# Vertical migration of municipal wastewater in deep injection well systems, South Florida, USA

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**Abstract** Deep well injection is widely used in South Florida, USA for wastewater disposal largely because of the presence of an injection zone ("boulder zone" of Floridan Aquifer System) that is capable of accepting very large quantities of fluids, in some wells over 75,000m$^3$/day. The greatest potential risk to public health associated with deep injection wells in South Florida is vertical migration of wastewater, containing pathogenic micro-organisms and pollutants, into brackish-water aquifer zones that are being used for alternative water-supply projects such as aquifer storage and recovery. Upwards migration of municipal wastewater has occurred in a minority of South Florida injection systems. The results of solute-transport modeling using the SEAWAT program indicate that the measured vertical hydraulic conductivities of the rock matrix would allow for only minimal vertical migration. Fracturing at some sites increased the equivalent average vertical hydraulic conductivity of confining zone strata by approximately four orders of magnitude and allowed for vertical migration rates of up 80m/year. Even where vertical migration was rapid, the documented transit times are likely long enough for the inactivation of pathogenic microorganisms.

**Résumé** Les injections par puits profonds sont largement utilisées au sud de la Floride (Etats-Unis) pour stocker les eaux usées, essentiellement du fait de la présence d'une zone d'injection ("zone des blocs" du Système Aquifère de Floride) apte à accepter des quantités considérables de fluides : plus de 75,000m$^3$/jour dans certains puits. Le plus grand risque potentiel associé à ces puits vis-à-vis de la santé publique est la migration verticale des eaux usées, qui contiennent des microorganismes pathogènes et des polluants, vers les zones aquifères d'eau saumâtre qui sont utilisées pour les projets alternatifs d'alimentation en eau, comme le stockage en aquifère et la reprise de pression. Des migrations ascendantes d'eaux usées municipales ont été observées dans une minorité de systèmes d'injection du sud de la Floride. Les résultats de la modélisation du transport de solutés sous le programme SEAWAT indiquent que les perméabilités mesurées de la matrice rocheuse ne permettraient qu'une migration verticale minime. Sur certains sites, la fracturation a multiplié la perméabilité verticale équivalente moyenne de la zone de confinement par quatre, permettant des vitesses de migration verticale de l'ordre de 80m/an. Même aux endroits où la migration verticale a été rapide, les temps de transits théoriques sont susceptibles d'être suffisamment longs pour permettre l'inactivation des microorganismes pathogènes.

**Resumen** La inyección de pozos profundos se usa ampliamente en el sur de Florida, Estados Unidos de América, para la eliminación de aguas residuales principalmente debido a la presencia de una zona de inyección ("zona de cantos rodados" del Sistema Acuífero Floridano) la cual es capaz de aceptar cantidades muy grandes de fluidos, en algunos pozos hasta 75,000m$^3$/dia. El riesgo potencial más grande para la salud pública asociado con pozos de inyección profundos en el sur de Florida es la migración vertical de agua residual, que contiene contaminantes y microorganismos patógenos, hacia zonas de acuífero de agua salobre que son usados en proyectos alternativos de abastecimiento de agua, tal como recuperación y almacenamiento de acuífero. Se ha registrado migración ascendente de agua residual municipal en una minoría de sistemas de inyección del sur de Florida. Los resultados del modelo de transporte de solutos usando el programa SEAWAT indican que las conductividades hidráulicas verticales medidas en la matriz de la roca permitirían únicamente migración vertical mínima. El fracturamiento en algunos sitios incrementa la conductividad hidráulica vertical promedio equivalente de una zona de estratos confinantes en aproximadamente cuatro órdenes de magnitud y permitió tasas de migración vertical de hasta 80m/año. Aún cuando la migración vertical fue rápida los tiempos de tránsito documentados probablemente son lo suficientemente largos para la desactivación de microorganismos patógenos.

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## Introduction

Over the past 30 years, deep well injection has become an essential method for the disposal of liquid wastes in parts of Florida. In 2002, for example, approximately 1,285,000 $m^3$/day of liquid wastes were injected in 126 active deep (class I) injection wells in Florida (Florida Department of Environmental Protection 2003a, b). The injection volume has subsequently increased as more injection wells have been constructed. Class I injection wells are defined by the United States Environmental Protection Agency (USEPA 2002), as wells that inject water below the deepest underground source of drinking water (USDW) within a quarter mile (402 m) radius of the borehole. A USDW is defined by the USEPA as an aquifer containing water with a total dissolved solids (TDS) concentration of less than 10,000 mg/L. The injected fluids in Florida consist of wastewater from municipal water reclamation facilities, and in much lesser quantities, the concentrate from reverse-osmosis desalination facilities, landfill leachates, and non-hazardous industrial wastewater. In the absence of deep well injection, the liquid wastes would require higher treatment levels, with associated greater costs, and would be disposed of using more environmentally objectionable methods such as surface-water outfalls.

Wastewater receives secondary treatment (solids settlement, biological treatment of the supernatant, and disinfection) prior to injection and typically meets nearly all of the health-based United States and Florida primary drinking standards (USEPA 2003; Bloetscher and Englehardt 2003). Environmental and public health concerns remain over the underground injection of municipal wastewater such as the impacts of elevated nutrient concentrations, pathogenic microorganisms, and emerging pollutants (e.g., pharmaceutically active substances, endocrine disrupting compounds). Risk assessments of municipal wastewater-disposal options in South Florida concluded that the risk to the environment and public health posed by class I injection wells is low, provided that significant vertical fluid movement does not occur (USEPA 2003; Bloetscher and Englehardt 2003; Bloetscher et al. 2005). The maximum identified risk associated with injection well disposal of wastewater in South Florida is the potential migration of wastewater to aquifer storage and recovery (ASR) wells in the vicinity of injection wells (Bloetscher and Englehardt 2003; Bloetscher et al. 2005). A similar risk occurs when brackish groundwater is blended with permeate in reverse-osmosis desalination plants.

