the state, both options are available as a result of the nearby deep waters of the ocean and a deep zone for injection. Both options require secondary treatment.

The fact that the southeast coast has more centralized systems makes expensive bulk disposal methods like deep wells and outfalls more cost effective than in other regions of the state, but over the last 10 years, issues have been raised about the appropriateness of outfalls and injection wells as disposal methods. These concerns are ostensibly related to environmental advocates and those who want to limit explosive growth.

A comparative assessment of the risks of the potential effluent disposal alternatives currently available to wastewater utilities in Southeast Florida was conducted in 2000 by the University of Miami (Englehardt, et al, 2000), and by the United States Environmental Protection Agency (EPA, 2001). The alternatives include:

- Deep well injection following secondary treatment
- Ocean outfall following secondary treatment
- Surface water (canal) discharges following secondary wastewater treatment, filtration and nutrient removal

For the studies, water quality data related to wastewater treatment plant effluent disposal were gathered from utilities, along with water quality data on the receiving waters. Comparison of the three disposal alternatives indicated that health risks associated with deep wells were generally lower than those of the other two alternatives.

The findings of the University of Miami study were confirmed by the EPA risk assessment, suggesting that injection wells had the least potential for impact on human health when compared to ocean outfalls and surface discharges. Surface water discharge was deemed to carry the highest risk.

Proximity of injection wells to aquifer storage and recovery wells was a determining factor relative to injection well risk, which was the subject of a follow-up paper; however, the issue continues to remain unresolved between utilities, Sierra Club and the regulators. A proposed increased level of treatment for "problem" wells and new wells was promulgated, but has already been targeted for litigation by all parties.

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The Rule the EPA Promulgated

The federal regulation for underground injection control is 40 CFR 146. The rules were established under the authority of Safe Drinking Water Act approved in 1974 and amended in 1986 and 1996.

The rules set forth standards for underground injection control programs that are mirrored in many states. The regulations include an extensive set of definitions concerning injection wells. The Underground Injection Control (UIC) legislation is used to

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Table 1

Layer	Formation	Top	Bottom	Thickness	Q Inj	Transm	Transm	Leakance	Storativity	Porosity	Water level	TDS
Number		ft ngvd	ft ngvd	ft	cu ft/d	gpd/ft	ft3/d				ft ngvd	mg/L
1	Limestone	6	-200	206	0	1,000,000	133689.8	0.01	0.001	0.35	2	500
2	Clay	-200	-365	165	0	5,000	668.4	0.01	0.001	0.35	5	2000
3	Clay	-365	-875	510	0	22,000	2941.2	0.000002	0.001	0.31	15	2750
4	Clay	-875	-1250	375	0	2,000	267.4	0.000001	0.0001	0.44	25	3500
5 - UMZ	Limestone	-1250	-1300	50	0	50,000	6684.5	0.004	0.003	0.43	38.5	4340
6	Limestone	-1300	-1750	450	0	50	6.7	0.000002	0.0001	0.41	30	10000
7 - LMZ	Limestone	-1750	-1805	55	0	650	86.9	0.0002	0.00001	0.41	6.75	34000
8	Lstone/Dolom	-1805	-1910	105	0	15	2.0	0.000002	0.00001	0.1	6	35000
9	Lstone/Dolom	-1910	-2300	390	0	75	10.0	0.000002	0.0003	0.1	6	36000
10	Lstone/Dolom	-2300	-2650	350	0	200	26.7	0.002	0.0001	0.27	6	38000
11	Lstone/Dolom	-2650	-2880	230	0	250	33.4	0.002	0.0001	.1/.3	6	40000
12	Lstone/Dolom	-2880	-2925	45	0	4,500,000	601604.3	0.01	0.01	.1/.3	6	40000
13 - IZ	Dolomite	-2925	-3000	75	400000	7,500,000	1002673.8	0.01	0.01	.1/.3	6	40000
14 - IZ	Dolomite	-3000	-3100	100	550000	10,000,000	1336898.4	0.01	0.01	.1/.3	6	40000
15 - IZ	Dolomite	-3100	-3200	100	550000	10,000,000	1336898.4	0.01	0.01	.1/.3	6	40000
16 - IZ	Dolomite	-3200	-3300	100	300000	6,000,000	802139.0	0.01	0.01	.1/.3	6	40000
17 - IZ	Dolomite	-3300	-3400	100	200000	3,000,000	401069.5	0.01	0.01	.1/.3	6	40000
18 - IZ	Dolomite	-3400	-3500	100	100000	1,000,000	133689.8	0.01	0.01	.1/.3	6	40000
19 - IZ	Dolomite	-3500	-3550	50	10000	100,000	13369.0	0.01	0.01	.1/.3	6	40000
20	Dolomite	-3550	-3600	50	0	4,000	534.8	0.002	0.0001	0.25	6	40000

