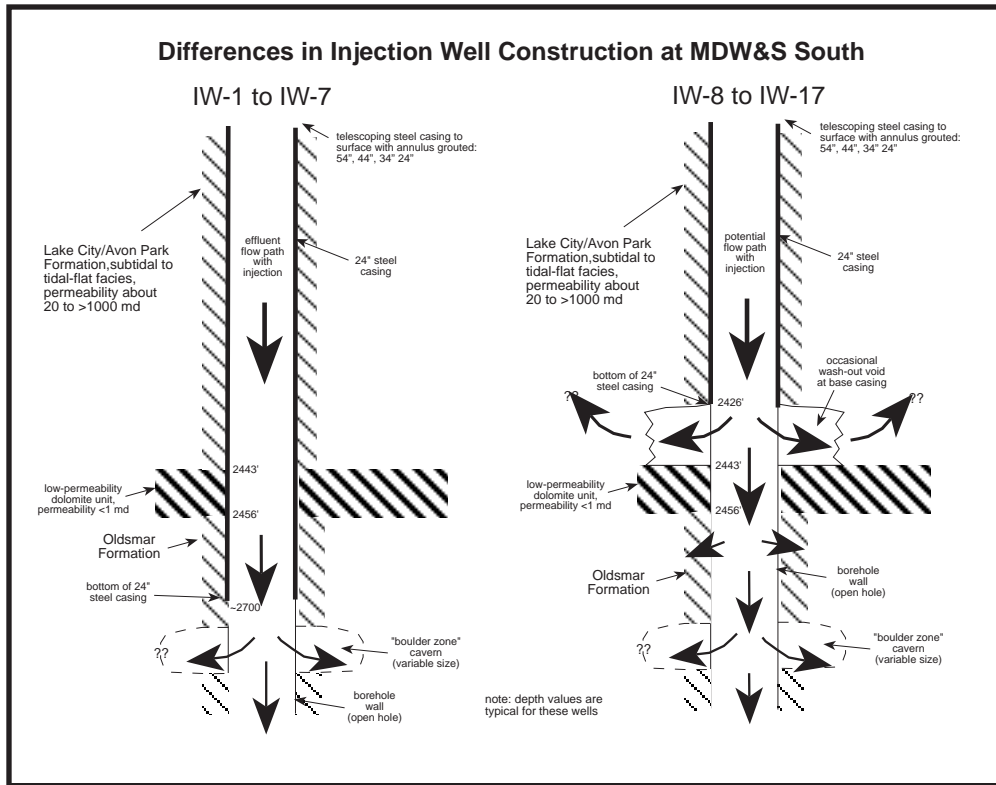


Final Report

A Review of Upward Migration of Effluent Related to Subsurface Injection at Miami-Dade Water and Sewer South District Plant



by

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A Review of Upward Migration of Effluent Related to Subsurface Injection at Miami-Dade Water and Sewer South District Plant

I - SUMMARY OF FINDINGS

A review of site-specific geological data and injection well construction methodology at the Miami-Dade Water and Sewer South District plant (South District) indicates that 10 of the 17 injection wells were constructed improperly relative to a key confining unit (at top of the Oldsmar Formation) that occurs throughout the region. The 10 injection wells were found to have their lowermost casing at a depth above the top of an important low-permeability interval. This low-permeability interval appears to act as a competent confining unit between the cavernous limestones of the Oldsmar Formation and the permeable limestones of the overlying Lake City and Avon Park Formations.

Injection wells number IW-1 to IW-7 were constructed with a maximum casing depth of between 2600' and 2700' below the surface datum. Injection wells IW-8 to IW-17, however, were cased to a shallower depth, between about 2400' and 2430' below surface datum. The top of the key confining interval lies between 2440' and 2460' below surface datum. Thus, in wells IW-8 to IW-17, the confining unit has been punctured and currently exists as an open hole. The combination of this open hole, and injection above the regional confining unit into the moderately- to highly-permeable Lake City/Avon Park Formations, has provided a relatively open pathway for the upward migration of effluent. The pressure injection of fluid above the confining unit, as well as the buoyancy contrast (the nearly freshwater effluent is considerably less dense relative to the surrounding saline formation water) provide the pathway and driving force for upward migration, respectively.

In addition to the well construction problems, the subsurface distribution of the effluent is clearly not known (beyond the limits of the site). A contour map that traces the base of the confining unit at the top of the Oldsmar indicates that the surface is deeper at the east side of the injection wellfield and shallower at the west side. The local subsurface elevation would likely suggest that a buoyancy-driven flow would dominate fluid movement below the confining unit, regardless of the background potentiometric surface. Thus, as a result of this westward shallowing of the confining unit's base, landward (westerly) flow is likely. Coincidentally, it is worth noting that monitor well FA-5 in the northwest corner (down-gradient) of active injection wells was first to detect ammonia in it's upper monitor zone,

even before injection commenced at adjacent well IW-13. The extent of this westward flow is unknown for several reasons: 1) the regional configuration of the confining unit is unknown outward from the injection site; 2) no monitor wells are located offsite that are regularly sampled to track potential landward migration; 3) the buoyancy potential of the effluent plume, and associated lateral migration along the base of this confining unit is not currently known, but is likely related to mixing of the effluent and the salinity of the native fluids; and 4) the competency of the confining unit offsite is also not known, so upward fluid loss may occur offsite at a “downstream” break in confinement. Overall, this lack of regional subsurface geologic knowledge and the physical properties of the mixed effluent preclude precise mapping of the extent of offsite migration and upward leakage.

A review of the hydraulic conductivity values collected from several studies at the injection site has provided a better picture of the permeable nature of the geologic units overlying the injection zone. What these data show is that the rocks separating the injection zone (Boulder Zone) from the Upper Floridan Aquifer are not nearly as impermeable as earlier proposed (CH2M Hill, 1977; CH2M Hill, 1981; MDW&S, 1992). A summary of the hydraulic conductivity calculations based on borehole aquifer testing shows that the Middle Confining Unit has widely scatter values, ranging from <0.28 ft/day to in excess of 28 ft/day. These borehole-based values are consistent with values calculated from core-based permeability data. We can now use these recently compiled hydraulic conductivity values to recalculate the upward travel time estimate that was first calculated in a 1977 report that was used to assess the feasibility of injection at South District (CH2M Hill, 1977). In that 1977 report, a travel time estimate for upward movement used a hydraulic conductivity value of 0.11 ft/day, which resulted in a value of 343 years for effluent to move upward from the injection interval to the base of the Upper Floridan Aquifer (2,790' to 1,690'). If we replace the hydraulic conductivity value in this calculation with the median and mean values from the hydraulic conductivity compilation, upward travel times of 17.5 years and 3.2 years result, respectively. Clearly, these later values are more in line with the actual migration time of 11 years 3 month from first effluent injection (Feb, 1983) to first ammonia detection (May, 1994).

In summary, the problem of upward migration of effluent at the South District plant has resulted from the inadequate geological characterization of the subsurface lithologies and their associated petrophysical properties. As a result, 10 of the 17 injection wells are not

cased deep enough to properly inject effluent below the important confining unit at the top of the Oldsmar Formation. As a result, effluent enters permeable rocks which allow buoyancy-driven upward migration. The Middle Confining Unit is not of sufficiently low permeability to confine the injected effluent. The degree of effluent movement offsite is unknown at this time, but below the confining unit onsite flow is probably landward. Above the confining unit, the combination of the potentiometric influences and buoyancy likely influence the flow, although upward flow is dominant as judged by the detection of ammonia in numerous monitor wells immediately overlying the injection zone. Currently, the ultimate fate of the injected effluent is unknown. The fact that effluent has reached the upper Floridan Aquifer some 30 times faster than first predicted, bodes poorly for quantitatively predicting the ultimate fate of these injected fluids. Furthermore, the considerable degree of uncertainty in the subsurface geology, hydrogeologic properties of the “confining” unit, and efficiency of effluent plume migration clearly demonstrates that no reasonable degree of certainty exists for the protection of underground sources of drinking water and nearby fragile marine and terrestrial ecosystems (Biscayne National Park, Everglades National Park, and the Florida Key National Marine Sanctuary).

II - UNANSWERED QUESTIONS REGARDING EFFLUENT MIGRATION

A number of unanswered questions now exist, all of them of fundamental importance with respect to protecting USDW, protecting public health and the environment, and tracking the ultimate fate of the upward migrating effluent.

1) As it appears that upward migrating effluent has reached the Floridan Aquifer at a rate some 30-times faster than initially predicted, what is the spatial distribution of effluent in the subsurface? This answer is of critical concern regarding the protection of USDW. We must determine where this effluent is going in order to protect the sole-source aquifer and the surrounding environment. To answer this question a new series of monitor wells and core holes (with geophysical logs), located outside the injection wellfield, are needed.

2) With the estimated volume of effluent available for upward migration (due to wells with too shallow casing depths and holes punctured in a key confining unit), what is the rate of vertical and lateral movement? Related to no. 1, this information is critical for assessing possible surface impacts if leakage occurs through the upper confining unit.

3) What is the regional competency of the dolomite confining unit at the top of the Oldsmar Formation? This is important for two reasons: first, it impacts the answer to no. 1; and second, if the shallow-cased wells can be corrected to utilize the confining layer, the regional extent of this horizon needs to be better characterized to ensure regional isolation of the treated effluent.

4) Likewise related to no. 1 and no. 2, how competent is the upper confining unit so as to prevent migration into the overlying Biscayne Aquifer, the sole drinking water aquifer in south Florida? This is especially important if fluid is migrating to the west, beneath and inland of the 1,000 mg/l isochlor that defines the boundary of the Biscayne Aquifer. It is currently unknown whether the Miocene rocks of the Arcadia Formation, that form the Upper Confining Unit, are breached due to sinkhole-like features or some other vertical communication. In addition, relatively little hydraulic conductivity exists locally for the overlying siliciclastics of the Peace River and Long Key Formations.

5) Finally, what is the ultimate fate of the effluent? Does it actually get diluted or biochemically consumed to a point that renders it safe as a component of an underground source of drinking water? Or, if it reaches the surface will it act as a nutrient source capable of altering the ecology of the coastal zone or a terrestrial ecosystem? The fact that saline water occurs nearby in both the surface and subsurface, makes the potential for buoyant fluids to reach the surface marine ecosystems even greater, and of critical concern. These are fundamental questions that so far have not even been asked, nor even considered in order to insure some reasonable degree of aquifer and ecologic safeguards. A statement borrowed from the 1977 CH2M Hill report (p. 1-6) on the feasibility of Miami-Dade County deep-well injection wrote:

“Where does the injected water go? Present technology does not yet offer practical and economical means to directly determine the direction of ground-water flow at considerable depth”.