Upward migration of municipal wastewater into USDWs has been documented at eight Florida injection well sites, and injected fluid movement has been detected in deep monitor wells completed below the deepest USDW in at least another nine injection wells systems. Municipal wastewater has a relatively high susceptibility to upward migration because of its lower salinity, and thus greater buoyancy, than the native saline water in injection and confining zone strata. The upward migration of reclaimed water at the 17 sites occurred at a much more rapid rate than expected at the times of both the design and construction of the injection wells. The objective of this investigation was to evaluate the nature and effectiveness of confining strata for class I injection wells in South Florida. Solute-transport modeling was used to simulate vertical fluid migration under different confinement (vertical hydraulic conductivity) scenarios. Calibration of the solute-transport model against operational results would provide insights into hydraulics of confining zone strata such as the extent of matrix versus fracture flow.

## South Florida injection wells

The study area for this investigation includes Miami-Dade, Broward and Palm Beach counties in southeastern Florida, and Collier, Lee, and Charlotte counties in southwestern Florida (Fig. 1). All class I injection well systems are required by the Florida Department of Environmental Protection (FDEP) 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. 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 fluids are detected in the monitoring zone. Stable water chemistry is evidence that a monitoring zone has not been impacted by injected fluids.

There are currently 32 active class I injection wells systems in southeastern Florida. The locations, type of injected fluids, and operational history of the injection wells are summarized in Fig. 1. Upwards 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). Upwards migration of municipal wastewater into a monitor zone open below the base of the USDW is known or suspected to have occurred at another seven injection well facilities in Broward and Palm Beach counties. In the majority of injection well systems, no vertical movement of injected fluids has been detected in the monitoring zones.

A total of 23 class I injection well systems are operational in Collier, Lee, and Charlotte counties. Fifteen of the 23 wells are used for the disposal of municipal wastewater or a combined municipal wastewater and reverse-osmosis concentrate flow. Injected fluid has not

**Fig. 1** Maps of study area and locations of southeastern Floridan injection well systems. Injection well sites are coded as to the type of fluid injected and whether injected fluids have migrated into a deep monitoring zone or into an underground source of drinking water (USDW) ▶


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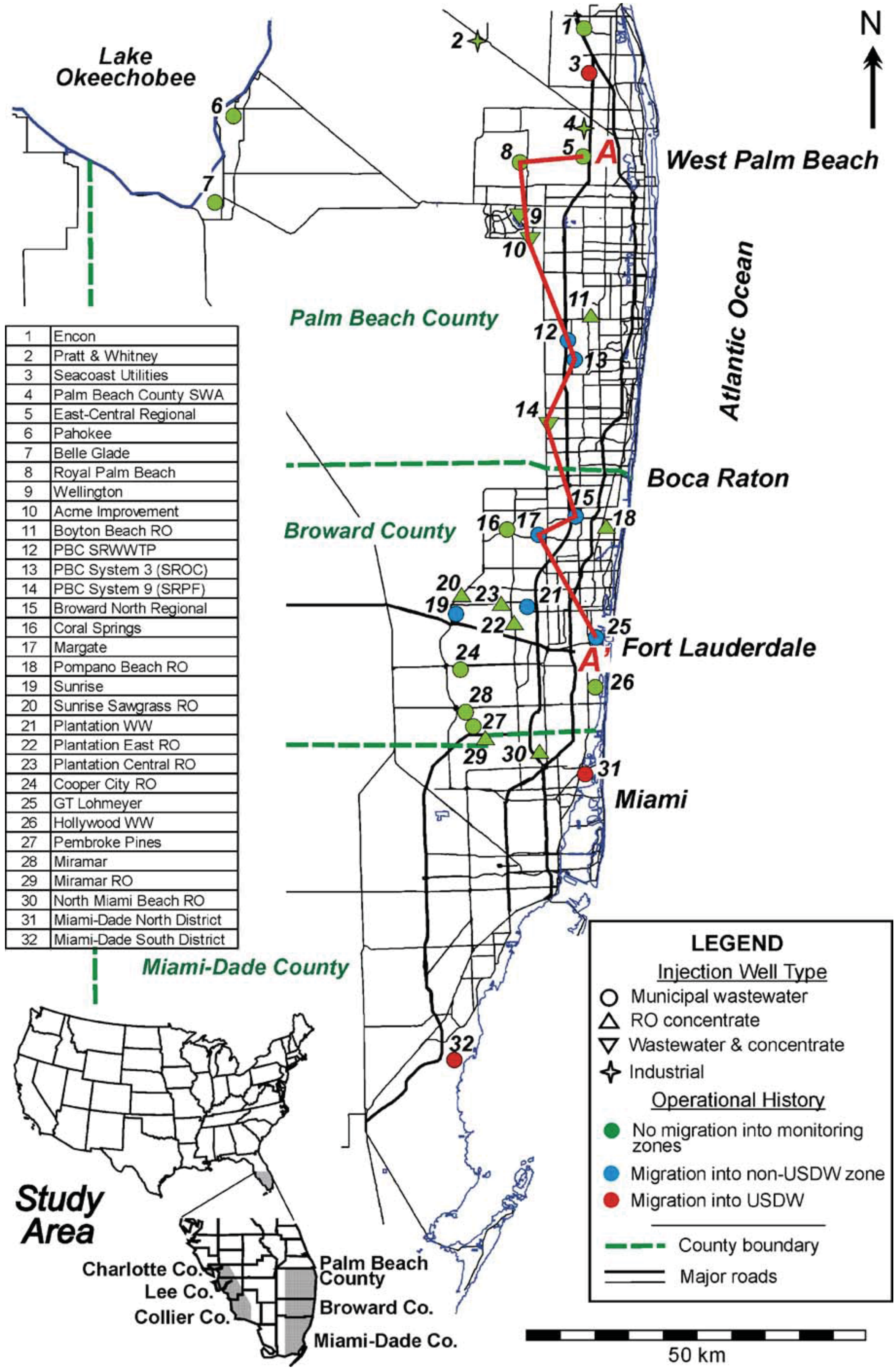
Lake Okeechobee
N
West Palm Beach
Atlantic Ocean
Palm Beach County
Boca Raton
Broward County
Fort Lauderdale
Miami
Miami-Dade County
A
A'
1 Encon
2 Pratt & Whitney
3 Seacoast Utilities
4 Palm Beach County SWA
5 East-Central Regional
6 Pahokee
7 Belle Glade
8 Royal Palm Beach
9 Wellington
10 Acme Improvement
11 Boyton Beach RO
12 PBC SRWWTP
13 PBC System 3 (SROC)
14 PBC System 9 (SRPF)
15 Broward North Regional
16 Coral Springs
17 Margate
18 Pompano Beach RO
19 Sunrise
20 Sunrise Sawgrass RO
21 Plantation WW
22 Plantation East RO
23 Plantation Central RO
24 Cooper City RO
25 GT Lohmeyer
26 Hollywood WW
27 Pembroke Pines
28 Miramar
29 Miramar RO
30 North Miami Beach RO
31 Miami-Dade North District
32 Miami-Dade South District
LEGEND
Injection Well Type
Municipal wastewater
RO concentrate
Wastewater & concentrate
Industrial
Operational History
No migration into monitoring zones
Migration into non-USDW zone
Migration into USDW
County boundary
Major roads
Study Area
Charlotte Co.
Lee Co.
Collier Co.
Palm Beach County
Broward Co.
Miami-Dade Co.
50 km