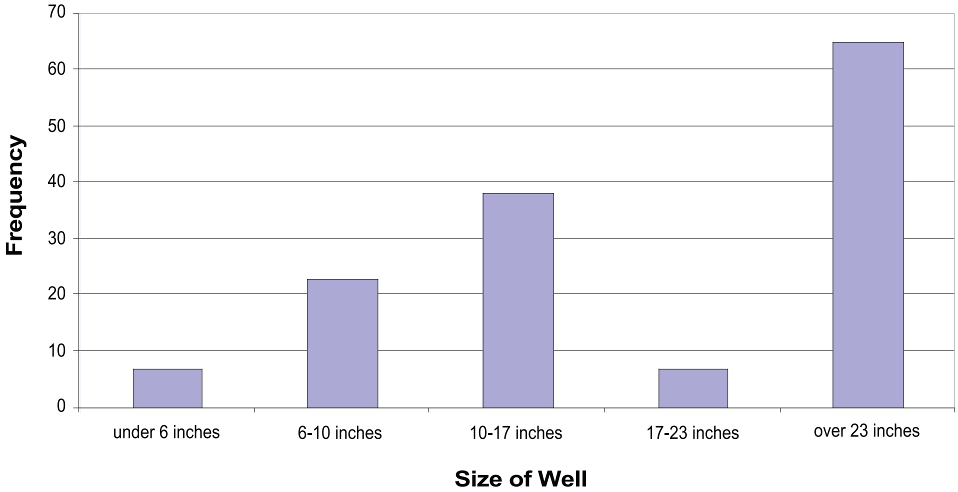

Figure 1 – Hollywood Aquifer Parameters for Modeling (shaded aquifer parameters are estimated)

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protect underground sources of drinking water, prevent degradation of the quality of other aquifers adjacent to the injection, and govern the construction and operation of injection wells. To address the issues raised by the challenges to the implementation of the UIC program in Southeast Florida, the EPA promulgated a revised rule (EPA, 2005), which states that:

"…continued injection would be allowed only if owners or operators met certain additional requirements that provide adequate protection for USDWs (underground sources of drinking water)." The EPA co-proposed two primary options for the additional requirements:

Option 1: Advanced Wastewater Treatment (AWT) With a Non-Endangerment Demonstration

The authorization to inject under Option 1 would have required that the owner and/or operator of a Class I municipal disposal well injecting domestic wastewater effluent treat the wastewater by advanced treatment methods and high-level disinfection, and to demonstrate that injection would not cause fluids that exceed the national primary drinking water regulations or other health-based standards to enter the USDW. The non-endangerment demonstration would focus on any contaminants that still exceed national drinking water regulations or other health-based standards after wastewater treatment.

Option 2: In-Depth Hydrogeologic Demonstration and Advanced Treatment, as Necessary

The authorization to inject under Option 2 would have required that the owner and/or operator of a Class I municipal disposal well injecting domestic wastewater effluent provide a hydrogeologic demonstration that the injection operation would not cause the USDW to exceed national primary drinking water regulations or other health-based standards.

The EPA anticipated that this demonstration would be an extensive evaluation, similar in detail to those required for a Resource Conservation and Recovery Act land ban no-migration petition; consist of an analysis of the contaminants in wastewater prior to injection; include monitoring data from deep wells at the base of the USDW; and include detailed hydrogeologic modeling of vertical and horizontal fluid transport in the injection zone and USDWs.

If it were anticipated that the fluids may enter the USDW, the demonstration would have to show that the fluids would not cause the USDW to exceed primary drinking water regulations in 40 CFR Part 141 or other health-based standards. Operators who could not demonstrate that the injection operation met these criteria would have been required to treat their injectate to address the contaminants of concern and satisfy additional requirements proposed to be added in a new 40 CFR 146.15(d).

This second option also proposed a provision whereby all facilities qualifying for authorization to inject under this option would be required to install *advanced wastewater treatment* and high-level disinfection by 2015 (emphasis added).

The EPA proposed to limit the application of the rule to existing Class I municipal disposal wells that have caused or may cause fluid movement into USDWs in specific counties and under certain geologic conditions in Florida. The proposed counties were 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. These counties were targeted in the proposal because they have the unique geologic conditions that are predominated by carbonate rocks.

