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Pathogen and chemical transport in the karst limestone of the Biscayne aquifer: 1. Revised conceptualization of groundwater flow

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[1] The Biscayne aquifer is a highly transmissive karst limestone that serves as the sole source of drinking water to over two million residents in south Florida. The aquifer is characterized by eogenetic karst, where the most transmissive void space can be an interconnected, touching-vug, biogenically influenced porosity of biogenic origin. Public supply wells in the aquifer are in close proximity to lakes established by surface mining. The mining of the limestone has occurred to the same depths as the production wells, which has raised concerns about pathogen and chemical transport from these surface water bodies. Hydraulic and forced gradient tracer tests were conducted to augment geologic and geophysical studies and to develop a hydrogeologic conceptual model of groundwater flow and chemical transport in the Biscayne aquifer. Geologic and geophysical data indicate multiple, areally extensive subhorizontal preferential flow zones of vuggy limestone separated by rock with a matrix pore system. The hydraulic response from an aquifer test suggests that the Biscayne aquifer behaves as a dual-porosity medium; however, the results of the tracer test showed rapid transport similar to other types of karst. The tracer test and concurrent temperature logging revealed that only one of the touching-vug flow zones dominates transport near the production wells. On the basis of the rising limb of the breakthrough curve, the dispersivity is estimated to be less than 3% of the tracer travel distance, which suggests that the fastest flow paths in the formation are likely to yield limited dilution of chemical constituents.

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1. Introduction

[2] In 2000, more than 226 m^3/s of groundwater were withdrawn from carbonate aquifers for domestic use in the United States [*Maupin and Barber*, 2005]. Consequently, there is great interest in understanding the physical and biogeochemical processes affecting groundwater quality in carbonate aquifers, particularly in carbonate formations that have undergone karstification. Karst aquifers are typically viewed as excellent municipal sources of groundwater because they contain highly permeable solution-enlarged pore space from which to extract water. Problems of contamination and waterborne pathogens associated with domestic water supplies withdrawn from karst aquifers have been well documented [*Aley*, 1984], some of which have resulted in disease epidemics [*Pokrajčić*, 1976; *Worthington et al.*, 2002]. Source water protection in karst aquifers, however, is difficult to achieve because of the potential for rapid movement of solutes in solution-enlarged zones and limited attenuation of pollutants.

[3] Simulation of groundwater flow, coupled with advective particle transport has become a standard quantitative method to define regulatory wellhead protection. The placement of wellhead protection boundaries based on groundwater flow simulations, however, rarely incorporates the complex aquifer heterogeneity associated with karst aquifers. Numerical simulations of groundwater flow in karst aquifers conducted at a scale suitable for defining the capture area of a production well will usually employ bulk hydraulic properties of the formation (e.g., S. Painter et al., Edwards aquifer parameter estimation project final report, 2002, Southwest Research Institute, available at http://www.edwardsaquifer.org/pages/research_optimization.htm). Bulk hydraulic properties are appropriate in defining a general water budget over the modeled area to reproduce measured sources and sinks of groundwater and hydraulic gradients, but they cannot accurately identify the local resolution for estimating flow direction, flow rate, or a point source of contamination [*Worthington et al.*, 2002; *Scanlon et al.*, 2003].

[4] This paper and two companion articles [*Shapiro et al.*, 2008; *Harvey et al.*, 2008] discuss the potential for the transport of dissolved chemical constituents and waterborne

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pathogens in the karst limestone of the Biscayne aquifer in south Florida. The purpose of this investigation is to demonstrate the inherent complexity of characterizing chemical and pathogen transport in karst aquifers. Water resources management in karst aquifers cannot be undertaken using simplified conceptual models of groundwater flow regimes based on estimates of bulk hydraulic properties. Characterization of karst aquifers requires the integration of data and interpretations from various hydrogeologic disciplines, including geologic mapping, geophysics, geochemistry, and hydrologic testing, including well-designed in situ tracer experiments conducted over the physical dimensions of interest [*Quinlan and Ewers*, 1985; *Field and Pinsky*, 2000].

[5] This investigation focuses on the characteristics of the karst limestone of the Biscayne aquifer in the vicinity of the Miami-Dade Northwest well field (NWWF) (Figure 1). The NWWF is a real-world example of the need to develop a comprehensive understanding of groundwater flow, chemical migration, and the potential for pathogen transport in a karst aquifer. The Biscayne aquifer is a designated sole source of potable water for 2.4 million citizens of south Florida [*Parker*, 1951; *Parker et al.*, 1955; *Federal Register*, 1979; U.S. Census Bureau, State and county quick facts. Data derived from 2000 population estimates, 2005, available at http://quickfacts.census.gov/qfd/states/12/12086.html]. The NWWF is Florida's largest municipal well field, with withdrawals averaging approximately 242,000 m^3/d in 2003.