been detected in a monitoring zone at any of the 23 southwestern Florida injection well systems.

## Hydrogeology

Two major aquifer systems underlie South Florida from land surface to a depth of approximately 950–1,100 m below land surface (bls); the Surficial Aquifer System and the deeper artesian Floridan Aquifer System. These two aquifer systems are separated by confining strata called the Intermediate Confining Unit or the Intermediate Aquifer System (Fig. 2). Only the Floridan Aquifer System, which contains brackish water in South Florida, is affected by class I injection wells. The freshwater resources of the Surficial Aquifer System and locally the upper part of the Intermediate Aquifer System are effectively isolated from the Floridan Aquifer System and class I injection well activities in South Florida by over 100 m (cumulative thickness) of clay-rich confining strata.

The Floridan Aquifer System is one of the most productive aquifers in the United States and underlies all of Florida and parts of Georgia and South Carolina for a total area of about 260,000 km$^2$ (Miller 1986). The Floridan Aquifer System consists of an extensive sequence of thickly bedded Tertiary-aged limestones (and less abundantly, dolostones) that were deposited in shallow-water environments. The permeability of the Floridan Aquifer System has a high degree of heterogeneity. Highly productive strata are interbedded with strata that produce very little water. Stratigraphically, the Floridan Aquifer System in southwestern Florida is composed of Oligocene and Eocene-aged strata that are part of the lower Hawthorn Group, Suwannee Limestone, Ocala Limestone, Avon Park Formation and Oldsmar Formation. In large parts of southeastern Florida, the limestones within the lower Hawthorn Group, Suwannee Limestone and Ocala Limestone are absent due to erosion (Guertin et al. 2000). The base of the Floridan Aquifer System is generally placed at the top of the uppermost evaporite (anhydrite) bed in the Cedar Keys Formation (Paleocene).

The injection zone for class I injection wells in South Florida is the so-called "boulder zone," a high-transmissivity zone in the lower Floridan Aquifer System that has been used for the underground disposal of various types of liquid wastes since 1943. The boulder zone is characterized by greatly enlarged borehole diameters, exceedingly long sonic transit times, relatively low resistivity, and changes in temperature and flow-meter log responses