The rule does not distinguish Central Florida and Southeast Florida wells. Note that litigation with the EPA and the Florida

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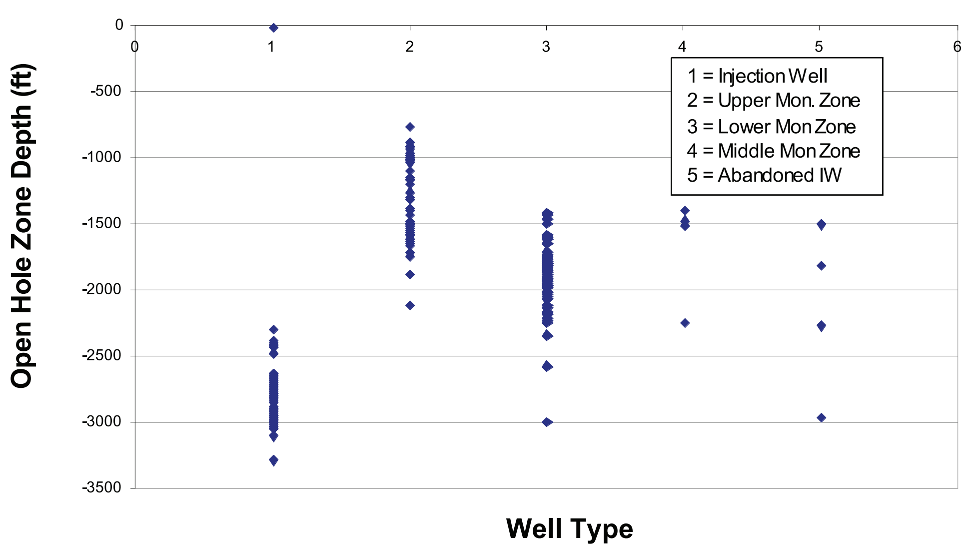

Figure 2 – Location of the Top and Bottom of Wells by Well Type: Injection wells, upper monitoring well zone wells, lower monitoring well zones, middle monitoring wells and plugged/abandoned wells

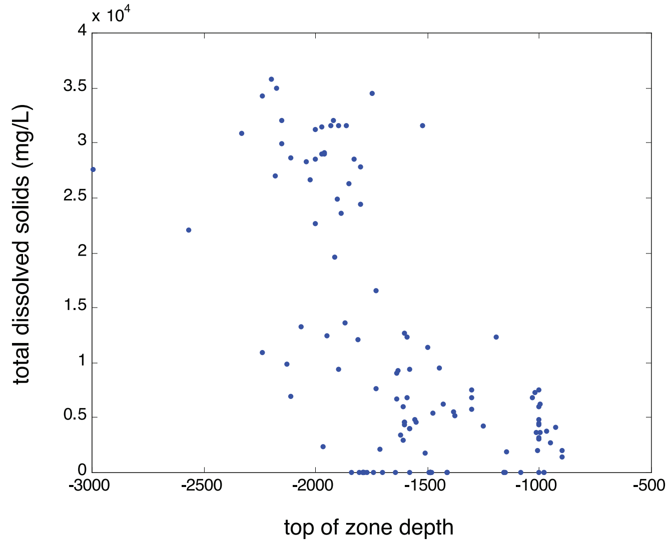

Figure 3 – Graph correlating Total Dissolved Solids and Top of Well Depth – all wells. (Note: The results of this graph are typical for the conductivity, sulfates, and total dissolved solids for all monitoring wells, regardless whether the x-axis was top, bottom or average well depth.) Source: Bloetscher and Muniz (2005)