Surprisingly, some 23 years later we still have relatively little information on where the effluent goes, besides that fact that it has, and continues to, move upward into an USDW.

III - DISCUSSION OF WELL CONSTRUCTION, AQUIFER TESTING, AND WATER QUALITY DATA

1.0 Change in Injection Well Final Casing Depth

The installation of the 17 injection wells at the South District Wastewater Treatment Plant was completed in four phases. The first phase served as the feasibility study and involved the installation of IW-5. The second phase included the installation of 8 injection wells (IW-1 to IW-4 and IW-6 to IW-9) and 3 monitor wells (BZ, FA-1, FA-2). The third phase installed 3 injection wells, IW-10 to IW-12, and 2 monitor wells (FA-3 and FA-4). The final phase added 5 injection wells (IW-13 to IW-17) and 12 monitor wells (FA-5 to FA-16). The current distribution of injection wells and monitor wells is shown in Figure 1.

The most significant event relevant to upward effluent migration occurred during the second phase of injection well installation, which began in April, 1979. Eight injection wells (IW-1 to IW-4, IW-6 to IW-9) and 3 monitor wells (BZ-1, FA-1, FA-2) were installed between April 1979 and the end of 1980. Injection wells IW-1 to IW-4, IW-6 and IW-7 were constructed as designed, to position the casing above the injection zone, with final casing to depths between 2600' and 2800' (Table 1). However, serious cementing problems were encountered with wells IW-6, IW-3, and IW-2. At these wells the cavernous nature of the Boulder Zone near the injection interval resulted in the loss of cement during the casing cementation. These cement fill up difficulties resulted in a re-evaluation of the injection zone based on pumpout tests conducted on IW-5. The IW-5 aquifer tests indicated that the interval around 2,450' was in hydrologic communication with the lower injection zone (CH2M Hill, 1977). Thus, it was decided to set the final casing to a shallower depth. The 1981 CH2M Hill report states: "...it was decided to set the 24-inch casings on I-8 and I-9 above 2,500 feet to avoid potential cement fillup problems and subsequent costs."

This change in construction of the final casing to a shallower interval at IW-8 and IW-9 resulted in the placement of casing above an important low-permeability confining unit at the top of the Oldsmar Formation (see Table 1 for casing and confinement depth summary). Part of the reason this low-permeability interval (see section 3.0 below) was not identified at South District is that no continuous cores were collected through this interval. Thus, the properties of this low-permeability interval were not linked to the geophysical log signature which could be used to trace it across the site. The final configuration of IW-8 and IW-9 placed part of the injection zone above the low-permeability confining unit. Effluent was subsequently injected into the basal Lake City/Avon Park Formation, and through the open-hole in the confining unit into the Oldsmar Formation.

Location of South District Injection and Monitor Wells

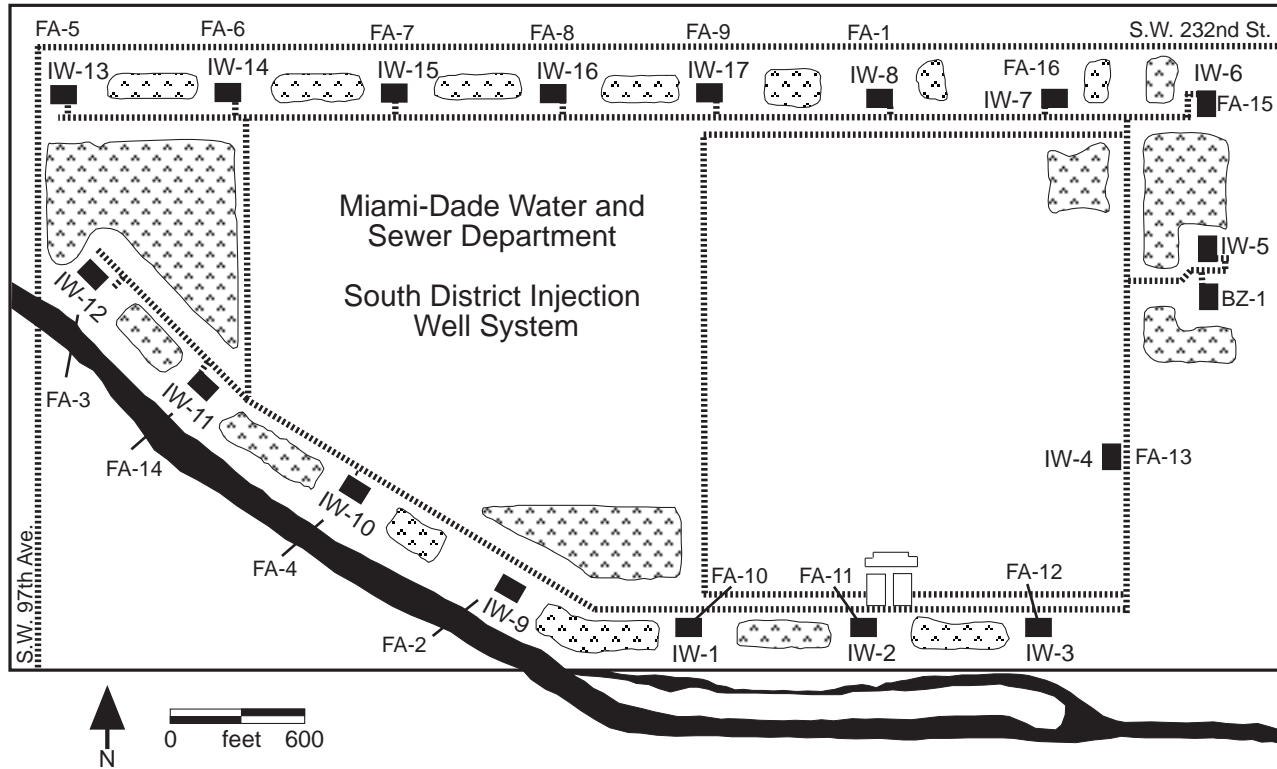


Figure 1. Location map showing injection wells (IW) and adjacent monitor wells (FA).

Table 1. Summary of “top Oldsmar dolomite” and Injection Well Casing Depth

Well	Top Dolomite (ft below pad) ¹	Base Dolomite (ft below pad) ¹	Base Casing (ft below pad)	Top Dolomite (feet-MSL) ²	Base Dolomite (feet-MSL) ²
IW-5	2460	2474	2746	2450	2464
BZ-1	2460	2475	2689	2450	2465
IW-1	2449	2464	2628	2439	2454
IW-2	2467	2483	2628	2457	2473
IW-3	2443	2460	2629	2433	2450
IW-4	2462	2474	2664	2452	2464
IW-6	2470	2484	2740	2460	2474
IW-7	2452	2470	2628	2442	2460
IW-8	2460	2468	2420	2450	2458
IW-9	2436	2448	2418	2426	2438
IW-10	2440	2450	2425	2430	2440
IW-11	2436	2444	2428	2426	2434
IW-12	2426	2442	2392	2416	2432
IW-13	2430	2442	2400	2420	2432
IW-14	2440	2456	2403	2430	2446
IW-15	2440	2455	2410 ³	2430	2445
IW-16	2448	2458	2420	2438	2448
IW-17	2451	2462	2410	2441	2452

¹ Note: depths in feet relative to surface well pad (approx. pad elevation +9 to +10 ft MSL).

² Determined by subtracting elevation of well pad datum (~10 ft MSL).

³ Incorrectly shown by MDWS at 2628 on Table III-2 (7/9/1998)

The two subsequent well-installation phases (IW-10 to IW-12 and IW-13 to IW-17) followed a design and construction similar to IW-8 and IW-9. The eight injection wells all had final casing positioned above the dolomite confining unit. Similar to IW-8 and IW-9, pressure injection of effluent entered the moderately- to highly-permeable limestones of the Lake City/Avon Park Formation, as well as through the open hole in the confining unit to the cavernous intervals of the Oldsmar Formation (Boulder Zone).

Our overall evaluation of the injection-wells indicates that 10 out of 17 wells at the South District are constructed so as to inject effluent above the regional confining unit at the top of the Oldsmar Formation. A schematic summary of this injection problem is shown in Figure 2. The limestones of the Lake City and Avon Park Formations that comprise the Middle Confining Unit have permeabilities that range from ~10 md to values in excess of 1 darcy (median value of 156 md) (Figure 3). Thus the confining capabilities of the Middle Confining Unit must be reevaluated and reconsidered for deep-well injection in south Florida.

2.0 Permeability and Hydraulic Conductivity of the Middle Confining Unit

A compilation of existing hydraulic conductivity values (Figure 4) and a new data set on the permeability (Figure 5) of rocks from the Middle Confining Unit at South District has been assembled to assess the competency of this unit to confine injected effluent. This is especially important in light of the fact that 10 of the 17 wells are constructed and operating so as to allow injection into the basal part of the Middle Confining Unit.

The hydraulic conductivity data collected from aquifer testing on South District wells indicates a very heterogenous nature to the Middle Confining Unit (Figure 4). Values in this interval range from a low of ~0.03 ft/day to ones in excess of 28 ft/day. The unit as a whole has a mean hydraulic conductivity of ~6 ft/day and a median value of ~1.5 ft/day (Table 2).

We have made high-resolution permeability measurements on several of the cores collected from the South District injection wells. Permeabilities were determined using a nitrogen-gas injection device placed on the slabbed face of the core. This gas permeameter is calibrated to limestone and sandstone standards that have had permeability determined by mercury-injection methodology. The core-based permeabilities for the Middle Confining Unit are shown in Figure 3. Similar to the packer-based hydraulic conductivity values, the permeabilities display a range of values, from about 10 md to in excess of 1 darcy. This permeability differential is due to changes in lithology related to the peritidal facies of the Lake City/Avon Park Formation (Figure 5). A comparison of hydraulic conductivity values with the core-based permeabilities is shown on