[6] The NWWF is located in the 230 km^2 Lake Belt area in south Florida. The Lake Belt area buffers high-density urban areas located to the east and freshwater wetlands of the Everglades and conservation areas to the west. The Lake Belt area is also the location of surface mining operations, where limestone of the Biscayne aquifer is mined to the same depth as the production zone in municipal supply wells of the NWWF. Extractive mining operations have transformed wetland areas in the vicinity of the NWWF into a patchwork of borrow pit lakes. By 2003, the cumulative surface area of borrow pit lakes totaled nearly 29 km^2 in the vicinity of the NWWF (Figure 2). Concerns over the potential for pathogens, such as *Cryptosporidium parvum* öocysts, to migrate from the surface water lakes through solution-enlarged, well-connected vuggy porosity in the Biscayne aquifer to the production wells was the motivation for this investigation. At the time of this writing, the regulatory protection boundaries of the NWWF are being reassessed to determine if proposed expansion of mining activities within the county's wellhead protection area may increase the risk of pathogen contamination in water supply wells. Current treatment of water withdrawn from the production wells of the NWWF is not sufficient to remove waterborne pathogens, in particular, *Cryptosporidium parvum* öocysts.

[7] The purpose of this article is to reevaluate the existing conceptual understanding of groundwater flow paths in the Biscayne aquifer. The Biscayne aquifer is not typical of other highly permeable karst settings, such as the Edwards aquifer, the Madison limestone, and the Paleozoic carbonate rocks of the Appalachians that are characterized by large conduits. Instead, the void space of the Biscayne aquifer appears to be dominated by pervasive small-scale dissolutional, lithostratigraphically concentrated features. Previous investigations have interpreted and modeled groundwater flow and chemical transport in the Biscayne aquifer by assuming uniformly permeable aquifer properties [*Merritt*, 1996; *Wilsnack et al.*, 2000], which in combination with the cumulative void space of the limestone that can greatly exceed 40%, yields long residence times that are inconsistent with chemical transport in other karst aquifers [*Camp, Dresser, and McKee, Inc.*, 1985]. This conceptual model has been used in groundwater flow and particle-tracking models along with assumed die-off rates of *Cryptosporidium parvum* öocysts to estimate time-based reductions in pathogens reaching the production wells of the NWWF [*Walker and Stedinger*, 1999; *CH2MHILL*, 2001]. Previous investigations have also included tracer tests using fluorescent dyes. The dyes were detected in observation wells at approximately 272 m from the injection location, but tracers were never detected in production wells [*Miami-Dade Department of Environmental Resources Management*, 1999, 2000; *Guha et al.*, 2003]. Transport velocities from these tracer tests reportedly ranged from approximately 1–30 m/d [*Miami-Dade Department of Environmental Resources Management*, 1999; *Guha et al.*, 2003; *Renken et al.*, 2005]; however, extreme rainfall during one of these tests resulted in poor recovery and dilution of the dye [*Guha et al.*, 2003].

[8] This article summarizes the results of hydraulic, geophysical, and tracer tests conducted in April 2003, which in combination with the improved stratigraphic mapping conducted by *Cunningham et al.* [2004b, 2004c, 2006a, 2006b, 2008] provide a better understanding of the character of the void space, and a hydrogeologic conceptual model of groundwater flow paths and residence times. Companion papers [*Shapiro et al.*, 2008; *Harvey et al.*, 2008] describe the results of a controlled tracer test conducted in February 2004. The results of the 2004 tracer test are used to examine in greater detail the factors affecting potential chemical and pathogen transport in the Biscayne aquifer. *Shapiro et al.* [2008] examine advective-dispersive transport to assess solute retention and diffusion in the karst features of the Biscayne aquifer. *Harvey et al.* [2008] examine the utility of micron-size fluorescent, carboxylated polystyrene microspheres as suitable surrogates for *Cryptosporidium parvum* öocysts under ambient physicochemical conditions, and assess the efficacy of the karst Biscayne aquifer to attenuate pathogen transport.

2. Biscayne Aquifer and the Miami-Dade Northwest Well Field

[9] The Biscayne aquifer in the vicinity of the NWWF is described as a heterogeneous sequence of carbonate and some siliciclastic rock and sediments from land surface to elevations that vary from −55 to −67 m [*Causaras*, 1987; *Labowski*, 1988; *Fish and Stewart*, 1991]. The Biscayne aquifer is divided into the shallow Miami Limestone and the deep Fort Thompson Formation, which is the main production zone associated with wells of the NWWF.

[10] *Fish and Stewart* [1991] compiled the results of aquifer and specific capacity tests conducted in the Biscayne aquifer over Miami-Dade County, with transmissivity values ranging from 0.4 to 3.1 m^2/s. These estimates of transmissivity are at the extreme high end of values reported for geologic materials [e.g., *Freeze and Cherry* [1979],