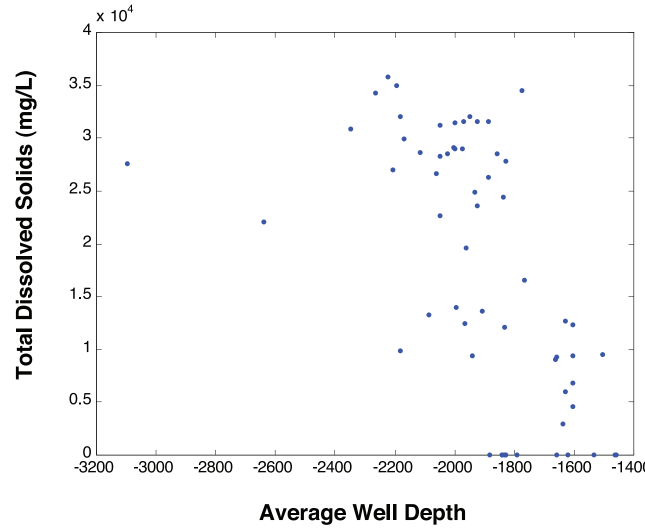

Figure 4 – Graph correlating Total Dissolved Solids and Top of Well Depth – for the lower monitoring zone only. (Note: The results of this graph are typical for the conductivity, sulfates, and total dissolved solids for lower zone monitoring wells, regardless whether the x-axis was top, bottom, or average well depth. Note that for the lower monitoring zone, a large percentage of the wells were below the USDW (greater than 10,000 mg/L TDS), but not all the wells. This would indicate that some of the lower monitoring zone wells are not located below the USDW.) Source: Bloetscher and Muniz (2005)

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Department of Environmental Protection (FDEP) is ongoing from the utilities, as a result of the belief that the risk assessment results do not warrant reuse-quality water for disposal.

Constructing a Model of Injection Wells in Southeast Florida

In 2005, a study was conducted to inventory all Class I wells in Southeast Florida as to their design and depth (Bloetscher and Muniz, 2005). Objectives of the research were to:

1. Compile well construction data for all Class I wells in Southeast Florida.
2. Compile and review water quality data for all Class I wells in Southeast Florida.
3. Review the veracity/accuracy of the data.
4. Review the data in light of the prior risk study to determine whether migration was occurring at any site.
5. Prepare a report addressing the findings of the above.
6. Develop some conclusions about the Class I injection well program in Southeast Florida.

At that time, there were 90 active Class I injection wells. There were 74 upper and 78 lower monitoring zones. Five wells had been plugged and abandoned. Most of the Class I injection wells were 24 inches in diameter (see Figure 1). Figure 2 shows the range of the top and bottom of the monitoring wells.

Water quality data were gathered from the FDEP computer data. The data is cumbersome to manipulate, but a download to EXCEL is possible. This data was reconfigured to review three parameters: sulfate, chlorides, and total dissolved solids (TDS). Having developed this inventory, the authors decided to analyze the data to determine their veracity and to determine if any trending was occurring. For the majority of injection well sites, the trends showed a consistent water quality.

Data was also collected on aquifer parameters, as summarized in Bloetscher and Muniz (2005). Finally, a series of data analysis steps were conducted to review:

- Water quality by well type
- Water quality by well depth
- Water quality by location north and east
- Water quality parameters to one another

Figures 3 through 5 are graphs that correlate total dissolved solids and top of well depth for all wells, for the lower monitoring zone only, and for the upper monitoring zone only (using MATLAB). The results of these graphs are typical for conductivity, sulfates, and total dissolved solids for all monitoring wells, regardless whether the x-axis was top, bottom, or average well depth. The conclusion is that the more shallow the well, the higher quality the water. This tracks with the expectation of the FDEP in locating the monitoring wells.

Figure 6 shows the generalized aquifer from the parameters given in the construction details. Only two sets of wells indicated any migration in the lower monitoring zone, and in both cases there were injection well construction issues that have long-standing relevance to the findings. None of the upper monitor wells showed migration. Water quality was stable in most of the wells with periodic fluctuations that have no apparent relationship to injection rates or well use. This information was used to develop a model of the city of Hollywood's injection well system.

Development of the Model

The city of Hollywood is a coastal community located in southeastern Broward

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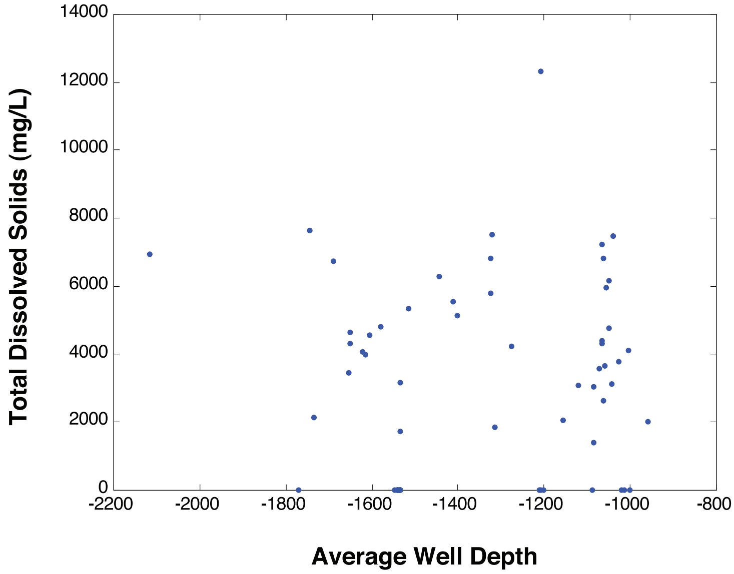