Differences in Injection Well Construction at MDW&S South

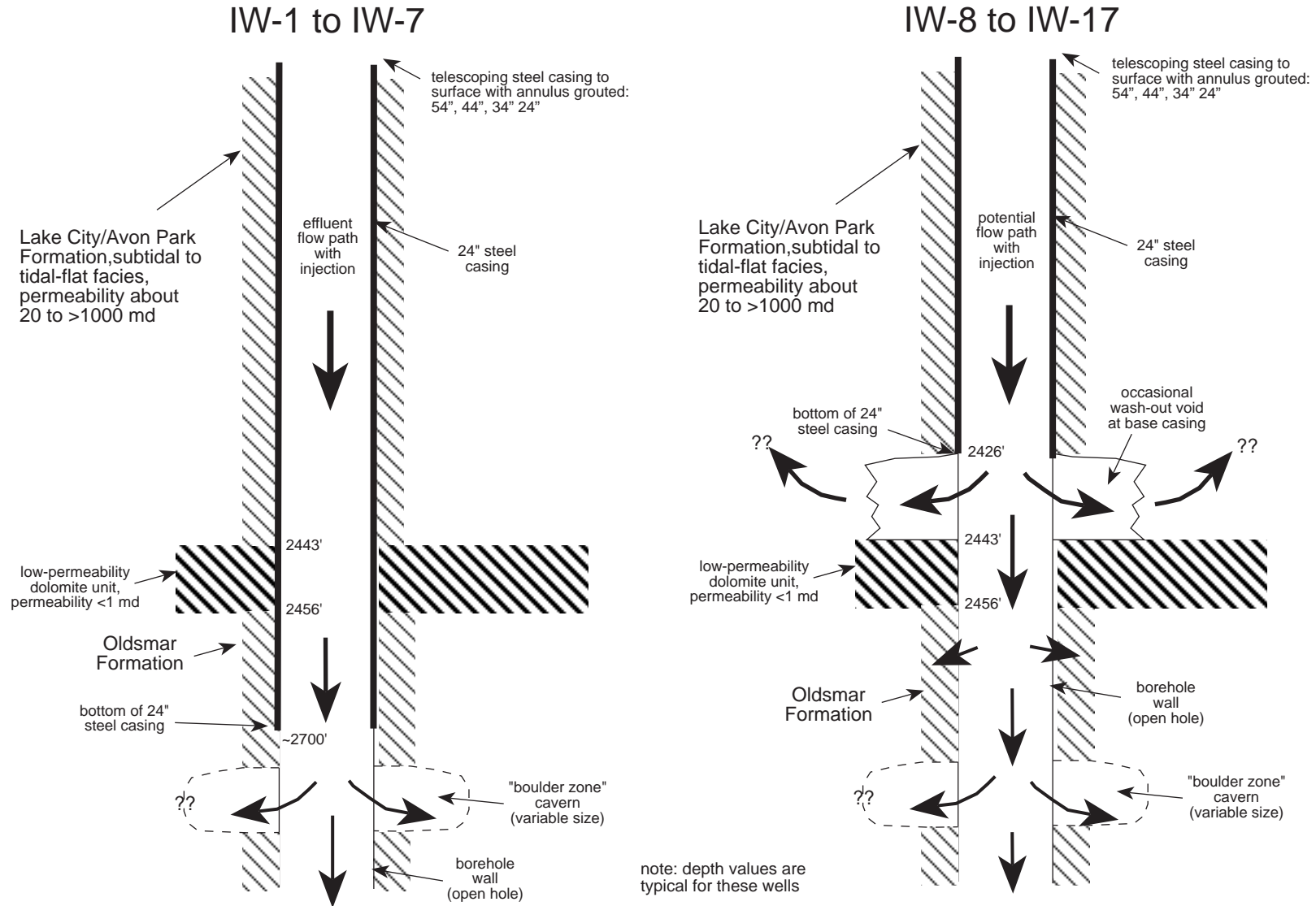


Figure 2. Schematic showing the differences in final casing depth between injection wells cased below the dolomite confining unit (IW-1 to IW-7) and those cased above the confining unit (IW-8 to IW-17). Those wells cased above the confining unit allow effluent to enter the Lake City/Avon Park Formation, part of the confinement (?) horizon.

South District Permeability Composite

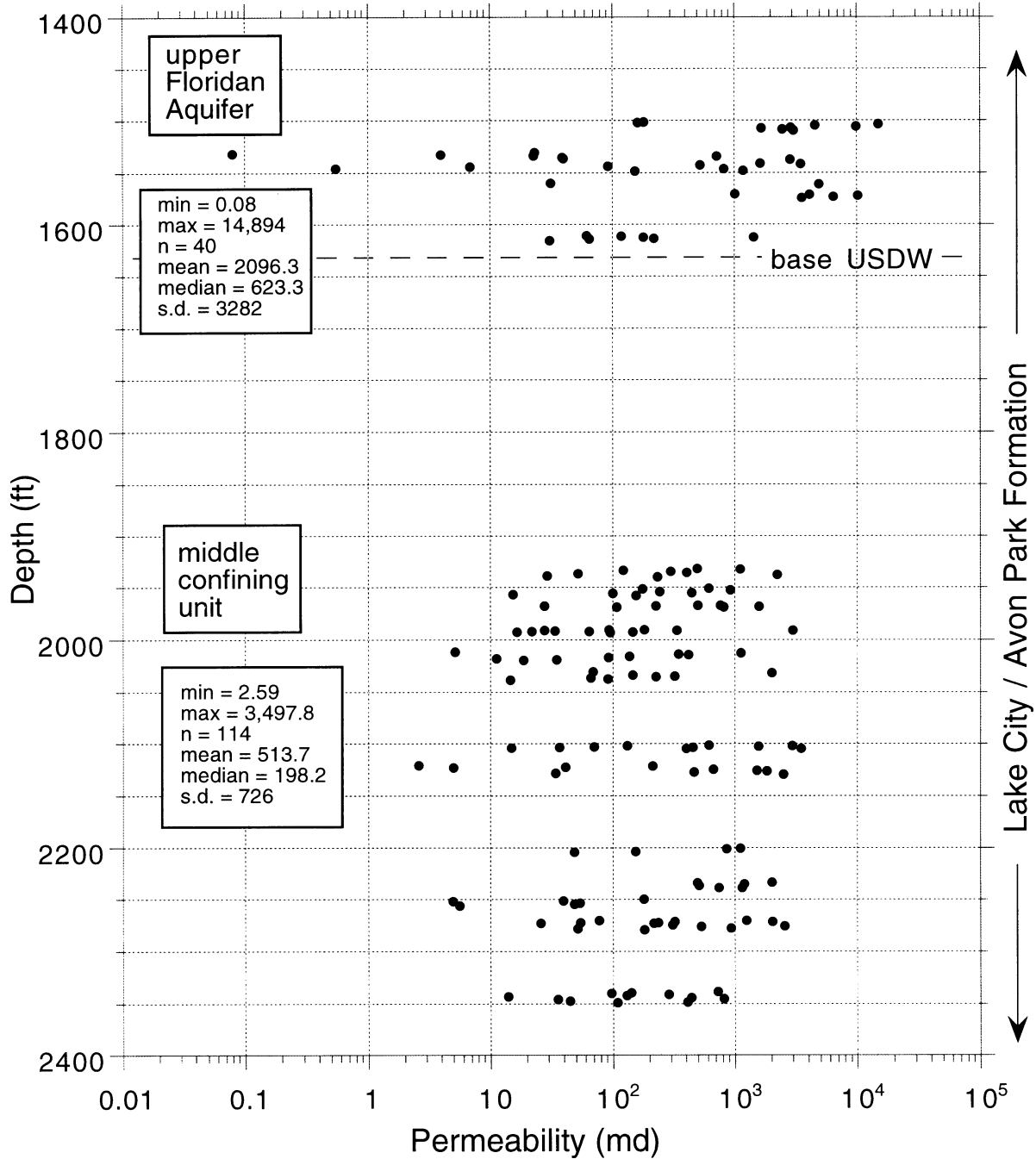


Figure 3. Composite permeability profile for the South District site based on horizontal measurements with a gas permeameter. Data was collected from cores from wells IW-13, IW-16, IW-14, IW-15, IW-17, FA-9, FA-10, FA-13.

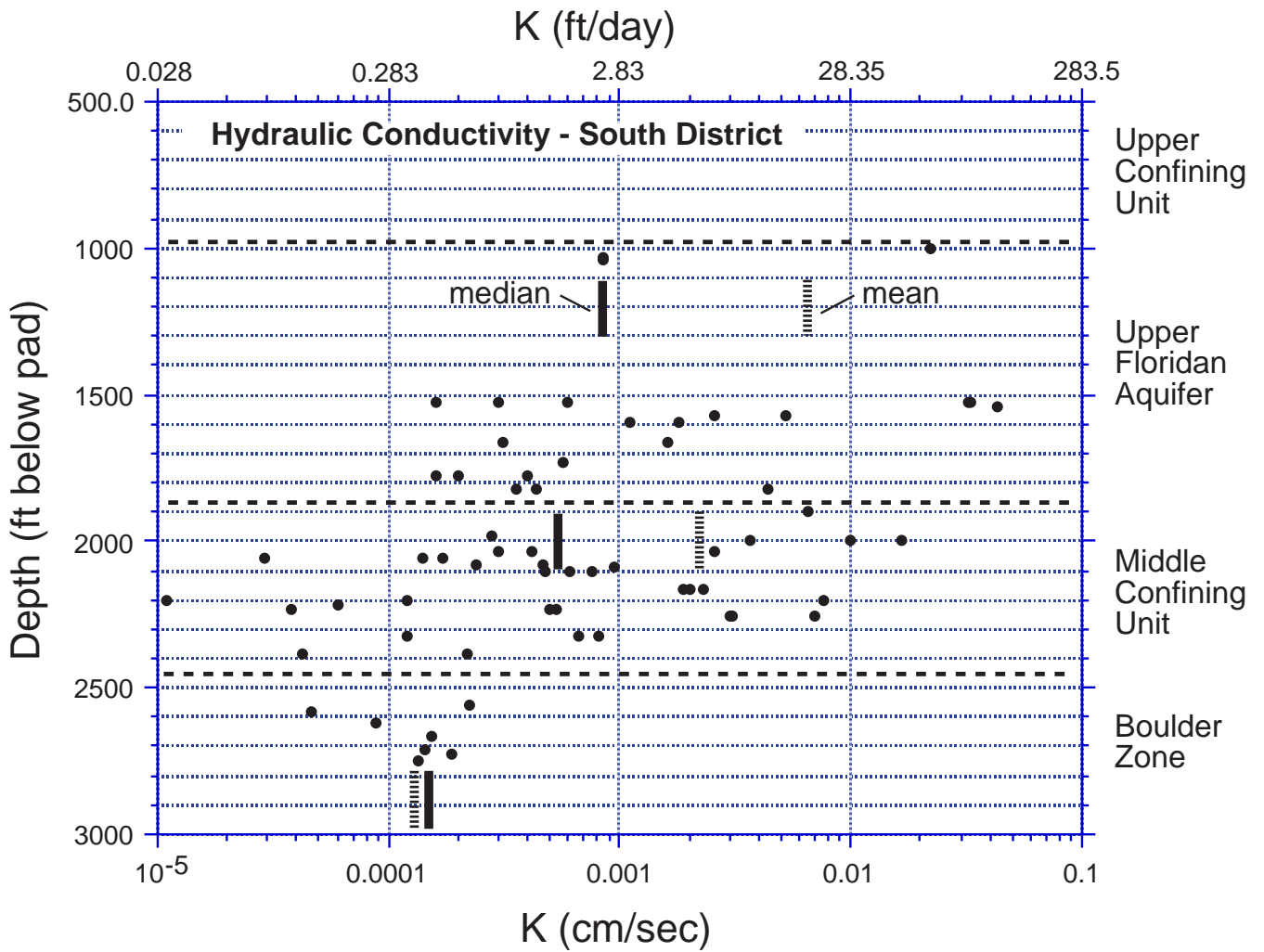


Figure 4. Compilation of hydraulic conductivity values reported in engineering reports to Miami-Dade Water and Sewer Department. The mean (vertical dashed line) and median values (vertical solid line) are shown for each hydrologic subunit shown on the right side of the graph.