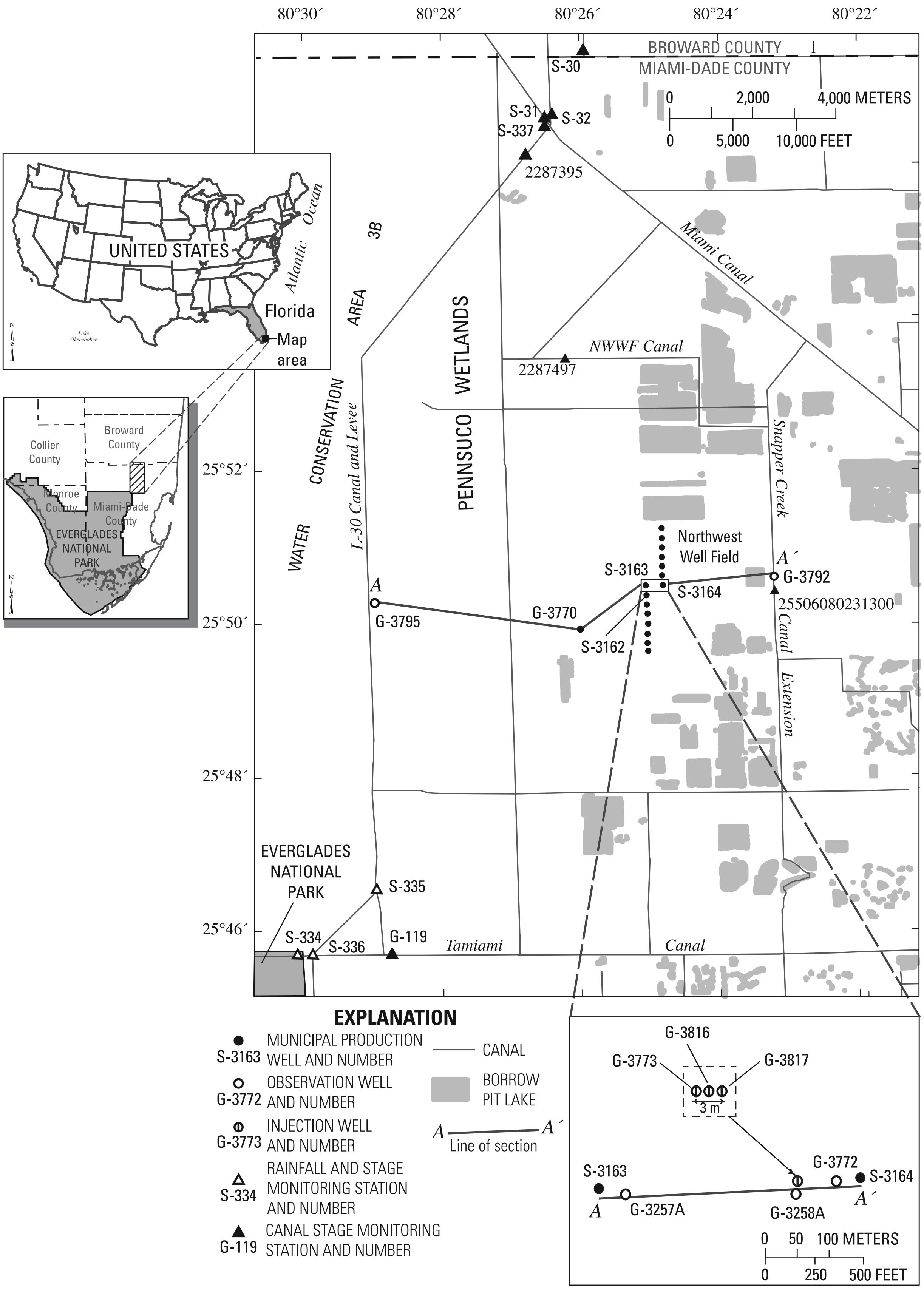

Figure 1. Location of production and observation wells in the vicinity of the NWWF in Miami-Dade County, Florida.