Figure 5 – Graph correlating Total Dissolved Solids and Top of Well Depth – for the upper monitoring zone only. (Note: The results of this graph are typical for the conductivity, sulfates, and total dissolved solids for the upper zone. It should be noted that all but one of these wells had a total dissolved solids concentration below 10,000 mg/L, the USDW value, as would be expected. The upper monitoring zone should be located above the USDW.) Source: Bloetscher and Muniz (2005)

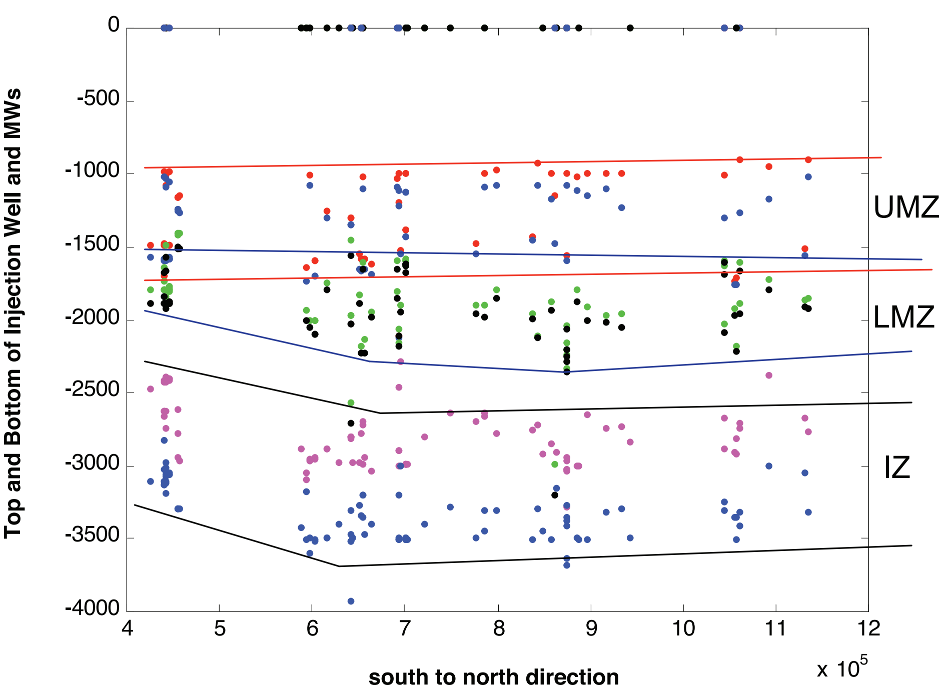

Figure 6 – Idealized aquifer based on drilling information in the 90 injection well projects.

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County. The city serves as a regional provider of wastewater treatment services for seven communities and a disposal provider for two more. As a result, a total of 350,000 people send their waste to Hollywood.

Beginning over 10 years ago, the city investigated a series of wastewater disposal projects, including reuse (4 MGD) and the first Florida salinity barrier to supplement disposal via its ocean outfall. Because the FDEP did not permit portions of the salinity barrier project quickly enough for the city to pursue further study of the project, Class I injection wells were required when the plant expanded beyond 42 MGD in 1999.

The city pursued and installed two Class I wells at the wastewater plant site with State Revolving Fund money, with a total disposal capacity of over 30 MGD. The city will revisit concentrate disposal as the concentrate from its membrane facility is permitted to be discharged to the ocean.

The two wells have operated since 2003 and were constructed to a depth of 3,550 feet deep. The injection horizon starts at depths of approximately 2,925 feet below land surface. One monitoring well is located between the two wells (150 feet from each).

The injection horizon is fractured dolomite formation overlain with dolomite and limestone that shows no fracturing near the borehole. The monitoring well measures two zones – a zone above the USDW in the Upper Floridan Aquifer between 1,250 and 1,305 feet below land surface, and a lower zone from 1,750 to 1,805 feet below land surface that is below the USDW but separated from the injection horizon. Both are limestone formations.

The upper zone is used for water supplies in Hollywood and aquifer storage and recovery wells in several nearby communities. The total dissolved solids measure 2,400 – 4,000 mg/L throughout South Florida.