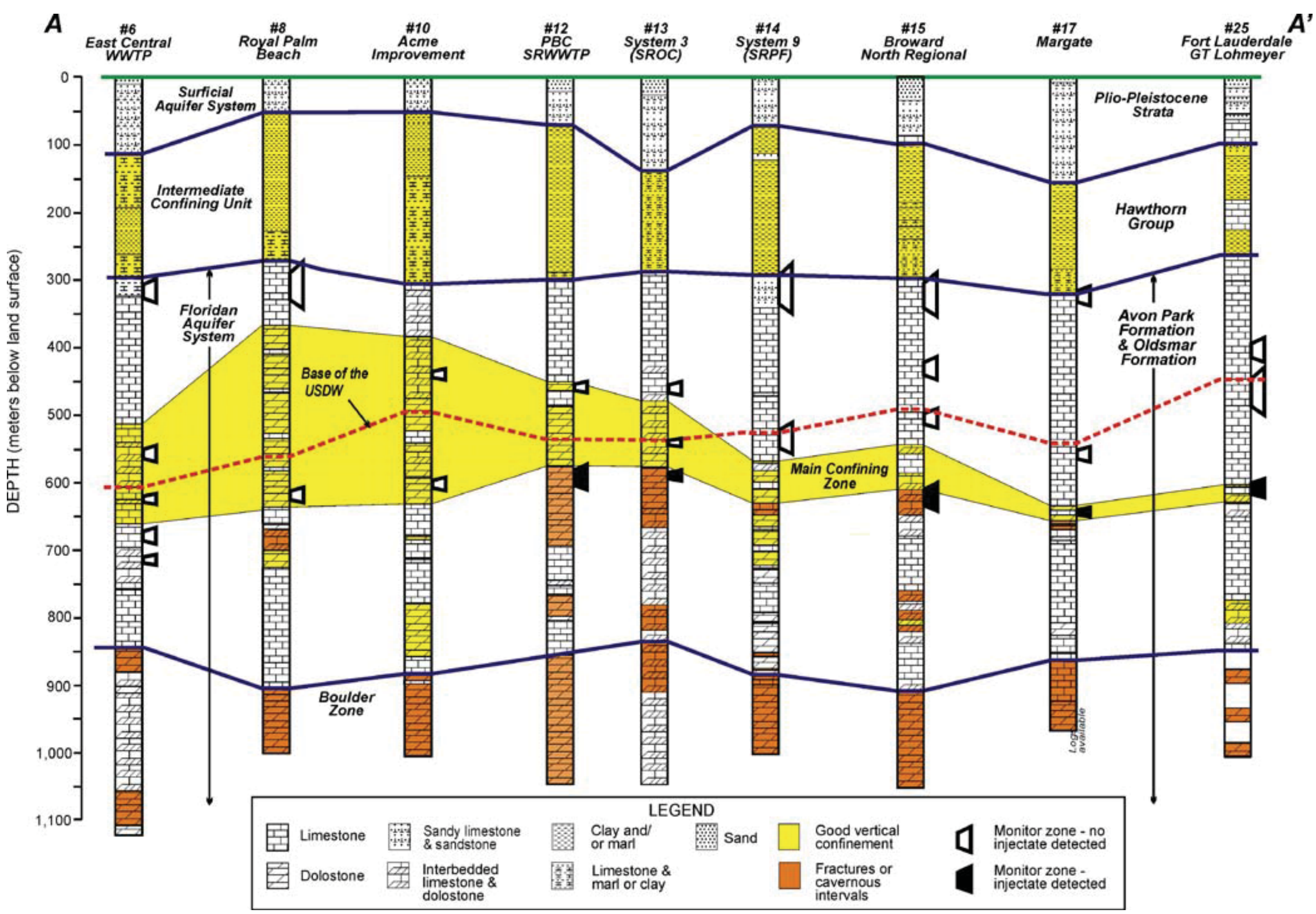


**Fig. 2** Hydrogeologic cross section through southern Palm Beach County and North Broward County Florida showing locations of high transmissivity (fractured strata), confining strata, and monitoring zones. The base of the deepest *USDW* is marked


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(Haberfeld 1991; Maliva and Walker 1998). The boulder zone consists mainly of fractured dolostones in which large cavities develop during drilling as the result of borehole collapse (Safko and Hickey 1992; Duerr 1995; Maliva and Walker 1998). Actual caves, as evidenced by bit drops during drilling, are rare.

The transmissivity of the boulder zone has been reported to be as high as $2.3\times10^7$ $m^2$/day (Singh et al. 1983). The high transmissivity allows for minimal increases in pressure during injection. For example, the bottom-hole pressure increase during a recent injection test at the Collier County South Water Reclamation Facility injection well IW-2 was only 0.32 bars at an injection rate of 70,860 $m^3$/day (CDM 2004a). The low injection pressures in South Florida imply that upwards migration of injected fluids is driven predominantly by the buoyancy of the municipal wastewater (USEPA 2003).

The base of the deepest USDW occurs in the upper or middle part of the Floridan Aquifer System (Fig. 2). The confining strata between the top of the injection zone and base of the deepest USDW consist of interbedded limestone and dolostones. A histogram of core plug data from 29 South Florida injection wells shows that the matrix vertical hydraulic conductivity of confining zone strata varies by eight orders of magnitude (Fig. 3). In general, dolostones tend to have lower vertical hydraulic conductivities than limestones.

## Vertical migration distance and rates

The distance and rate of upward migration of injected municipal wastewater can be estimated from operational

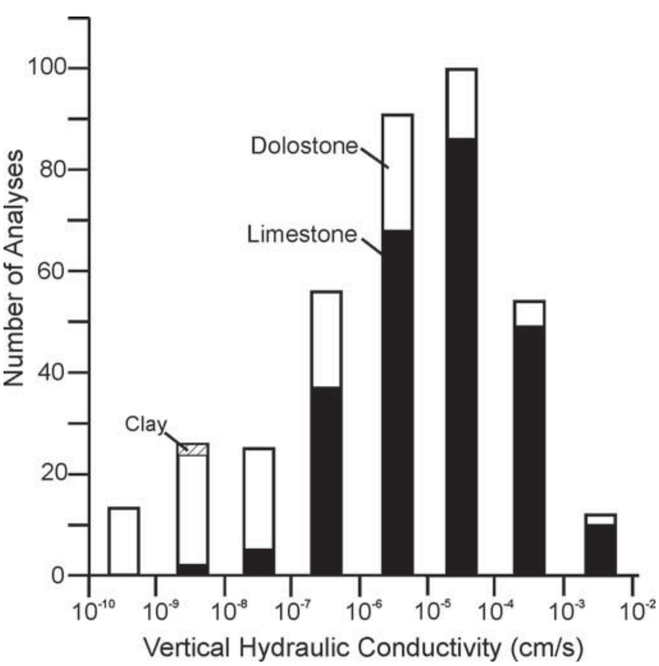


**Fig. 3** Histogram of core-plug vertical-hydraulic conductivity data from the confining zone strata of 29 South Florida injection well systems. Dolostones tend to have lower hydraulic conductivities than limestones

monitoring data. Detection of increased nutrient concentrations and a decrease in salinity in a monitoring zone are evidence that the injected water has migrated upwards at least as far as the bottom of the monitoring zone. Dating of the first detection of wastewater in a monitoring zone is not exact because of variation in the monitoring data. Statistically significant changes in multiple parameters are necessary for a conclusive determination of wastewater presence in a monitoring zone.