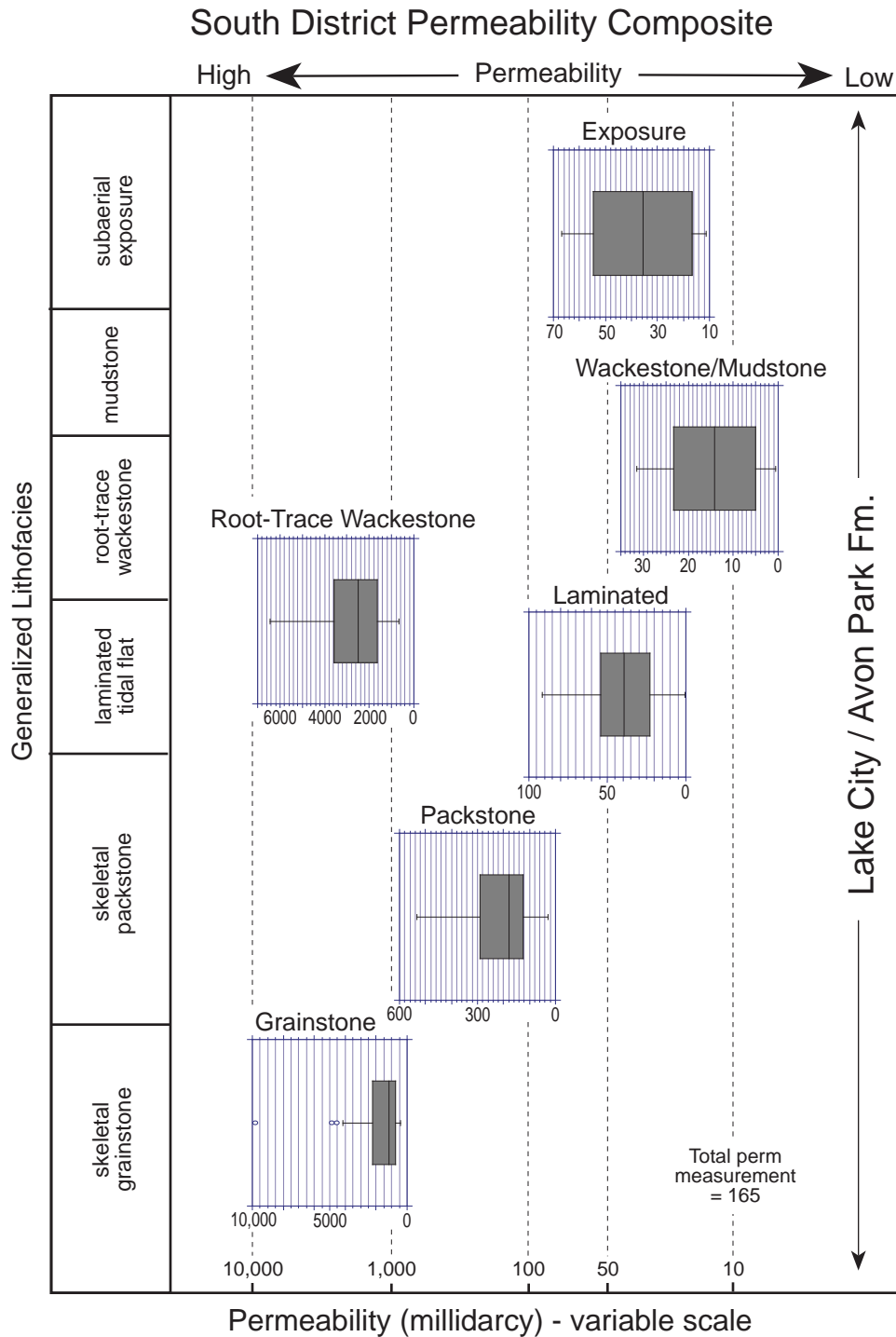


Figure 5. Distribution of permeability with respect to lithofacies in South District cores. The extremely high values in some lithology types and the lower values in others combine to produce an interval with net permeability in the moderate- to high-range.

Table 2. Summary of hydraulic conductivity in cm/sec (ft/day) for South District

Subsurface Zone	N	mean	median	stan. dev.	min.	max.
Upper Floridan Aquifer (1000'-1825')	23	0.0067 (19.00)	0.00084 (2.38)	0.013	0.00016 (0.45)	0.043 (121.8)
Middle Confining Unit (1895'-2383')	35	0.0021 (6.00)	0.00053 (1.50)	0.0035	0.000011 (0.03)	0.017 (48.16)
Boulder Zone (2500'-2748')	7	0.00013 (0.37)	0.00015 (0.43)	0.000059	0.000046 (0.13)	0.00023 (0.65)
All Zones Combined	65	0.0035 (9.92)	0.00053 (1.50)	0.0082	0.000011 (0.031)	0.043 (121.8)

Figure 6. Note that both values are in general agreement, confirming a moderate to high permeability. We interpret these data as not of sufficiently low-permeability to provide confinement. This interpretation is in contrast to that proposed by Miami-Dade Water and Sewer Department in their 1991 report (p. 2), which states “The middle confining unit is about 400 feet thick with estimated hydraulic conductivity values ranging from 10^{-4} cm/sec to 10^{-8} cm/sec and is thus sufficiently confining to retard and prevent upward migration of treated effluent into the overlying aquifers.” This statement is misleading in that the range of hydraulic conductivities mentioned only accounts for the 5 lowest values out of a data set of 35 (see Figure 4). Twenty-nine of the hydraulic conductivity values are greater than 10^{-4} cm/sec (Figure 4). The authors of this 1991 report argue that the type of aquifer test (inflatable packer test) measures only the most transmissive zones within the ‘packed-off’ interval. This may be true to some extent, but the core-based data indicates that all the lithologies have sufficient permeability to transmit fluids.

It is also worth noting that a comparison of vertical to horizontal permeability within the Lake City/Avon Park Formations that comprise the Middle Confining Unit show very little directional heterogeneity (see Figure 7). These horizontal and vertical permeabilities were collected on sawed cubes of limestone from each of the lithofacies within the Middle Confining Unit. What the data clearly show is that at the bed-scale level, there is no anisotropy to the permeability. This is especially important since the assessment of hydraulic conductivity in the Middle Confining Unit has assumed that vertical values are considerably less than the measured horizontal values. This assumption is promoted in the following statement from the Miami-Dade Water and Sewer 1991 report:

“The previous analyses are measurements of horizontal hydraulic conductivity for a typical section of the Floridan Aquifer middle confining unit. Vertical hydraulic conductivity which is a measure of the tightness of the confining unit, is generally in orders of magnitude less than the horizontal hydraulic conductivity. Therefore, based on these analytical results coupled with the interpretation of lithologic logs and geophysical logs, this zone of the Floridan Aquifer between 1930 and 2380 feet is an adequate confining unit for injection of wastewater into the boulder zone at this site in Dade County.” (from Appendix 8 in a letter report to Florida Department of Environmental Regulation).

Our review of the existing data, coupled with our new permeability data from South District cores, suggests that this is an extremely dangerous assumption. In addition, the fact that effluent is being injected into the base of this moderately- to highly-permeable “confining unit”, make an assumption such as this of even greater concern.

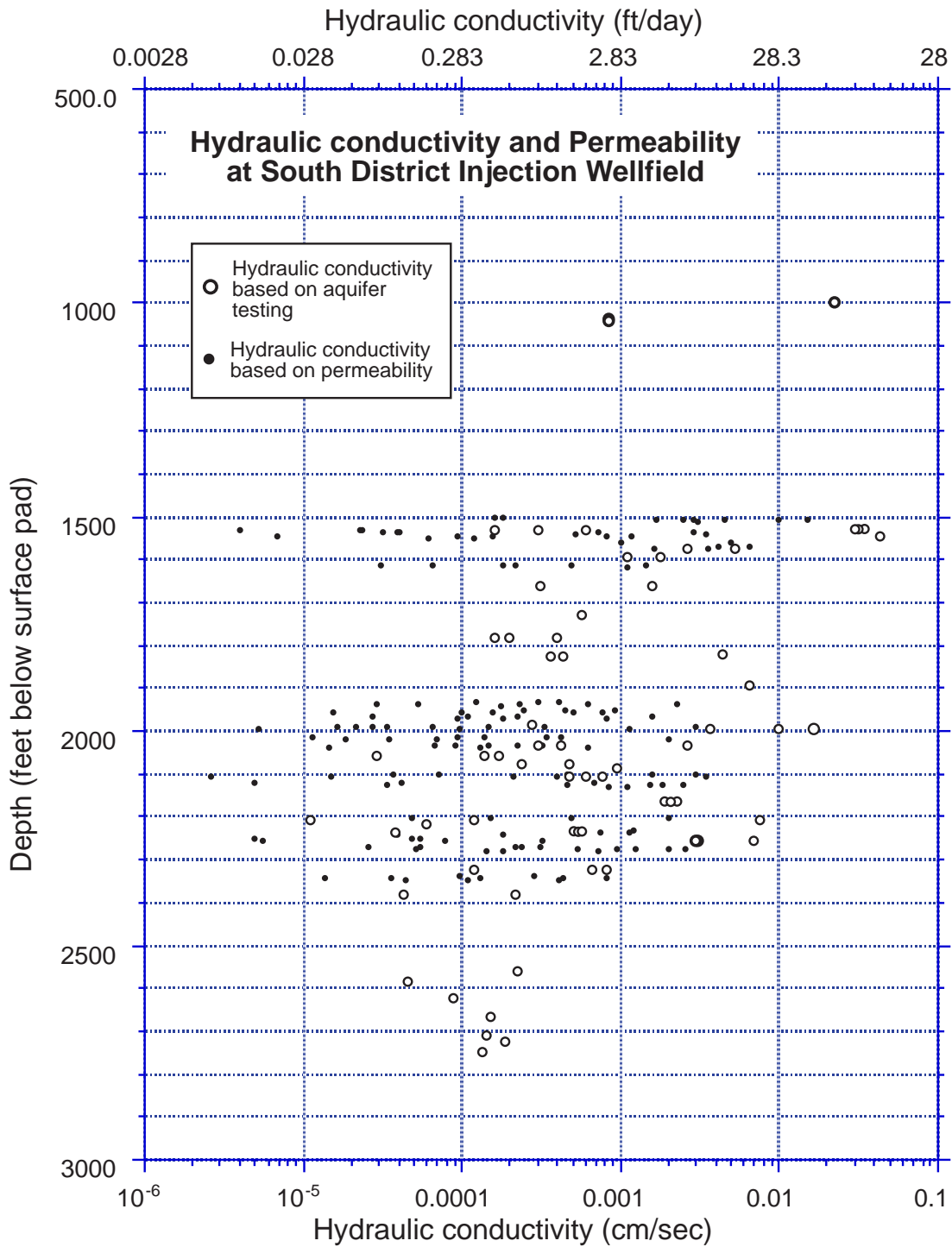


Figure 6. Comparison of hydraulic conductivities based on aquifer test data from South District wells with hydraulic conductivity values based on a conversion from permeability measurements. Aquifer test data was compiled from MDW&S engineering report related to injection well installation.