The intermediate Floridan Aquifer System (FAS) confining units, upper FAS, Hawthorn, and Biscayne zones were characterized during drilling in both wells. FAS hydraulic conductivity and secondary porosity are extremely high, and as a result are very difficult to measure (borders on being unlimited).

Televised logs indicate very large vugs, or rock cavities, in the formation. Drilling mud has been lost by a number of drillers as a result of the high secondary porosity, so estimates were utilized for these zones based on the judgment of drilling and geologic personnel.

Table 1 outlines the basic parameters that were reported from the well completion reports. The shaded areas indicate parameters that were estimated (Bloetscher and Muniz, 2007).

Authors Muniz and Bloetscher were involved with the design and construction of injection wells in Hollywood. The data from

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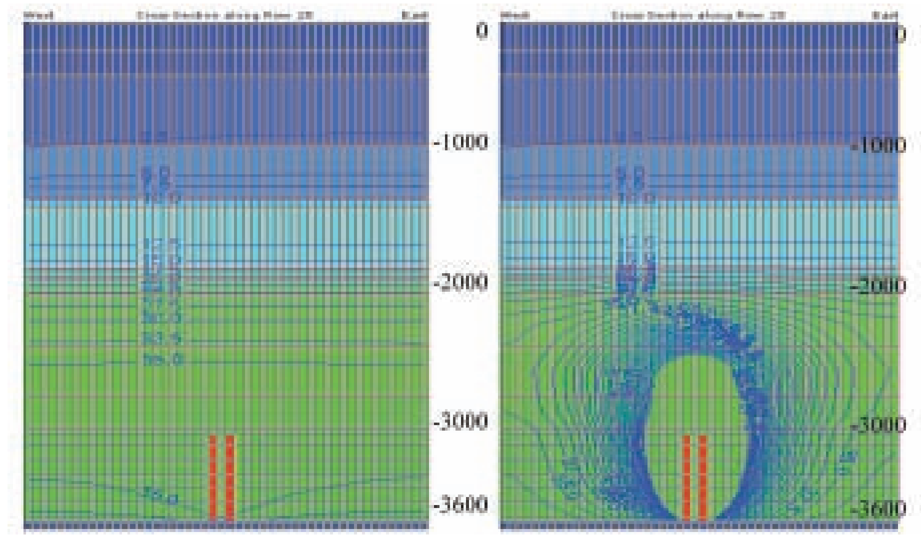

Figure 7 - Graphic of initial model results for Hollywood well after two years of pumping using SEAWAT /MT3DMS. The point of SEAWAT is to account for density differential. The model obviously indicates leakage which does not exist in the wells. Two of many trials are shown. Figure 7a shows pressure and likely fluid migration upward in the formation in two years. Figure 7b shows pressure changes by making the hydraulic conductivity of the boulder zone smaller. Neither replicates the actual situation.

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these wells were gathered specifically with the idea that modeling could be performed at those locations to answer some of the questions not specifically answered in the prior risk assessments. Because the 2005 study showed the similarities among all Southeast Florida wells, it is believed that the results from the Hollywood and Fort Lauderdale wells can be translated to other sites.

The general geology in South Florida indicates that the upper portions of aquifers appear to have higher transmissivity than lower levels. An estimate of the transmissivity was performed for the injection horizon based on the authors' experience.

Finally, the actual leakance value appears to be at least a magnitude less in the upper FAS, based on modeling (otherwise there would be pressure changes caused by the native water that have never been observed). This data was used in a groundwater simulation model that combines MODFLOW, MT3DMS, and SEAWAT through a pre-processor designed by Groundwater Vistas (Bloetscher and Muniz, 2007).

To construct the model, the aquifer and pumping data were entered into 20 layers. The finite element grid system was designed using 1,000 feet x 1,000 feet. Smaller grids were used initially, but they were found to be inadequate to trace long-term injection. As a result, the two injection wells (located 150 feet apart) were placed in the same grid cell in the center.