More accurate data on the extent of upwards migration of injected fluids can be obtained during the drilling of a second injection well at an operational injection well facility. Water-quality data obtained from packer tests and the discharge from reverse-air rotary drilling, and geophysical log data may provide evidence for down-hole changes in water quality that are indicative of the top of the strata containing injected fluids (Maliva and Walker 1998, 2000).

The injection-well systems at the Collier County South County Water Reclamation Facility (SCWRF) and the Palm Beach County Southern Region Wastewater Treatment Plant (SRWWTP) are two end members as far as vertical migration history in South Florida. Data collected during the drilling of a second injection well (IW-2) at the Collier County SCWRF, approximately 85 m from the first well (IW-1), indicate that virtually no upward migration of wastewater had occurred after approximately 7 years of operation of injection well IW-1 (CDM 2004a). The dual induction logs for the strata above the injection zone in IW-1, run before the start of injection, and in IW-2, run after 7 years of on-site injection, are very similar and show no evidence for an increase in resistivity that would be expected if fresh wastewater had displaced saline native groundwater (CDM 2004a).

Very rapid vertical fluid migration occurred at the Palm Beach County SRWWTP. Injection wells IW-1 and IW-2 were completed in December 1990 and placed into service in 1991. The seat depths of the final (injection) casing string in wells IW-1 and IW-2 are 810.8 and 806.2 m bls, respectively. Wastewater was detected in the deep monitoring zone (579.1–604.7 m bls) in the middle of 1993. The vertical migration rate was thus approximately 200 m in 2.5 years (80 m/year). Wastewater has not been detected in monitoring zones located from 452.6 to 458.7 m bls and 304.8 to 334.1 m bls.

A sonic log of the confining zone strata between the base of the injection casing and the top of the deep monitoring zone indicates that the majority of the strata are fractured dolostone, as indicated by very long sonic transit times (Fig. 4) and enlarged boreholes (Haberfeld 1991; Maliva and Walker 1998). The remaining, apparently unfractured strata, consist of soft, porous limestone. Unfractured dolostones with low porosities and hydraulic conductivities, as indicated by short (≤170 μsec/m) transit times, are present within the injection zone (Fig. 4) and between the top of deep monitor zone and base of the USDW (Fig. 2).

In Broward and Palm Beach counties, an interval of tight and apparently unfractured dolostones, referred to as “main confining zone,” provides the primary confinement


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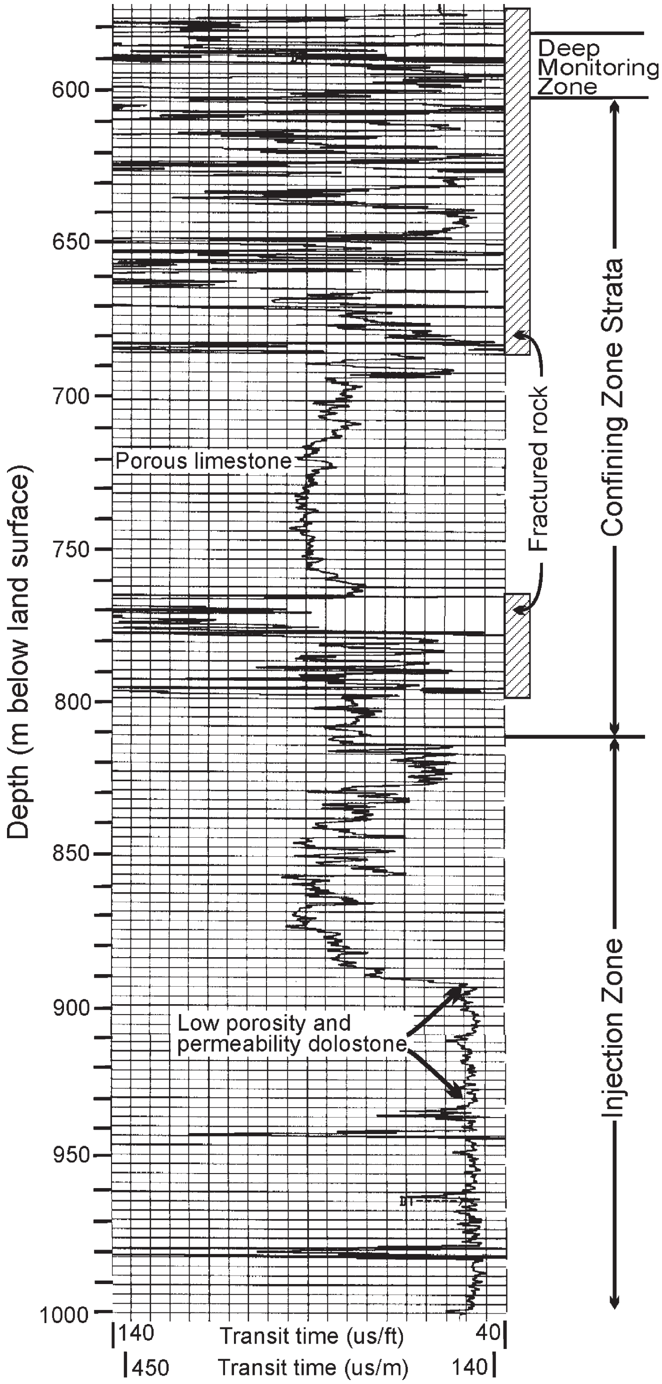


**Fig. 4** Sonic log from the Palm Beach County SRWWTP injection well system (IW-1), which experienced rapid vertical migration of injected wastewater into a deep monitoring zone. Fractured strata are characterized by very long transit times. Strata with low hydraulic conductivities, as indicated by short transit times, are not present between the injection zone and lower monitoring zone

below the base of the USDW (Fig. 2). At the Palm Beach County SRWWTP and six other injection well sites, wastewater has been detected in monitoring zones open below or within the main confining zone, but not in monitoring zones open immediately above the main confining zone.