**Vertical versus Horizontal Cube Permeability
Middle Confining Unit - South District Core Borings**

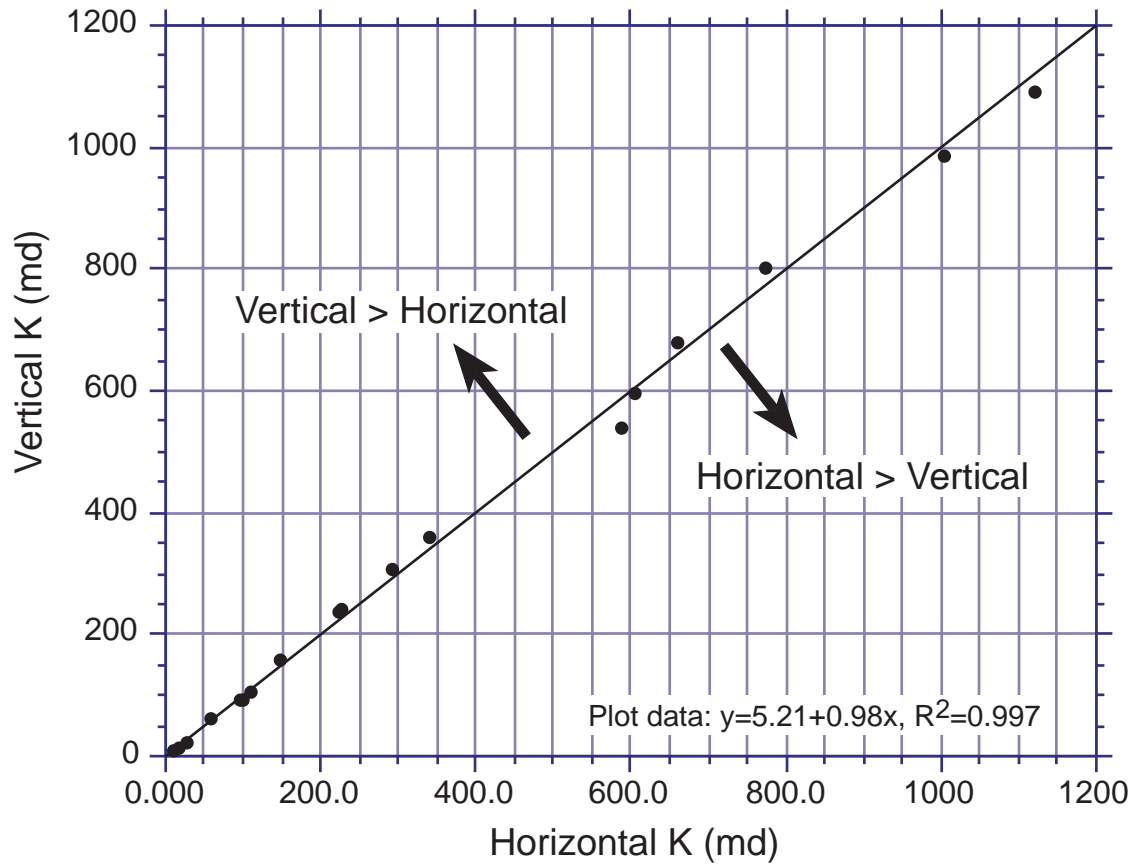


Figure 7. Plot of vertical and horizontal permeability values measured from the same rock cube from cores within the Middle Confining Unit. The rock cubes were cut from each of the lithofacies shown in Figure 5. These data suggest relatively little anisotropy between the vertical and horizontal permeability

3.0 The Low-Permeability Confining Unit: top of the Oldsmar Formation

A low-permeability unit exists at the contact between the Oldsmar Formation and the overlying Lake City/Avon Park Formation, here referred to as the “top Oldsmar dolomite aquitard or confining unit”. This unit consists of a dense, extremely well-cemented dolomite. This interval has been identified from geophysical logs, lithologic cuttings from South District wells, and also regionally where it has been cored. Unfortunately, this low-permeable dolomite was not cored at South District because only selected intervals were chosen (mostly in the Middle Confining Unit), and no continuous core was ever collected at the injection site. This same interval was, however, cored at the Sunrise injection site and calibrated with the geophysical logs from that site. The South District geophysical logs across the top of the Oldsmar Formation are extremely similar to those from Sunrise, except for the slightly deeper position of the unit in southern Miami-Dade County. A review of the logs of the lithologic cuttings from the various injection well installation phases, also confirms the existence of this dense, low-permeable interval at South District (see CH2M Hill, 1977 and 1981 reports, MDW&S, 1991 report).

We obtained cores from the Sunrise injection well field that recovered the low-permeability dolomite at the top of the Oldsmar Formation. Permeability from this unit is extremely low, with most values on the order of 0.1 md (Figure 8). This dense dolomite has permeabilities about 100 to 10,000 times less than the overlying Middle Confining Unit (recall that the Middle Confining Unit at South District has values of between 10 and 1000 md).

The confining competency of this low-permeability dolomite is further supported by a set of temperature logs collected from IW-13 before operational testing and permitted effluent injection. A temperature log was run four times over a period of ~3 months across the dolomite confining interval. What these temperature logs show is that when first punctured, a temperature gradient exists below the base of this low-permeability interval. With subsequent log runs, the thermal gradient move successively up the bore hole (see Figure 9). We interpret this upward migrating thermal anomaly to be a result of drilling through a competent confining unit and subsequent upward migration of fluids (effluent?) from the underlying unit.

Permeability of Dolomite Aquitard - Sunrise Injection Well

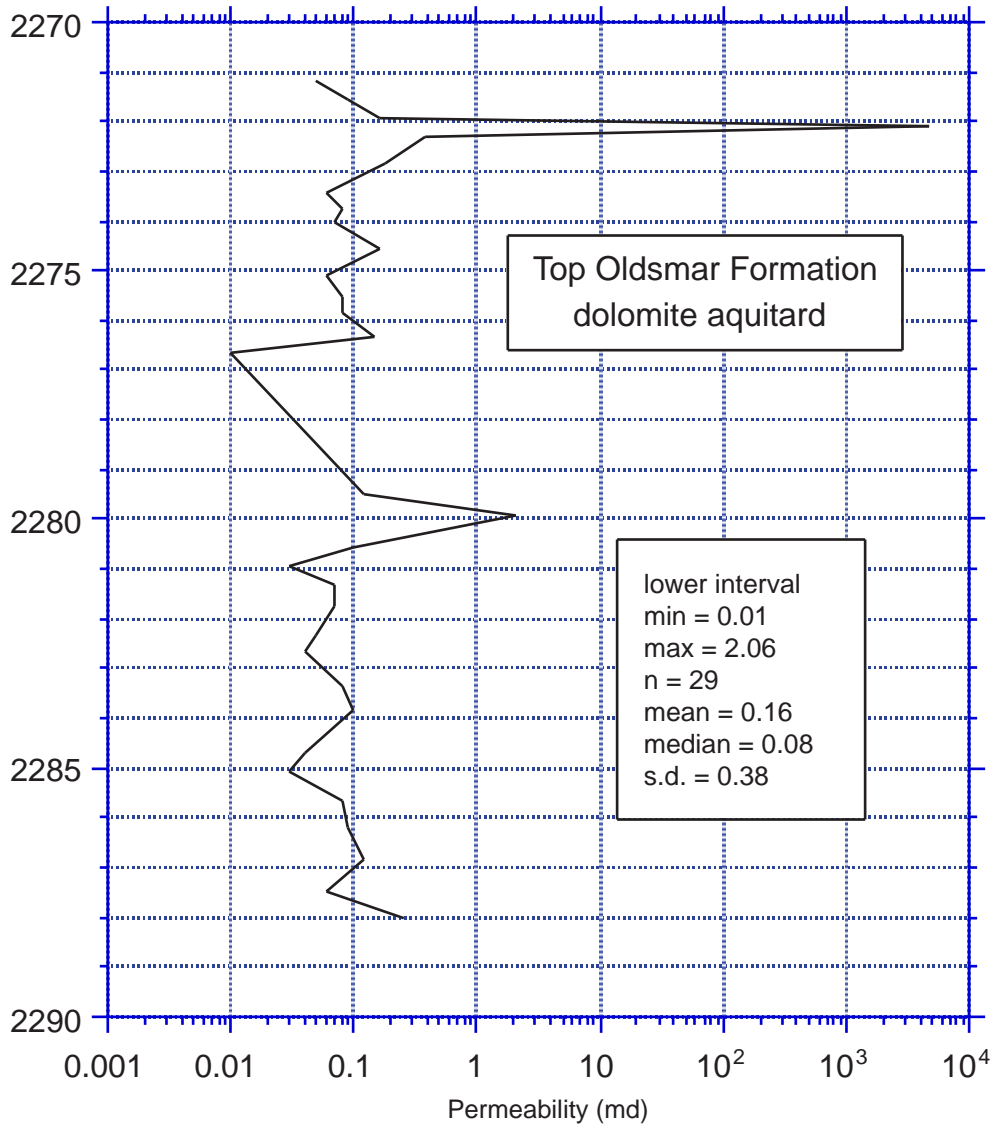


Figure 8. Example of low-permeability dolomite unit capping the Oldsmar Formation at the Sunrise injection well. The geophysical log characteristics of this low-permeable unit are nearly identical to those from the South District logs.