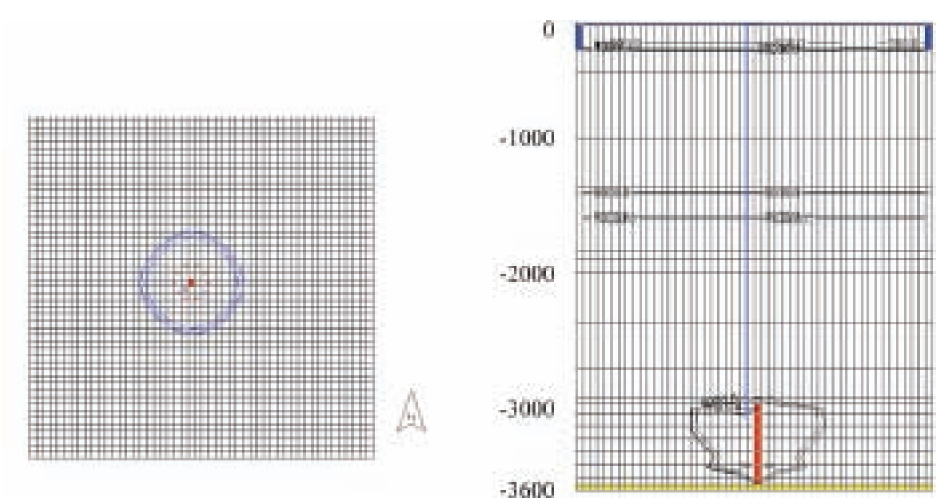

Figure 8 - Graphic of model results for Hollywood well after 10 years of pumping using SEAWAT /MT3DMS. The point of SEAWAT is to account for density differential. The density differential makes the injectate migrate toward the top of the injection horizon. This is the calibrated version, which is substantially different from the initial estimates.

The model was initially designed for a 30-day time-step, with the intent of modeling it for 365, 1,825, and 3,650 days. After one year, the expectation is that the waste should not have moved more than 3,000 feet from the injection well (based purely on a volumetric calculation).

It should be noted that the pressure does not change significantly with time in Class I wells injection into the Boulder zone horizon. Calibration was to water quality in the monitoring wells and injection zone pressure measured at the surface.

Since MODFLOW does not address the density differential issue, SEAWAT was used to accomplish this purpose. SEAWAT is a program developed through the U.S. Geological Survey that is designed to specifically address the density differential problem. It was assumed that the injected water has a TDS concentration of 1,000 mg/L, while field measurements indicate the injection horizon has a TDS concentration of 40,000 mg/L.

Table 1 (far right column) outlines the TDS by layer. Figure 7 shows the graphic results of two of the early trials to run the model using field measured results. They clearly indicate things that are not present at the site (migration, excessive pressure).

Modifications to leakance were made to calibrate the model to comport with the limited data that exists for the injection horizon. Figure 8 shows the SEAWAT changes. The profile does not indicate a significant increase in the injection zone pressure over any period. The pressure changes in the upper and lower monitoring zones do not appear to be impacted by the injected water. This comports with the existing field data for pressure in the monitoring and injection zones (see Figure 9).