## Solute-transport modeling

Solute-transport modeling was performed to simulate the behavior of wastewater injected into the boulder zone in South Florida. A simplified model of the boulder zone and overlying confining strata in South Florida was created to simulate the general behavior of injected wastewater. The main objectives of the modeling were to evaluate (1) potential vertical migration rates through strata having vertical hydraulic conductivities similar to values measured in core samples, (2) the vertical hydraulic conductivity that would be required for documented rapid vertical migration rates such as at the Palm Beach County SRWWTP, (3) the potential effectiveness of tight dolostones of the main-confining zone to provide vertical confinement, and (4) the potential effects of vertical high transmissivity flow zones. The SEAWAT (Guo and Langevin 2002; Langevin and Guo 2006) program for the simulation of flow with variable density was used in this investigation. SEAWAT couples two commonly used programs, MODFLOW (McDonald and Harbaugh 1988) and MT3DMS (Zheng and Wang 1998).

The baseline model used for the simulations is summarized in Table 1. The grid cells were 50×50 m in horizontal dimensions. The densities of the injected and formation fluids were calculated from salinity values using a uniform temperature of 20°C. The model had no initial vertical or horizontal hydraulic gradients. Horizontal boundaries were constant head cells and the vertical boundaries were no flow. In all simulations, a constant injection rate of 18,932 $m^3$/day (5 million gal/day) was used, which simulates a small to moderate-sized municipal wastewater treatment plant. Inasmuch as downhole injection pressures are typically very low, the simulation results are not dependent upon injection rates, so long as the injection zone is locally filled with wastewater to allow for the maximum buoyancy-driven migration. The injection zone and confining zone strata are modeled as containing seawater, with the exception of the upper 45 m of the confining unit, which is modeled as containing water with a TDS concentration of 10,000 mg/L. The wastewater was conservatively assigned a low TDS concentration of 200 mg/L. Taking advantage of the symmetry of the problem, only one quadrant of the aquifer was modeled and the injection rate was reduced to 25% of the assumed value of 18,932 $m^3$/day.

## Migration rates using measured core hydraulic conductivities

Core plug data provide information on the vertical hydraulic conductivity of the matrix of the limestones and dolostones that constitute the confining strata between the injection zone (boulder zone) and the base of the lowest USDW. Simulations using a vertical hydraulic conductivity of $1\times10^{-7}$ cm/s indicate minimal vertical migration after 10 years (Fig. 5a) and 25 years. Similar

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**Table 1** Baseline solute-transport model summary

| Layer(s) | Layer thickness (m) | Cumulative thickness (m) | Vertical hydraulic conductivity ($K_z$, cm/s) | $K_{x,y}/K_z$ | TDS (mg/L) |
|---|---|---|---|---|---|
| 1 | 15 | 15 | 0.012 | 10 | 10,000 |
| 2–4 | 15 | 60 | $1\times10^{-7}$ | 10 | 10,000 |
| 5 | 15 | 75 | $1\times10^{-7}$ | 10 | 35,000 |
| 6–11 | 5 | 105 | $1\times10^{-7}$ | 10 | 35,000 |
| 13–25 | 15 | 315 | $1\times10^{-7}$ | 10 | 35,000 |
| 26 | 42 | 357 | 0.023 | 10 | 35,000 |

Effective porosity is 20%; storage coefficient is $1\times10^{-4}$; longitudinal dispersivity is 30 m; transverse dispersivity is 1 m; vertical dispersivity is 1 m

vertical migration rates were obtained using a vertical hydraulic conductivity of $1\times10^{-6}$ cm/s.

## Calibration against measured migration rates

Wastewater at the Palm Beach County SRWWTP migrated approximately 200 m in 2.5 years. Modeling results indicate that the average vertical hydraulic conductivity would need to be approximately $1\times10^{-3}$ cm/s to obtain the documented SRWWTP migration rate (Fig. 5b). The vertical hydraulic conductivity obtained by calibration against measured migration rates is approximately four orders of magnitude greater than core-plug data.

## Effects of the main confining zone

Core analyses of the low porosity (<15%) dolostones from the main confining zone in the Palm Beach County Southern Region Operations Center (SROC) gave vertical hydraulic conductivities of less than or equal to $1.7\times10^{-8}$ cm/s (CDM 2004b). The lowest recorded value was $2.7\times10^{-9}$ cm/s. A simulation was performed with an 30-m-thick confining zone present above the strata with enhanced vertical hydraulic conductivity ($1\times10^{-3}$ cm/s). The simulation evaluates the hydrogeologic conditions at the Palm Beach County SRWWTP and SROC sites, where the main confining zone separates the wastewater-invaded strata from the base of the USDW. The main confining zone strata were assigned a vertical hydraulic conductivity of $1\times10^{-8}$ cm/s. The simulation results show that the wastewater did not penetrate the main confining zone strata during the 10-year (Fig. 5c) and 25-year simulation periods.

## Effects of a vertical high-transmissivity flow zone

The initial simulations with enhanced vertical hydraulic conductivities assumed that the higher values were present throughout the confining zone. An alternative scenario is that strata with greater hydraulic conductivities have a limited horizontal extent and thus acts as a "chimney" for vertical wastewater migration. A vertical flow zone was simulated as 1-grid cell in horizontal dimensions, located 100 m from the injection well, and that extends upwards from the top of the injection zone to the base of the main confining zone. The remaining cells in the confining zone were all given a vertical hydraulic conductivity of $1\times10^{-7}$ cm/s. The flow zone cells were assigned a vertical hydraulic conductivity of $1\times10^{-3}$ cm/s. After 10 years, there was limited vertical movement because of the low hydraulic conductivity of the strata surrounding the flow zone; a chimney cannot be an effective flow zone if its sides and top are essentially sealed.