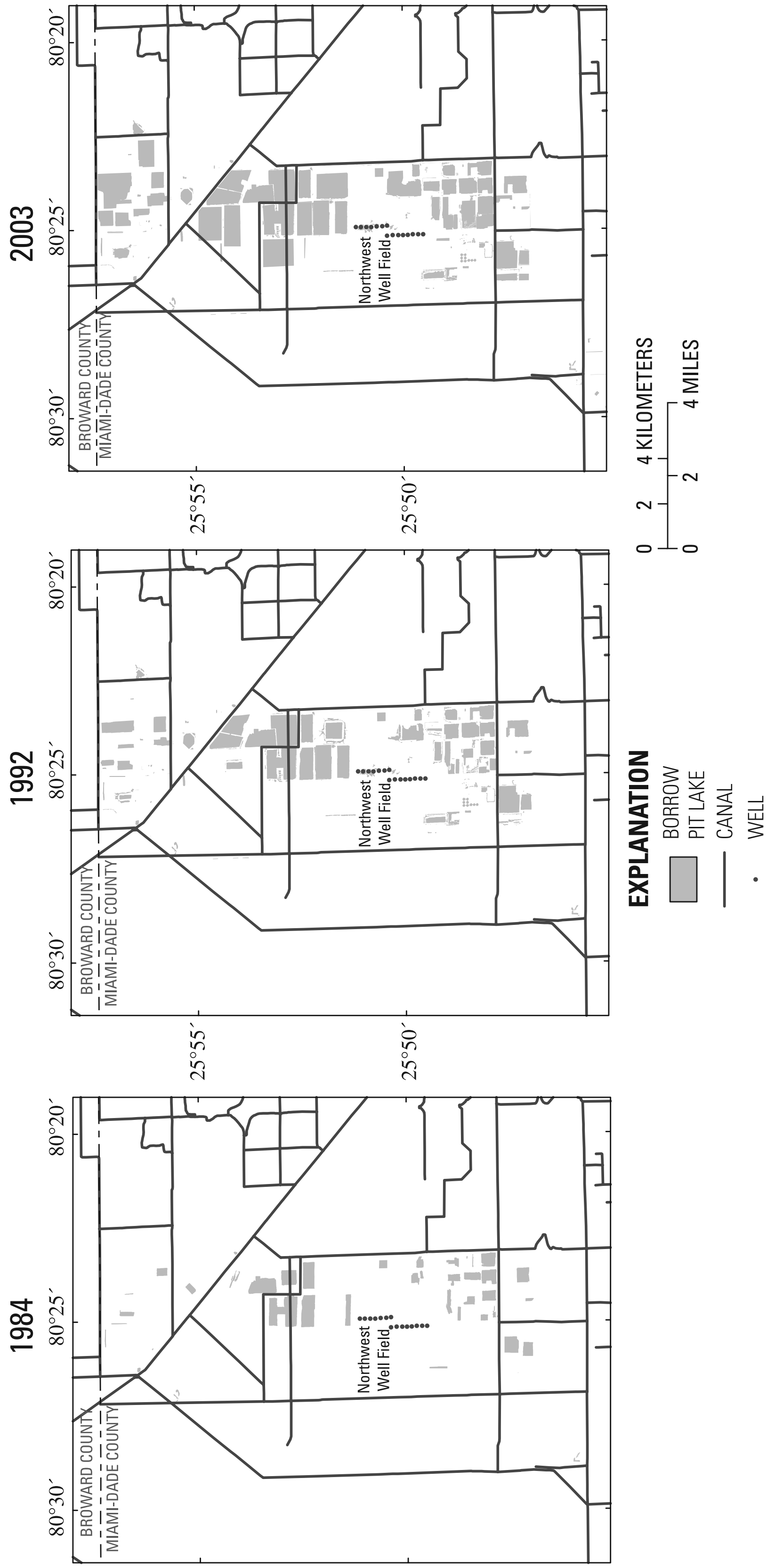

Figure 2. Expansion of borrow pit mines between 1984 and 2003 in the Lake Belt area of Miami-Dade County, Florida.

Figure 3. Photograph showing touching-vug porosity in a Miami limestone rock sample.

indicating the prolific nature of the Biscayne aquifer. Similar values of transmissivity have been reported for the Edwards aquifer near San Antonio, Texas [*Halihan et al.*, 2000; *Mace and Hvorka*, 2000] and the Madison limestone near Rapid City and Spearfish, South Dakota [*Greene*, 1993; *Greene et al.*, 1998]. In the Edwards aquifer and Madison limestone, high transmissivity is attributed to a few large-diameter, interconnected conduits that have developed from geochemical alteration of the rock along flow paths. Also, in the Floridan aquifer, an apparent scaling effect is exhibited in estimates of transmissivity, where the highest reported transmissivities are generally associated with large-scale tests that include the effects of conduit flow systems [*Martin et al.*, 2006]. The nature and distribution of the pore structure in the Biscayne aquifer, however, differs dramatically from conduit-controlled flow (solution-enlarged fractures and bedding planes) in other karst settings.

[11] *Cunningham et al.* [2006a, 2006b] investigated the pore structure of the Biscayne aquifer in the area surrounding the NWWF. The mostly Pleistocene-age Biscayne aquifer is described as a geologically young karst of an eogenetic carbonate pore system. The term, eogenetic karst, is applied to the land surface and the pore system of young limestone (generally not older than Quaternary age) undergoing shallow, early burial diagenesis [*Vacher and Mylroie*, 2002]. *Cunningham et al.* [2004a, 2004b, 2004c, 2006a, 2006b, 2008] described the Biscayne aquifer in a cyclic depositional context to define the effects of relative sea level change and sedimentary processes that produce observed stratigraphic cycles. This work builds on the concept of five Quaternary marine units proposed by *Perkins* [1977] for the Miami Limestone and Fort Thompson Formation. The Biscayne aquifer is described as a dual-porosity pore system, consisting of (1) a matrix (interparticle and separate vugs) porosity providing much of the storage and (2) a touching-vug porosity creating stratiform, areally extensive, groundwater flow pathways and less common conduit porosity composed mainly of bedding-plane vugs, semi-vertical solution pipes and cavernous vugs. Vuggy pore space occurs as dissolved particles or is substantially larger than particles and may include fractures, but is not interparticle pore space [*Lucia*, 1983]. The touching-vug flow zones are characterized by dissolution-enhanced burrows, interburrows, and fossil molds forming stratiform zones of high permeability.

[12] In the NWWF, it is hypothesized that most of the groundwater flow is controlled by the areally extensive, stratiform, toughing-vug porosity. An illustration of touching-vug porosity is shown in Figure 3. Conduit porosity was not observed in the nine wells in the NWWF study area, but has been uncommonly observed at other locations in the Biscayne aquifer. An east-west section showing digital optical borehole wall images illustrates the continuity of high-permeability stratiform touching-vug units within the NWWF (Figure 4).

[13] The porosity of the Biscayne aquifer has also been estimated in several previous investigations, including *Fish* [1988], *Merritt* [1996], and *CH2MHILL* [2001], with values varying from 10 to over 50%. *Cunningham et al.* [2004a, 2004b, 2006b] used whole core samples and digital optical borehole wall images to estimate the porosities of the different types of void space in the Biscayne aquifer, and reported values ranging from less than 6 to greater than 50%. The wide range in estimates of porosity makes predictions of residence time uncertain. In addition, none of these estimates of porosity have been based on in situ tracer experiments. Therefore, previous estimates of the porosity in the Biscayne aquifer may not accurately account for the connectivity of void space and the potential for preferential flow through a fraction of the total void space.