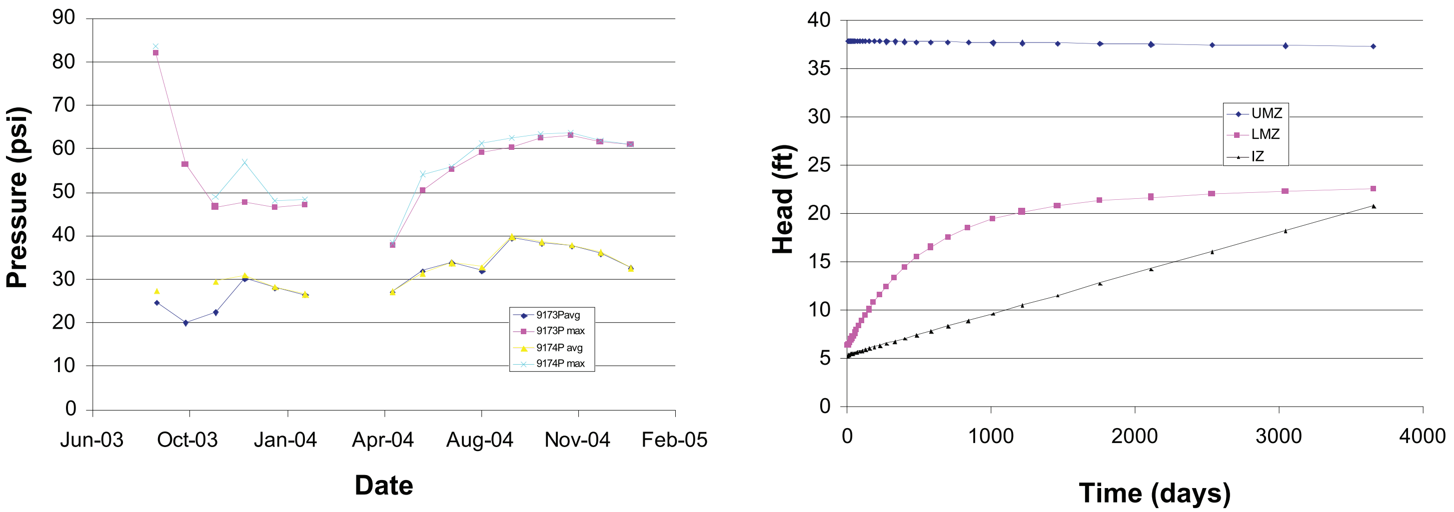

Figure 9 – Graph of the pressure changes with time in monitoring wells at the Hollywood Injection site. Note the well commenced operation in mid-2003 and had a period of no pumping in early 2004 (start-up). Well 9173 is the upper monitoring well, while Well 9174 is the lower monitoring well. Note that the UMZ and LMZ pressures are similar to those found in the modeling.

Conclusions & Recommendations

Class I injection wells have been used extensively for the disposal of secondary treated wastewater and concentrate in Southeast Florida. Two previous risk assessments indicated that Class I injection wells posed the least risk to the public (Englehardt, et al, 2000 and EPA, 2001). In both studies, injection wells were found to be the option with the lowest relative risk of impact to water consumers in the southeast coast.

A prior study by the authors found that all the injection wells were over 2,400 feet deep and typically over 3,000 feet deep. Only two sets of wells indicated any migration in the lower monitoring zone, and in both cases there were injection well construction issues that have long-standing relevance to the findings. None of the upper monitor wells showed migration. Water quality was stable in most of the wells with periodic fluctuations that have no apparent relationship to injection rates or well use.

Using field data, a model was constructed for the Hollywood injection wells. The data gathered for this project was used to valuate modeling of individual wells. The intent was to determine the real likelihood of there being migration, and what might stop that migration.

Density differential and diffusion were likely causes of any migration. The model was calibrated to wellhead pressure and monitoring well water quality. No migration was noted in Hollywood's wells.

These preliminary results indicate that Class I wells can be modeled and that migration of injectate upward would be noticed relatively quickly. To achieve the field results, the field measurements of leakance needed to be reduced by three magnitudes to mimic the actual pressure conditions found in Hollywood. Leakance above the injection horizon in South Florida is very small. The hydraulic conductivity was much higher than initially anticipated.

The modeling is intended to initiate modeling discussions – that more calibration and comparisons are required. The results indicate there is much work to do. It is expected that other wells would exhibit similar characteristics, since they are located in close proximity.

The lack of monitoring wells any distance from the injection well may limit the ability to refine models and calibrate them further. Far-field calibrations are not possible at this time. Far-field monitoring wells would be useful for calibration purposes. A monitoring well 1,000 to 2,000 feet away might be useful.

The results appear to confirm the findings of the University of Miami and EPA risk studies, which indicated that injection wells were the disposal method that presented the least likely human health impact. As a result, the fact that the EPA rules for Florida do not differentiate between the Southeast Florida wells and the Central Florida wells may place an additional level of conservatism on South Florida wells that is not warranted.

References

- Bloetscher, F. and Muniz, A. (2005), "Summary Of Class I Injection Wells In South Florida," *Annual Forum of the Groundwater Protection Council Proceedings – Portland, OR*, Oklahoma City, OK.
- Bloetscher, and Muniz (2007), "Class I Injection Wells In Southeast Florida: Evaluation And Preliminary Modeling," *World Water Congress Annual Conference Proceedings – Tampa, FL*, ASCE, Reston, VA.
- Englehardt, James D.; Amy, Vincent P.; Bloetscher, Frederick; Chin, David A.; Fleming, Lora E.; Gokgoz, Sinem; Solo-Gabriele, Helena; Rose, Joan B.; and Tchobanoglous, George (2001), *Comparative Assessment of Human and Ecological Impacts for Municipal Wastewater Disposal Methods in Southeast Florida: Deep Wells, Ocean Outfalls, and Canal Discharges*, University of Miami, Coral Gables, FL.
- USEPA (2001), *Class I Underground Injection Control Program: Study of the Risks Associated with Class I Underground Injection Wells*, EPA 816-R-01-007, http://www.epa.gov/safewater/uic/classi.html.
- USEPA (2005), *Final Rule – Revision to the Federal UIC Requirements for Class I Municipal Disposal Wells in Florida - 70 FR 70513 November 22, 2005*, http://www.epa.gov/region4/water/uic/downloads/finalrule.pdf