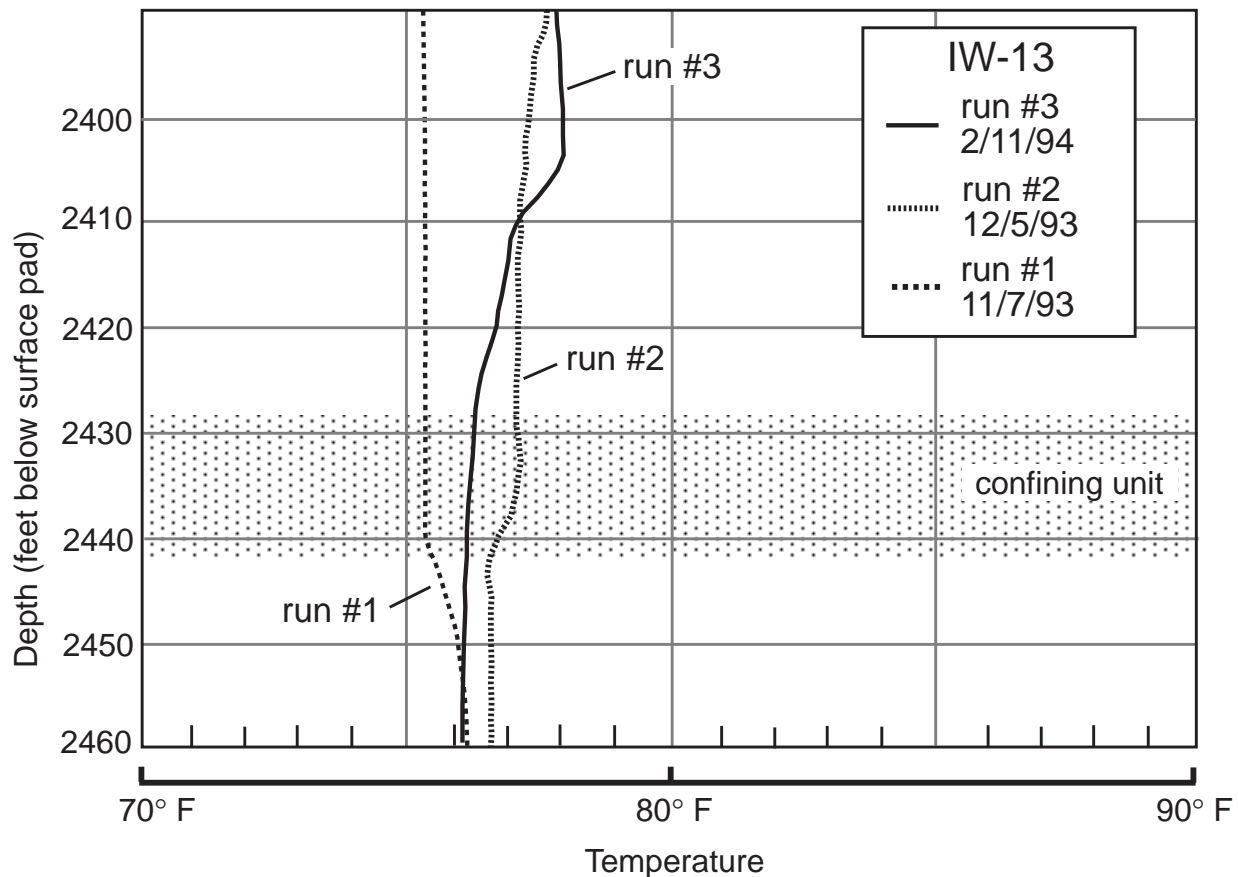


Figure 9. A sequence of temperature logs over a 3-month period were run in IW-13 prior to operational testing with effluent injection. The temperature data from the earliest log run (#1) indicated a thermal gradient near the base (warmer water below) of the low-permeability dolomite. A subsequent log, run 1-month later, shows that the thermal profile has inverted, perhaps due to less dense (warmer) water moving upward in the borehole. The thermal gradient during run #2 was positioned within the low-permeability dolomite. The third temperature log, run 2 months later, shows a profile similar to run #2. However, the thermal gradient has moved further up the borehole to a position about 25 feet above the dolomite confining unit. The thermal inversion and upward moving thermal gradient likely reflect movement of warmer, less-dense fluids from below the confining layer, through the confining layer, and ultimately upward away from the confining layer. These warmer, less dense fluids likely originate from effluent that has migrated from one of the downgradient operating wells. Consistent with this interpretation is that a fluid-density log from run #2 showed less-dense fluids beneath the confining unit and more-dense fluids above the confining unit. The depth of this density gradient between these two fluid masses is coincident with the thermal gradient.

Additional commentary on the nature of the dolomite confining unit is provided by the following passage from the 1991 MDW&S report (p. 15) on the installation of IW-10 as the low-permeability dolomite was punctured by the drill:

“During the drilling of the I-10 pilot hole to the estimated depth of 2,450 feet below land surface, serious problems were encountered. Once the highly transmissive dolomite layer at about 2,447 feet below land surface was penetrated, during drilling, upward migration of treated freshwater effluent from nearby operating injection well I-9 was detected. The less dense fresh water coupled with the highly transmissive zone made it difficult to stop the well from overflowing. Also, large quantities of cement were lost into the cavernous formation.”

We believe that the confining potential of this low-permeability dolomite unit was not recognized at South District. As a result, the positioning of final casings above this confining unit (Table 1) does not take advantage of this regionally continuous(?) horizon. Injection of effluent above this aquiclude promotes the rapid upward migration of the less dense fluids.

4.0 Configuration of the Top Oldsmar Dolomite Aquitard at South District

The distinct nature of the low-permeability dolomite at the top of the Oldsmar Formation on geophysical logs allows for a structure contour map to be constructed on the top and bottom of this unit. The most useful log for picking the top and bottom of this dolomite unit is the dual-induction resistivity log, although it is also reflected with less resolution on the gamma-ray log, the sonic velocity log, as well as the caliper log. The contour map on the top of the dolomite interval shows lower (deeper) elevations in the east and northeast side of the injection site, and shallowing depths to the west and southwest (Figure 10). An anomalously shallow depth occurs in the southeastern corner of the site. More important is the contour map of the bottom of this dolomite unit (Figure 11), for this will influence the direction that buoyant fluid travels. The bottom topography, similar to the top, shows the surface deeper in the east and shallower in the west. This inclination across the site suggests that buoyancy-driven fluids will travel to the west or southwest across the site.

The buoyancy-driven fluids would likely override any influences of the natural potentiometric flow. We therefore expect plume migration below this confining unit to be predominantly westward from the site. The extent of the plume and its mixing dynamics are unknown at this time due to the lack of offsite wells that monitor water quality in this interval. In addition,

Contour Top of Oldsmar "Dolomite" Aquitard (contour interval 10 ft)

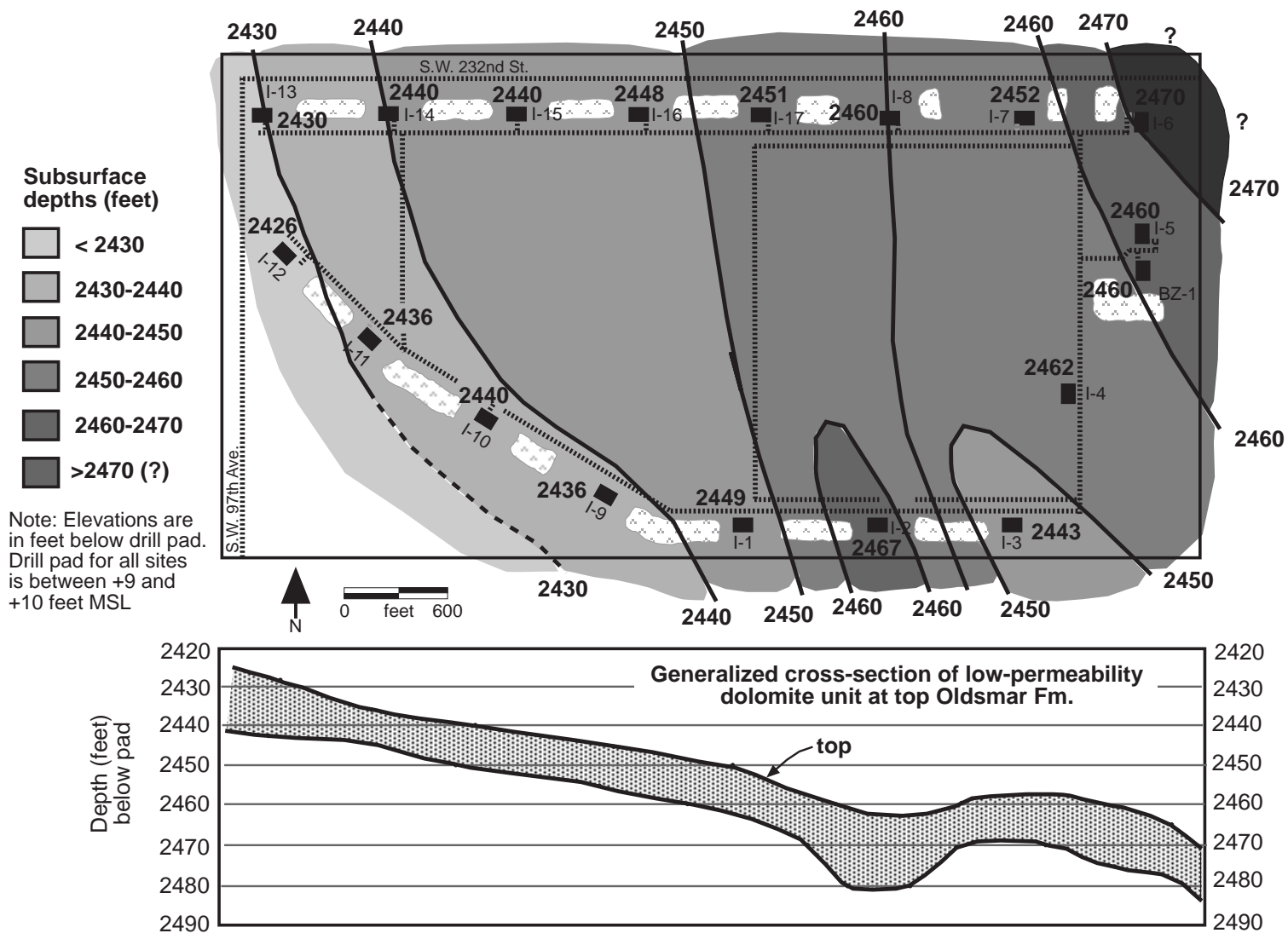


Figure 10. Structure contour map on top of the low-permeability dolomite unit at the top of the Oldsmar Formation. The inclination of the surface from east to west is evident in this map.