[14] Groundwater within the Biscayne aquifer is regarded as being unconfined in the shallow subsurface, but confined at depth [*Prinos et al.*, 2004]. In wells completed in the shallow subsurface, groundwater levels respond quickly to precipitation events, and canal stage changes. Groundwater flow in the vicinity of the NWWF is controlled by the low physiographic relief and canals that surround the well field. The water table at the NWWF occurs near land surface, even with the extensive pumping associated with the production wells. During the dry season in south Florida (December through early May), the depth to water is approximately 0.6–1.2 m below land, whereas during the latter half of the wet season (late May through November), there is usually standing water over the Holocene deposits that cap the Biscayne aquifer. The dominant regional groundwater movement is eastward from wetland areas, with local movement toward the NWWF [*Klein*, 1985a, 1985b; *Labowski*, 1988].

[15] Gated control structures located on canals that surround the NWWF are primarily used to maintain canal stages and groundwater levels, control flow from the wetland areas, increase recharge to the production zone, and limit production well capture of more easily contaminated water underlying nearby urban areas. A comparison of the short-term effects of precipitation, canal stage, and groundwater levels observed during dry season months of 2003 suggests that there is rapid communication between the canal stages and the groundwater levels in the Biscayne aquifer over distances of 3 km or more. During the hydraulic and tracer tests conducted in the NWWF that are described in this article, canal operation did not impact canal stages and groundwater levels in the vicinity of the NWWF.

3. April 2003 Aquifer Test

[16] Aquifer and tracer tests were conducted using production and observation wells in the NWWF in April 2003.

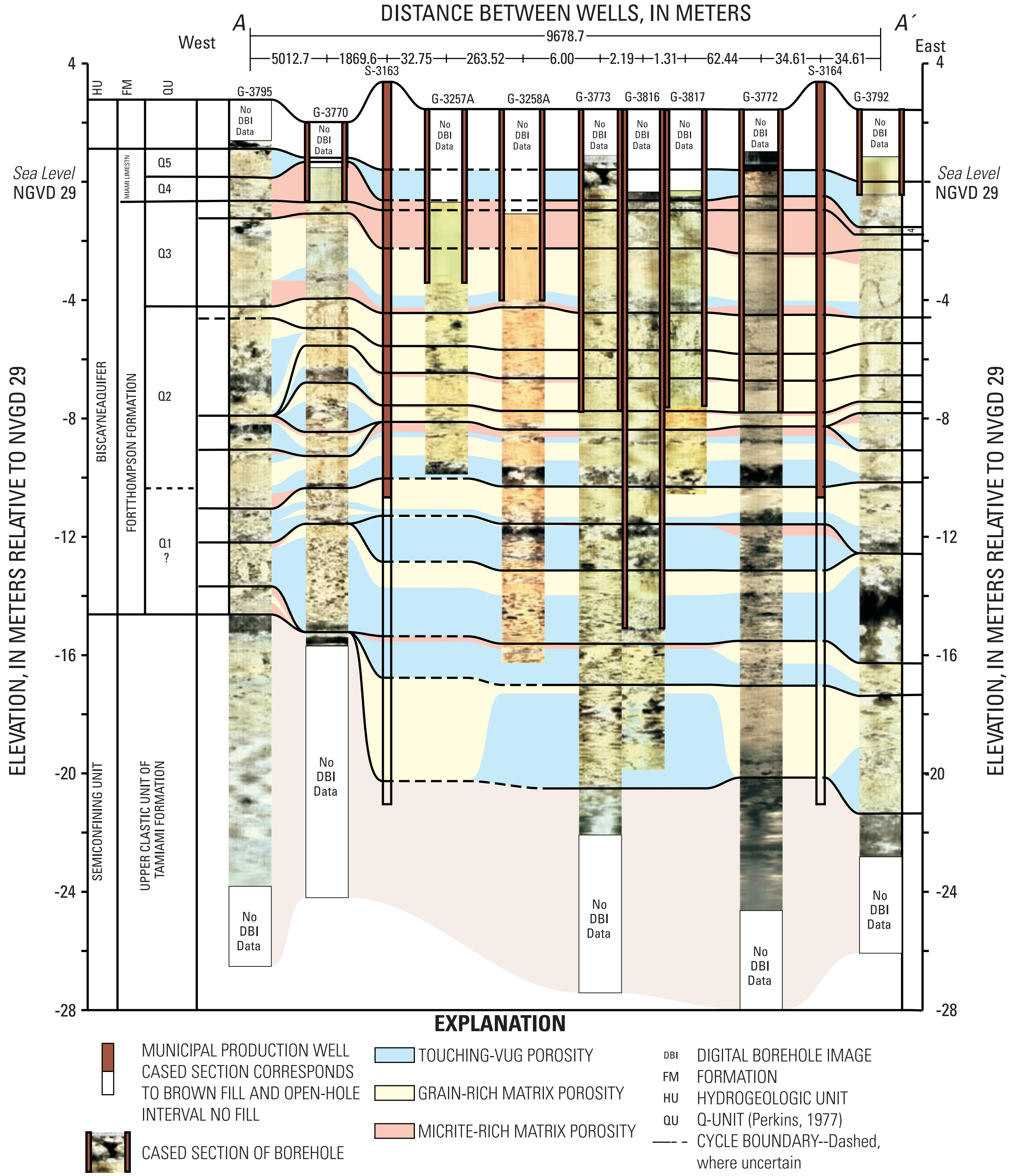

Figure 4. Line of section A-A′ showing principal geologic and carbonate flow units underlying the NWWF (see Figure 1).