A second simulation was performed in which a high-transmissivity zone was simulated below the base of the main confining zone, which actually occurs in some of the studied southeastern Florida injection wells (Fig. 2). The simulated transmissive zone had a thickness of 15 m and a horizontal hydraulic conductivity of $1\times10^{-2}$ cm/s. The transmissive zone allowed for a much greater amount of vertical migration. The simulations show wastewater traveling upwards and then horizontally outwards below the base of the overlying confining unit (Fig. 5d). Large parts of the confining zone strata are bypassed by the injected wastewater and still contain saline native formation water. In the 10-year simulation duration, the wastewater did not penetrate through the confining unit.

## Discussion

Injected wastewater in South Florida will slowly migrate upwards because of the density, and thus buoyancy, differentials between the wastewater and the saline formation waters of the injection zone and overlying confining strata. Solute-transport simulations indicate that the matrix hydraulic conductivities of the limestones and dolostones that constitute the confining strata between the injection zone and base of the USDW in South Florida are sufficiently low to retard significant vertical fluid movement.

The rapid vertical migration that has occurred in some injection-well systems requires that the equivalent vertical hydraulic conductivity of strata above the injection zone be roughly four orders of magnitude greater than the values indicated by the core plug data. The enhanced vertical hydraulic conductivity appears to be due to fracturing, which is evident in the geophysical logs of wells that experienced rapid vertical fluid migration. From a modeling perspective, the fracturing increased the bulk vertical hydraulic conductivity of the equivalent porous media.

The fracture zones may have a limited horizontal extent, creating chimneys that were conduits for vertical fluid