Contour Base Oldsmar "Dolomite" Aquitard (contour interval 10 ft)

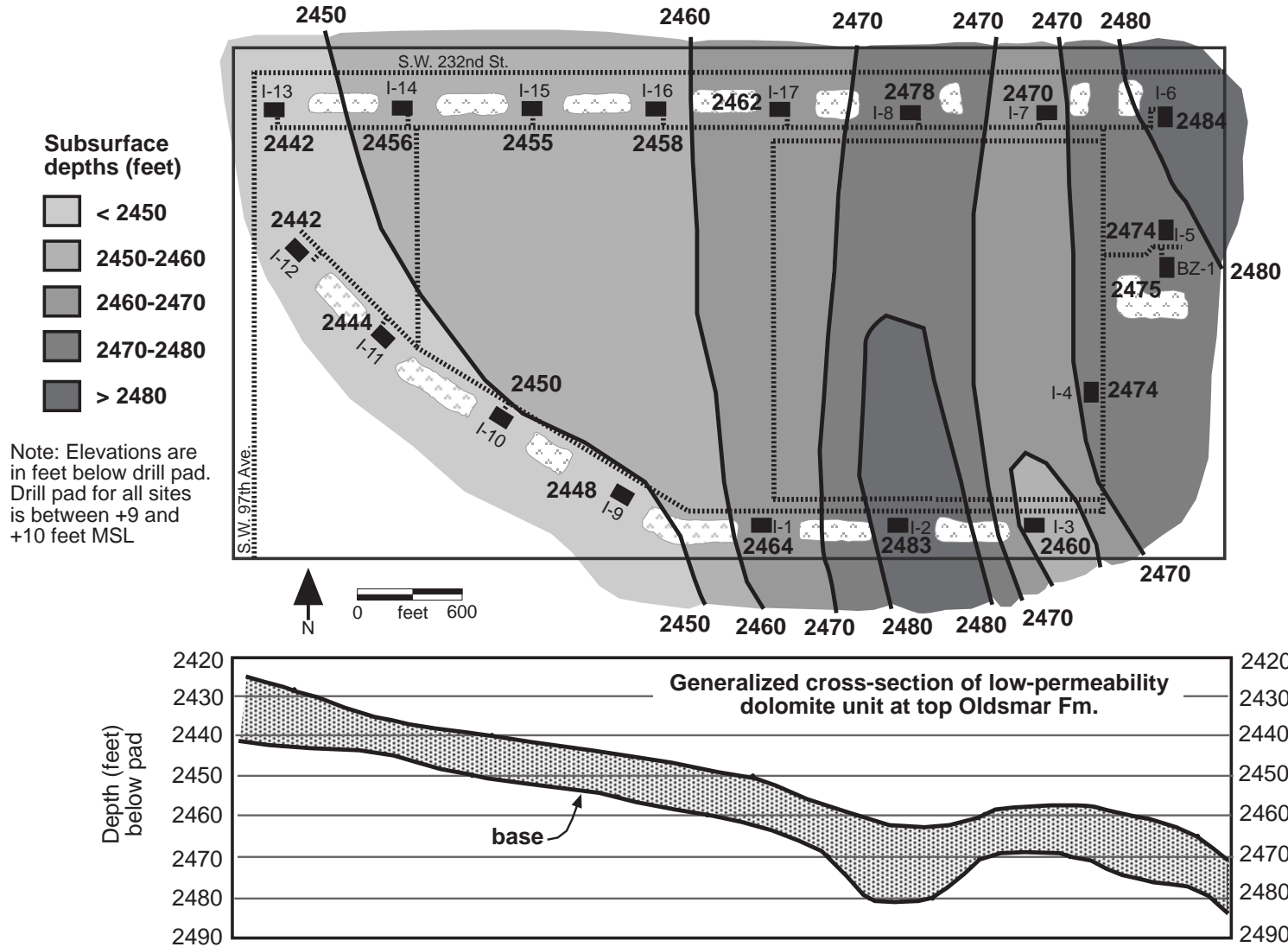


Figure 11. Structure contour map on the base of the low-permeability dolomite unit at the top of the Oldsmar Formation. As with the upper surface of this horizon, the inclination from east to west is readily apparent from in this map. Buoyant fluids at the base of this low-permeable dolomite would tend to flow from east to west.

the regional configuration of this low-permeability horizon is uncertain, given only a few wells provide data from this depth and have adequate geophysical logs needed to reliably map the dolomite.

One interesting note is that the position of the monitor well where effluent was first found is in the northwest corner of the site (adjacent to IW-13). This monitor well is down gradient with respect to the suspected flow direction (westerly) beneath the confining unit, as well as having the confining unit punctured by several nearby drill holes (uncased) in IW-13, IW-14, and IW-15. Furthermore, this well was constructed around 1990, and was not permitted for injection until 1999. Thus, the punctured confining unit at IW-13, located “downstream” of the operating injection wells, provided ~9 years of potential upward leakage even before it became operational (as did injection wells IW-14 to IW-17).

5.0 Upward Travel Time Estimates (1977) and Revised Calculations

In the 1977 feasibility study that drilled and tested the first injection well (IW-5) an estimate of vertical travel time was made to show that deep-well injection was both feasible and environmentally safe. In that 1977 report, a travel time estimate for upward movement used a hydraulic conductivity value of 0.11 ft/day, which resulted in a value of 343 years for effluent to move upward from the injection interval to the base of the Upper Floridan Aquifer (2,790' to 1,690') (see Figure 12). If we replace the hydraulic conductivity value in this calculation with the median and mean values from the all the hydraulic conductivities determined from the site, upward travel times of 17.5 years and 3.2 years result, respectively (Figure 12). Clearly, these later values are more in line with the actual migration time of 11.25 years from first effluent injection (2/83) to first ammonia detection (5/ 94).

Detection of ammonia in the shallowest monitor wells after about 11 years is not inconsistent with physical properties of the rocks given the permeability and hydraulic conductivity measured at South District. The new permeability results, the buoyant nature of the injected effluent, the widespread spatial distribution of ammonia, and the injection of these fluids above a key confining unit all combine to show that upward travel times on the order of 30-times faster than first predicted do indeed exist. The Middle Confining Unit has only moderate to poor confining capabilities and offers minimal protection of underground sources of drinking water and nearby environmentally sensitive areas.

Upward Travel Time Estimates

Original Injection Well Study, 1977 (CH2M Hill report)

T, interval transmissivity = 900 gpd/ft (cumulative)

ϕ , estimated porosity = 0.25

l, upward gradient = 20' in 1000' = 0.02

M, distance from injection to lower Floridan Aquifer (2,790'-1,690 = 1,100')

$$K = T/M = 900/1,100' \quad K = 0.82 \text{ gpd/ft}^2$$

$$K = 0.82/7.48 = \text{ft}^3/\text{day} \times 1/\text{ft}^2 = 0.11 \text{ ft/day} \quad (3.8 \times 10^{-5} \text{ cm/sec})$$

Average Upward Velocity

$$V = Kl/\phi = 0.11 \text{ ft/day} \times 0.02 \times 1/0.25$$

$$V = 0.0088 \text{ ft/day} \quad \text{or} \quad \mathbf{V = 3.21 \text{ ft/year}}$$

REACH the FLORIDAN AQUIFER in **343** years

Upward Travel Time Using Median and Mean of Hydraulic Conductivity

$$K = 2.15 \text{ ft/day}$$

MEDIAN

Average Upward Velocity

$$V = Kl/\phi = 2.15 \text{ ft/day} \times 0.02 \times 1/0.25$$

$$V = 0.172 \text{ ft/day} \quad \text{or,} \quad 62.8 \text{ ft/year}$$

Reach the FLORIDAN AQUIFER in **17.5** years

.....

$$K = 11.73 \text{ ft/day}$$

MEAN

Average Upward Velocity

$$V = Kl/\phi = 11.73 \text{ ft/day} \times 0.02 \times 1/0.25$$

$$V = 0.938 \text{ ft/day} \quad \text{or,} \quad V = 342.5 \text{ ft/year}$$

Reach the FLORIDAN AQUIFER in **3.2** years

.....

Figure 12. Comparison of travel time estimates for the upward migration of effluent. The original (1977) calculation for the injection feasibility study is shown at the top. The calculation is recomputed with the median and mean value of hydraulic conductivity based on our compilation of values from MDW&S aquifer tests.

6.0 The Middle Confining Unit: Not “...relatively impermeable rock.”

In a recent MDW&S report, the Middle Confining Unit is referred to as “...constituted by about 1,000 ft of relatively impermeable rock.” (p. 4, Report No. A, Monitoring Well Purging Report Update, 2000). Based on a review of the site’s hydraulic conductivity properties (discussed above, Table 1) and the core-based permeability data (Figure 3), it is clearly a misnomer to label this unit “relatively impermeable”. With the existing hydraulic conductivity values alone, the suitability of the Middle Confining Unit to act as a confining unit has to be seriously questioned.

7.0 The Spatial and Temporal History of Ammonia at South District

A cursory review of the ammonia data in water samples from the South District monitor wells was performed based on data supplied by the Miami-Dade Water and Sewer Department. The concentration of ammonia is used here as an indicator of the presence of injected effluent. The concentration of ammonia in the effluent varies from analysis to analysis, but chemical analysis of the effluent in 1985 and 1986 had typical ammonia values of 8.0 mg/l, 11.0 mg/l, 13.45 mg/l and 20.55 mg/l (MDW&S South District Chemical Reports). Some of the maximum values of ammonia in the monitor wells, as reported by MDW&S, range from 17.2, 12.14, 14.02, 14.10, 9.04, 7.01, and 3.45 mg/l. Clearly, relatively little mixing and dilution (< 1 volume) of the effluent with native saline waters (background concentration ~0.3 mg/l or less) has occurred before upward migration to monitoring zones within the Floridan Aquifer.