Injection of the tracer solution took place on 22 April 2003, and the period preceding tracer injection was used to conduct a controlled hydraulic test and establish a quasi-steady flow regime for the tracer test. The testing was conducted during south Florida's dry season to minimize the confounding effect of extensive precipitation on the test results. Meteorologic stations located between 7.6 and 15 km (km) of the NWWF recorded scattered showers during 16–22 April 2003 with daily precipitation amounts ranging from less than 0.254–3.56 cm (cm). Continuous monitoring of groundwater levels in the NWWF was conducted throughout April 2003 and showed no noticeable effect of precipitation.

[17] Aquifer and tracer tests were conducted in the NWWF using production well S-3164, observation well G-3772 and the tracer injection well, G-3773 (Figure 1). Wells G-3772 and the G-3773 are located regionally up gradient from S-3164, and are approximately 35 and 100 m west of S-3164. Both G-3772 and G-3773 were completed with open-hole intervals extending from an elevation of approximately −7.8 to −17.5 m. Production well S-3164 is completed as an open interval from an elevation of approximately −10.7 to −21.0 m. Borehole flowmeter logs conducted in G-3772, G-3816, and G-3817 indicate a touching-vug flow zone is highly permeable between −9.6 and −10.4 m. Production well S-3164 was not available for flowmeter or borehole image logging; however, it is assumed that the areally continuous features observed in the section shown in Figure 4 also intersect S-3164.

[18] Because the NWWF is a significant contributor to the public water supply in the Miami-Dade area, it was logistically impossible to eliminate groundwater withdrawals from all of the production wells during the aquifer and tracer tests. During the aquifer and tracer tests in April 2003, the production wells closest to S-3164 were not operated. The four southernmost production wells in the NWWF (distances of 793 m or more to the southwest of S-3164) and the three northernmost production wells (distances of 914 m or more north of S-3164) were operated and maintained at constant withdrawal rates.

[19] The controlled aquifer test was conducted by turning off the production well S-3164 on 9 April 2003 and allowing groundwater levels to equilibrate. Well S-3164 was then restarted on 16 April 2003 and maintained at a constant rate for 6 days, 18.5 h prior to initiation of the tracer test. The average pumping rate during the test was 501 L/s, and the pumping rate varied by approximately ±3%. Pressure transducers were used to measure water-level changes during the aquifer test in production and observation wells that ranged from 35 to 2587 m from S-3164.

4. Aquifer Test Results

[20] After approximately 1 day of constant pumping, less than 0.16 m of drawdown was observed in G-3772, located 35 m to the west of the production well, and 0.05 m of drawdown was recorded in S-3162, approximately 465 m to the southwest of the production well (Figure 5). Oscillatory water level responses were recorded in wells G-3772 and G-3773 in the first minute of pumping and are considered indicative of highly transmissive formations [*Shapiro*, 1989]. The magnitude of the oscillatory response diminishes with distance from the pumped well. In wells G-3257A and S-3162, located approximately 368 and 465 m from S-3164, respectively, there were no measured oscillations in the water levels.

[21] After the oscillatory water level responses were damped in wells G-3772 and G-3773, the drawdowns displayed responses characteristic of a dual-porosity aquifer; a period of pumping where there is almost constant drawdown is followed by drawdown that increases with continued pumping. A similar response is seen in the wells that are at greater distances from the production well. The conceptual hydrogeologic model of stratiform beds of touching-vug porosity separated by limestone beds having matrix porosity (interparticle and separate vug) is consistent with the hydraulic responses of a dual-porosity aquifer. Touching-vug flow zones are conceptualized as having high transmissivity that initially supply water to the pumped well. During the period of near constant drawdown, water contained within matrix porosity is released from storage and supplements the water in the touching-vug porosity. A period of increased drawdown follows because water released from the matrix pore space cannot fully replenish water withdrawn from the high-transmissivity, touching-vug pore space.

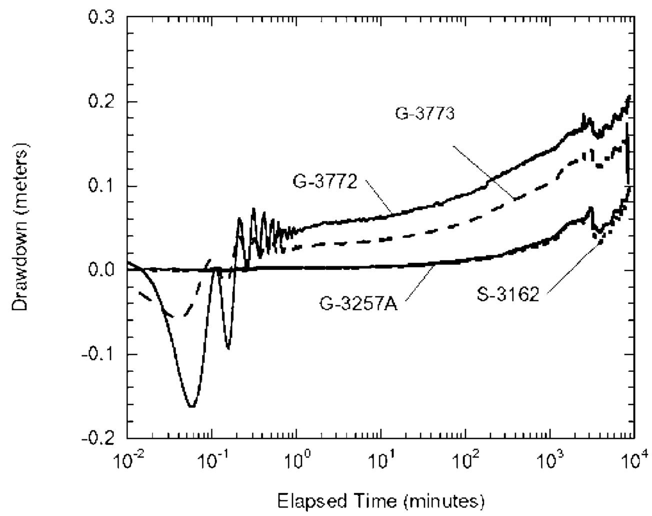

Figure 5. Drawdown versus time for selected wells in the NWWF during aquifer test conducted in April 2003.