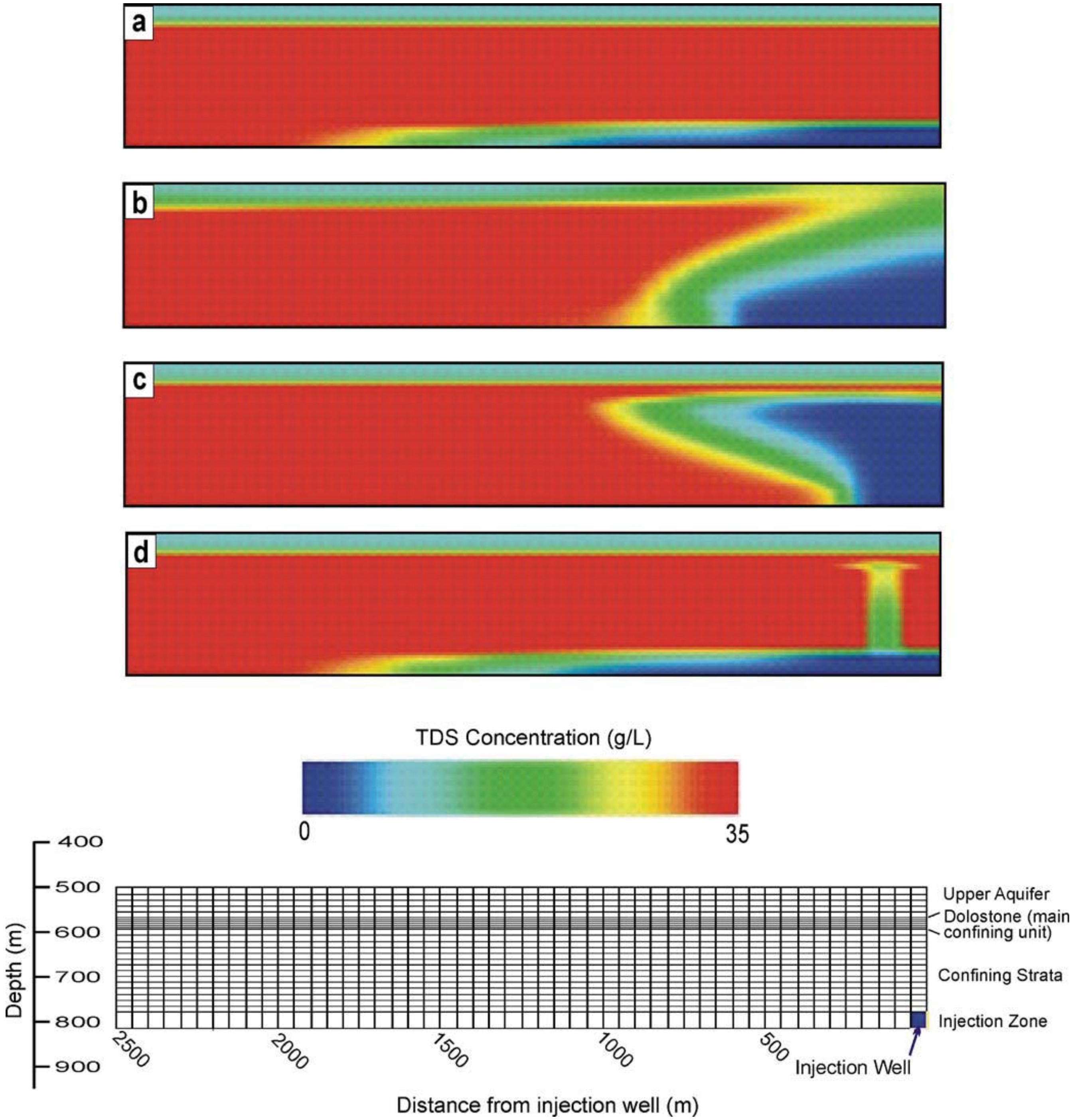


**Fig. 5** Total dissolved solids concentration profiles for solute-transport modeling simulations. Profiles are for 10years of injection. A cross-sectional diagram of the model grid and total dissolved solids (TDS) concentration scale are provided at the *bottom* of the figure. **a** Minimal vertical migration occurred where the confining zone was assigned a vertical hydraulic conductivity of $1\times10^{-7}$cm/s, typical of measured core plug values. **b** Vertical hydraulic conductivity was increased to $1\times10^{-3}$cm/s, which resulted in modeled vertical migration rate that approximately matched the rate observed in some southeastern Florida injection wells (e.g., Palm Beach County SRWWTP). **c** A 9.1-m-thick confining zone with a vertical hydraulic conductivity of $1\times10^{-8}$cm/s was added to the top of the confining zone to simulate the dolomitic main confining zone present in southeastern Florida. The simulation shows the injected fluid reaching the base of, but not penetrating through, the main confining zone, and then spreading out laterally. **d** Simulation of a high vertical hydraulic conductivity ($1\times10^{-3}$cm/s) "chimney" that terminates in a conductive layer below the main confining zone. Injected water migrate upwards and outwards beneath the main confining zone

migration. In southern Palm Beach County and northern Broward County, wastewater has reached the deep monitoring zone of some injection well systems, but has not reached the base of the USDW. Monitoring data and modeling results indicate that unfractured dolostones with low hydraulic conductivities (main confining zone) can locally provide sufficient effective confinement to prevent wastewater from reaching the deepest USDW, irrespective of fracturing of


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underlying rock. The focus of confinement analyses should, therefore, be on the extent and distribution of fracturing rather than analyses of the properties of the rock matrix.

The distribution and cause of the development of fractures, and possibly other flow conduits, in the Floridan Aquifer System, is important for understanding vertical fluid migration. South Florida has traditionally been considered to be a tectonically quiescent environment. However, seismic reflection profiles and stratigraphic data indicate that folding of likely tectonic origin is widespread in the subsurface of Florida (Missimer and Maliva 2004; Maliva et al. 2006). The main deformation event occurred in the Late Miocene to Early Pliocene, and may be related to coeval tectonism in the Caribbean. The structural deformation may be responsible for fracturing in the Floridan Aquifer System.

Another suspected explanation for upwards migration at some sites is well construction problems. If the reamed hole for a casing string diverged from the pilot hole, then the pilot hole may become a conduit for vertical fluid migration. However, well construction problems as a cause for vertical fluid migration have not yet been conclusively confirmed at any injection well site.

A critical question concerning vertical fluid migration is to what extent are microorganisms and compounds in wastewater that are an identified or possible threat to human health attenuated between the time of injection and entry into potential pathways for human exposure. The degree of attenuation will depend upon time and travel distance as well as the survivability and stability of the microorganisms and compounds in the groundwater environment. The size of the microorganisms compared to pore-aperture size will determine the extent to which different groups of microorganisms are filtered out in the aquifer.

In injection well systems with minimal fracture development above the injection zone such as the Collier County SCWRF, projection of historic migration rates suggests that municipal wastewater will not reach the base of the USDW for centuries, if at all. At sites where fracturing is well developed such as the Palm Beach County SRWWTP, wastewater has vertically migrated substantial distances in a very short time (approximately 200 m in 2.5 years).

Pathogenic surface water and wastewater microorganisms undergo inactivation in groundwater systems. Microbial inactivation is usually expressed in terms of $\log_{10}$ declines per day. Published studies of microbial survival in groundwater indicate mean viral and bacterial inactivation rates of 0.02–0.2 $\log_{10}$ $\text{day}^{-1}$ (John and Rose 2005). In bench-scale experimental studies that simulated storage of surface water in ASR systems in Florida, *Giardia lamblia* had the slowest first-order inactivation rates of 0.0042–0.081 $\log_{10}$ $\text{day}^{-1}$ (John et al. 2004). Decay rates of microorganisms associated with wastewater are greatest in the presence of indigenous groundwater microorganisms (Gordon et al. 2002; Toze and Hanna 2002). The available data suggest that pathogenic microorganisms in injected wastewater will not be detectable after 2–3 years in a Florida groundwater environment. Thus, even where vertical migration was rapid such as at the Palm Beach County SRWWTP, there was still adequate time for the inactivation of harmful microorganisms.

The attenuation rates of emerging pollutants such as endocrine disrupting compounds (EDCs) and pharmaceuticals and personal care products (PPCPs), is variable between compounds. Some compounds rapidly biodegrade or adsorb onto aquifer rock and organic matter, while others are much more resistant to biodegradation in soil and groundwater environments (e.g., Khan and Rorije 2002; Drewes et al. 2003; Heberer et al. 2004; Snyder et al. 2004; Ying et al. 2004). The concentration of refractory compounds in migrating injected wastewater will still be reduced by dilution and dispersion. The major human and environmental health concern with EDCs and PPCPs is serious impacts from long-term chronic exposure. Risk assessments of underground injection assume that withdrawals would stop, and thus human exposure quickly terminated, if wastewater were detected in part of an aquifer used for public water supply (Bloetscher et al. 2005). Nevertheless, there would still be economic impacts in the local loss of use of the resource.

## Conclusions

The principal risk element of class I injection wells in South Florida is vertical migration of injected wastewater containing pathogens and contaminants into a brackish-water zone of the Floridan Aquifer System that is being used for a public water-supply project such as an aquifer storage and recovery (ASR) system. Solute-transport modeling results demonstrate that the rapid vertical migration that has occurred in some injection well systems require that the equivalent vertical hydraulic conductivity of strata above the injection zone be roughly four orders of magnitude greater than the values indicated by the core plug data. The increase in vertical hydraulic conductivity is likely due to fracturing. Where fracturing is not significantly developed, low porosity dolostones and limestones provide effective vertical confinement of injected fluids and very long transit times, which are favorable for the natural attenuation of wastewater constituents of public health concern. Confinement analyses should, therefore, focus on characterizing the distribution and properties of fracture systems, which may have been caused by regional tectonism.

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