A compilation of “first date analyzed” and “first date NH₃ detected” for the South District monitor wells show that 11 wells (FA-5, FA-6, FA-7, FA-8, FA-9, FA-10, FA-11, FA-12, FA-14, and FA-16) had ammonia already present at their first sampling (see Table 3). The vertical and horizontal distribution of upward-migrated effluent appears to be influenced by several factors. Generally higher ammonia concentrations in the upper monitoring zone are found in the northwest corner of the site. This may be a combination of the westward shallowing of the dolomite confining unit and the concentration of improperly cased wells along the northern and western sides of the site. The wells that have casing at too shallow a depth have allowed effluent to directly enter the formation above the dolomite confining unit. As a consequence of this injection, upward migration to a shallow interval of the Floridan

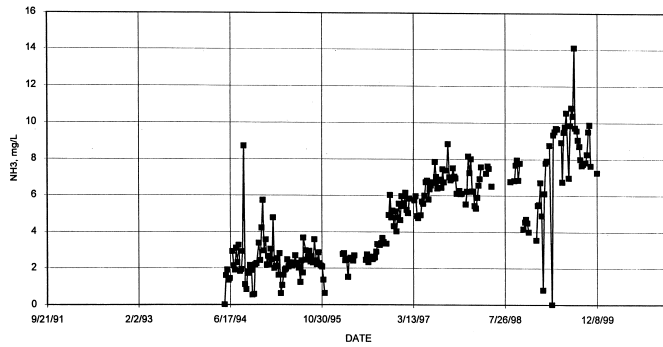
Table 3. Summary of the Chronology of Ammonia Detection in Monitor Wells at the Miami-Dade Water and Sewer South District Injection Wellfield

Well No. (depth)	First date analyzed	NH ₃ conc. (mg/L)	First date NH ₃ detected*	NH ₃ conc. (mg/L)	Comments
FA-1 U (980-1,090 ft)	12/1/83	0.2	N/A	N/A	
FA-1 L (1,840-1,927 ft)	12/1/83	0.2	N/A	N/A	
FA-2 U (980-1,020 ft)	12/1/83	0.1	N/A	N/A	
FA-2 L (1,645-1,672 ft)	12/1/83	0.3	N/A	N/A	
FA-3 U (981-1,050 ft)	1/1/91	0.05	N/A	N/A	
FA-3 L (1,771-1,892 ft)	1/1/91	0.05	N/A	N/A	
FA-4 L (1,702-1,840 ft)	12/17/91	0.20	N/A	N/A	
FA-5 U (1,490-1,588 ft)	5/3/94	7.30	5/3/94	7.30	NH ₃ detected first sample, range 4-12 mg/L
FA-5 L (1,790-1,890 ft)	5/10/94	0.0	N/A	N/A	
FA-6 U (1,490-1,584 ft)	5/17/94	0.00	5/24/94	1.60	FA-6U: TKN and NH ₃ show increasing trend in concentration, near 10 mg/L in 1998
FA-6 L (1,790-1,890 ft)	5/17/94	1.80	1/7/96	>5.0	FA-6L: increasing trend to 0.50 mg/L NH ₃
FA-7 U (1,488-1,580 ft)	8/22/94	8.10	8/22/94	8.10	NH ₃ detected first sample, range 4-12 mg/L
FA-7 L (1,805-1,872 ft)	8/22/94	0.09	12/16/97	2.95	NH ₃ and TKN increase sharply, NH ₃ up to as high as 8 mg/L
FA-8 U (1,490-1,575 ft)	8/29/94	5.30	8/29/94	5.30	NH ₃ detected first sample, range 2-8 mg/L
FA-8 L (1,790-1,890 ft)	8/22/94	0.09	N/A	N/A	
FA-9 U (1,490-1,587 ft)	5/2/95	0.00	7/18/95	1.19	NH ₃ increasing trend to about 2 mg/L
FA-9 L (1,790-1,880 ft)	5/2/95	0.00	N/A	N/A	
FA-10 U (1,490-1,592 ft)	2/27/96	0.33	N/A	N/A	
FA-10 L (1,790-1,890 ft)	2/27/96	2.74	2/27/96	2.74	NH ₃ detected first sample, range 1.5-3.0 mg/L
FA-11 U (1,490-1,588 ft)	2/21/96	0.12	8/19/97	1.01	NH ₃ steady increase to values of 1.0-2.0 mg/L, some peak values of ~5.0 mg/L in 1998/1999
FA-11 L (1,790-1,890 ft)	2/21/96	9.62	2/21/96	9.62	NH ₃ detected first sample, range 6-10 mg/L
FA-12 U (1,495-1,597 ft)	2/21/96	0.56	6/11/96	1.06	Steady NH ₃ between 1.0-2.0 mg/L
FA-12 L (1,790-1,890 ft)	2/21/96	11.32	2/21/96	11.32	NH ₃ detected first sample, range 10-14 mg/L
FA-13 U (1,480-1,585 ft)	2/21/96	0.65	N/A	N/A	Steady NH ₃ between 0.4-0.8 mg/L
FA-13 L (1,740-1,845 ft)	2/21/96	0.38	N/A	N/A	Increasing trend to 1.0 mg/L
FA-14 U (1,490-1,575 ft)	2/21/96	3.03	2/21/96	3.03	NH ₃ detected first sample, increasing trend to ~5 mg/L
FA-15 U (1,490-1,575 ft)	2/21/96	3.96	2/21/96	3.96	NH ₃ range between 2 and 6 mg/L
FA-15 L (1,790-1,890 ft)	2/27/96	0.05	N/A	N/A	
FA-16 U (1,490-1,590 ft)	2/21/96	4.06	2/21/96	4.06	NH ₃ detected first sample, 3-5 mg/L range
FA-16 L (1,790-1,890 ft)	2/21/96	0.08	N/A	N/A	
BZ-1 (1,005-1,037 ft)	3/1/84	0.13	N/A	N/A	Few peaks of 2-3 mg/L in 1990-1993, range usually <1.0 mg/L
BZ-2 (1,577-1,664 ft)	3/1/84	0.22	2/13/96	1.19	Steady increase in NH ₃ to ~2.5 mg/L in 1999

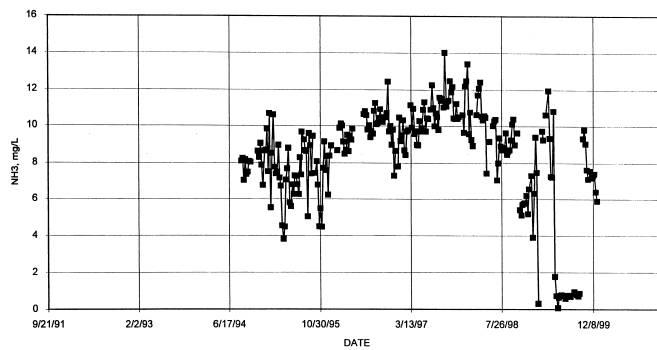
Source of data: Miami-Dade Water and Sewer Department, Report No. A Monitoring Well Purging Report Update, February 23, 2000

*A repeated level of 1.0 mg/L is used as an indicator of NH₃

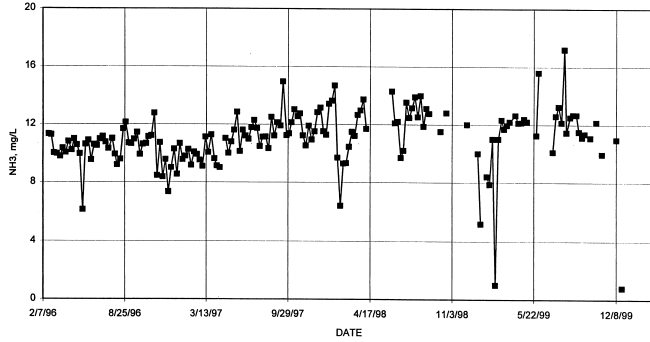
Ammonia Concentrations - South District



Monitor Well
FA-6U



Monitor Well
FA-7U



Monitor Well
FA-12L

Monitor Well
FA-16U

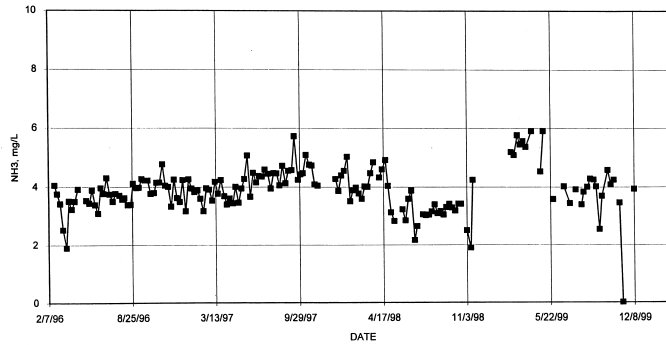


Figure 13. Ammonia time-series for selected monitor wells at the South District injection wellfield. Data from MDW&S Department Report, 2000.

Aquifer may be preferential to the northwest corner of the injection site. The cause of higher ammonia concentrations in the southeast corner of the site in the lower monitor zone is more difficult to explain. It is worth noting, however, that the base of the dolomite confining unit is anomalously shallow in the vicinity of IW-3, perhaps acting as a localized pooling point for the more buoyant effluent. Ammonia concentrations in lower FA-12 (at IW-3) have remained relatively steady around 12 mg/l, perhaps indicative of a constant pooling effect related to this shallow pocket in the confining unit. Alternatively, the cementing difficulties encountered at IW-2 and IW-3 due to cavernous zones, and the need for gravel backfill to a depth within the confining unit before casing cementation was possible (CH2M Hill, 1981), may have contributed to the production of a leaky confining unit. In turn this leakage through the confining unit may have contributed to upward migration of effluent found at both the lower and upper monitoring zones of FA-12 and FA-11.

The fact that more of the monitor wells record ammonia in the shallow zone as opposed to the deep monitor zone is also intriguing. One possible speculation on the cause of this relationship is that the route of upward migration through the "Middle Confining Unit" is by partially isolated vertical flow routes (due to the slightly lower hydraulic conductivities) that promote upward bypass to shallower depths. Some type of bypass of the lower monitor zone would be consistent with a greater buoyancy drive in the more saline (lower) parts of the Floridan, as opposed to the transition to brackish water at the upper monitor zone.

The time-series plots of ammonia concentrations in the monitor wells where it has been detected at values consistently >5 mg/l (upper monitoring zone FA-5, FA-6, FA-7, FA-8, FA-15, FA-16; lower monitoring zone FA-7, FA-11, FA-12) generally show either increasing or relatively steady trends (see Figure 13 for some examples). These types of trends suggest that ammonia is being supplied as a upward migrating plume from a constant source (or individual point sources as suggested by the scattered nature of the contaminated monitor wells). The absence of trends that contain a sequential increase-peak-decrease in ammonia concentration suggests that the ammonia is not part of a finite volume of water that was somehow released and is now confined (i.e., a leaky well casing). The combination of too shallow a casing depth and a punctured confining layer could both contribute to a continuous source of ammonia-rich effluent (for as long as injection continues).

8.0 References

CH2M Hill, 1977. Drilling and testing of the test-injection well for the Miami-Dade Water and Sewer Authority. Contract No. S-153. EPA Contract No. C120377020.

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9.0 Author Biography

Dr. Donald F. McNeill is a sedimentologist specializing in carbonate rocks and sediments, especially their petrophysical characteristics, stratigraphy, and geophysical log properties. Dr. McNeill holds a MSc. degree (1983) in geology from the University of Florida, and a Ph.D. (1989) in marine geology and geophysics from the Rosenstiel School, University of Miami. He is a licensed professional geologist in the State of Florida (No. 273). He is principal geologist of McNeill Geological Services, Inc. For the past 15 years he has been involved with the stratigraphy and log correlation of carbonates rocks as part of the Industrial Associates Program at the Comparative Sedimentology Laboratory, University of Miami. He is currently an Associate Scientist in the Division of Marine Geology and Geophysics at the Rosenstiel School of Marine and Atmospheric Science, University of Miami.