[22] A thorough analysis of the drawdown responses from all observation wells measured during the aquifer test is beyond the scope of this article; however, approximate estimates of transmissivity of the cumulative effect of all touching-vug flow zones intersecting the pumped well can be made by evaluating the slope of the drawdown versus the logarithm of time (Figure 5) [*Cooper and Jacob*, 1946]. It is assumed that during late times (>100 min), the aquifer behaves as an isotropic and homogeneous system, under confined conditions because the drawdown is small relative to saturated aquifer thickness. The transmissivity estimated from wells G-3772 and G-3773 is 1.8 m^2/s, whereas the estimated transmissivity at more distant wells, G-3257A and G-3162, is 3.3 m^2/s. These values fall within the range of the transmissivity compiled by *Fish and Stewart* [1991]. A more detailed numerical analysis is needed to assess the presence of spatially heterogeneous and directionally dependent formation properties. In addition, the magnitude of the pumping rate in well S-3164 is likely to have induced turbulent conditions in the production well and the surrounding aquifer. Turbulent conditions result in head losses in the aquifer. The increased drawdown resulting from turbulent head losses at wells near the production well would reduce transmissivity estimates determined under assumptions of laminar flow. This could explain the disparity between the lower transmissivity estimated at monitoring wells near the production well as compared to the transmissivity estimated from distant wells.

[23] Evidence of anisotropy and heterogeneity in the Biscayne aquifer is likely to be concealed by the aquifer's

Table 1a. Chronology of Events During April 2003 Tracer Test[a]

Event	Time
Pump off	9 Apr 2003, 0620:00
Pump on (501 L/s)	16 Apr 2003, 1500:00
Start of tracer test	22 Apr 2003, 0930:00
Temperature increase observed in G-3772	22 Apr 2003, 1252:00
Time of first arrival at S-3164	22 Apr 2003, 1300:00
Time of peak arrival at S-3164	22 Apr 2003, 1600:00
Test termination and end of aquifer test	22 Apr 2003, 2215:00

[a]A rhodamine WT-deuterium mixture used in the initial injection was "chased" with tracer-free formation water.

exceptionally high transmissivity. The measured drawdown responses exhibit rapid outward propagation. In general, larger hydraulic diffusivity yields a faster propagation of the drawdown responses. Also, recharge from surface water boundaries surrounding the well field may further hide effects of anisotropy and heterogeneity by diminishing drawdown at observation wells.

5. April 2003 Tracer Test

[24] The tracer test conducted in April 2003 in the NWWF was designed to test the significance of the highly permeable and areally extensive intervals of touching-vug porosity in the Biscayne aquifer. A convergent tracer test was conducted using Rhodamine WT (RWT) and deuterium (^{2}H) as tracers injected into well G-3773 and recovered in the water discharged from S-3164. RWT is a fluorescent dye used in numerous tracer tests conducted in carbonate formations, including aquifers used for domestic water supply [*Field*, 1999]. Deuterium is a naturally occurring isotope of hydrogen and can be detected at concentrations approximately 0.1 mg/L above background concentrations [*Becker and Coplen*, 2001]. On the basis of previous experiences, both tracers were expected to be nonreactive with the geologic material [*Field*, 1999; *Becker and Shapiro*, 2000; *Becker and Coplen*, 2001].

[25] The tracer solution was prepared with 50 kg (dry) mass of RWT that was premixed in a solution of 227 L, and mixed with 15 kg of a 70% solution (approximately 14 L) of deuterium oxide (2.1 kg ^{2}H). The mass of RWT and ^{2}H used for injection was based on calculations from a model of a pulse injection of a conservative tracer subject to advection and dispersion in a radially converging flow regime [*Moench*, 1989]. Calculations were based on estimates of the porosity that ranged from 5% to more than 40% [e.g., *Cunningham et al.*, 2006b] and the permeable thickness of the Biscayne aquifer was assumed to be the cumulative thickness (10 m) of the touching-vug pore space observed in wells G-3772 and G-3773.

[26] The tracer solution was pumped from land surface through a pipe that extended to an elevation of −8.5 m in well G-3773. The outlet of the down-hole pipe corresponded to the uppermost permeable section in the open interval of well G-3773. A total of 241 L of the tracer solution was injected on 22 April 2003 and was followed by the injection of approximately 6056 L of a tracer-free solution that consisted of water previously pumped from well S-3164 and stored in tanks at land surface. The tracer-free solution was injected through a pipe that extended to the bottom of the well. The volume of the tracer-free solution injected into well G-3773 was approximately 7 times the volume of the fluid column in the borehole. Details of the injection procedure are given in Tables 1a and 1b.

[27] Water samples were collected from a sampling manifold at well S-3164 that diverted water from the 1.22-m-diameter discharge pipe. Water samples for analyses of RWT were stored in 250-mL amber (opaque) plastic bottles to prevent degradation, and water samples for analysis of ^{2}H were collected in 60-mL glass bottles with polyseal caps. A filter fluorometer was used to analyze water samples for the concentration of RWT, and for verification, selected water samples were analyzed using a photospectrofluorometer. The concentrations of ^{2}H in water samples were determined using methods described by *Coplen et al.* [1991].

6. Breakthrough Curves for RWT and ^{2}H

[28] First detection and peak concentration of RWT at production well, S-3164, were recorded at 3.5 and 6.5 h, respectively, after the tracer injection (Figure 6). The peak concentration for RWT was 3.41 mg/L. The rapid breakthrough and the peak concentration exceed the simulated range predicted from the preliminary calculations in designing the tracer test. The peak concentration of RWT was in the range where RWT is visible in solution, and the concentration of RWT did not recede rapidly after the peak concentration was recorded. During the aquifer and tracer tests, the water pumped from S-3164, was routed through the water distribution network of Miami-Dade County. At 22:15 on 22 April 2003 (approximately 12.75 h after the tracer injection), the Miami-Dade Water and Sewer Department and the U.S. Geological Survey decided to terminate pumping at the production well to prevent the discoloration of water supplied to the community.

[29] There was concern that RWT could still reside in the formation in the vicinity of the injection well and migrate to the production well over an extended period of time. After the first detection and rapid rise in the RWT concentration at the pumped well, additional tracer-free water was injected into well G-3773. The tracer-free water used for this injection was obtained from the southernmost NWWF production well, which operated continuously during the tracer test. Approximately 9080 L of tracer-free water was injected at the bottom of tracer injection well, G-3773, between 1330 and 1400, 4 h after the initial injection of the tracer solution (see Tables 1a and 1b). The subsequent injection of tracer-free water resulted in a slight increase in the RWT concentration that is observed in the declining limb of the breakthrough curve (Figure 6). The slight increase in the RWT concentration occurred at an elapsed

Table 1b. Injected Volume, Time, and Duration on 22 April 2003[a]

Injected Volume (L)	Start Time	End Time	Duration (min)
241	0930:00	0933:35	3.75
3217	0935:19	0946:27	11.13
946	0953:00	0959:30	6.50
1893	1019:24	1032:25	3.02
9088	1327:42	1355:45	24.50

[a]A rhodamine WT-deuterium mixture used in the initial injection was "chased" with tracer-free formation water.

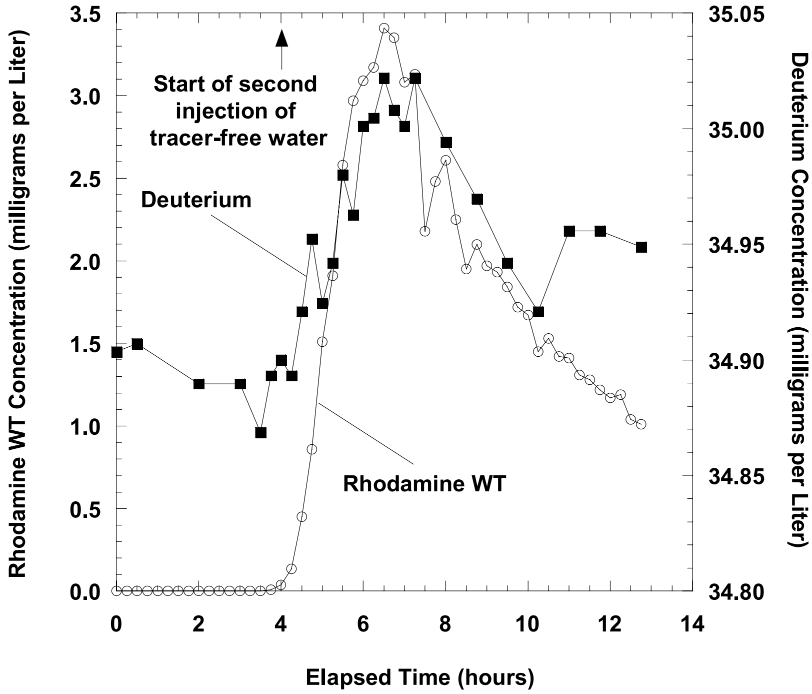

Figure 6. Concentration of RWT and ^{2}H at production well S-3164 versus elapsed time from the start of tracer injection.

time of 7.75 h after the initial tracer injection, and 3.75 h after the second injection of the tracer-free solution, which is consistent with the elapsed time for the first detection of the tracer solution at the production well.

[30] The breakthrough curve for ^{2}H (Figure 6) shows a similar response to the concentration of RWT. Following the injection of the tracer solution, there is a slight decrease in the concentration of ^{2}H followed by a rise in the ^{2}H concentration at the first detection of RWT at the production well. The decrease in the ^{2}H concentration at the onset of the tracer injection is most likely the result of the natural variability of ^{2}H in water drawn from the Biscayne aquifer. The source of recharge to the Biscayne aquifer includes infiltration from precipitation, and surface water seepage from canals and borrow pit lakes in the vicinity of the NWWF, all of which are likely to have different isotopic signatures of ^{2}H. The declining limb of the breakthrough for ^{2}H is also marked by an increase in the ^{2}H concentration starting at an elapsed time of 10.25 h after the tracer injection. This increase in the ^{2}H concentration could be an artifact of the natural variability in the waters of the Biscayne aquifer coupled with the injection of a large volume of tracer-free water (having a different isotopic signature of ^{2}H) 4 h after the initial tracer injection.

[31] The rate of mass arrival per injected mass is shown in Figure 7 for RWT and ^{2}H at S-3164. The rate of mass arrival per injected mass is calculated by multiplying the tracer concentration by the pumping rate and dividing by the injected mass. In this calculation, the concentration of RWT and ^{2}H are first adjusted by removing the background fluorescence for RWT (1.2 μg/L) and background concentration for ^{2}H (34.89 mg/L). The assumed ^{2}H background concentration does not account for natural variability of groundwater in the Biscayne aquifer. In Figure 7, both tracers show similar rates of mass arrival per injected mass and similar shapes for the rising limb of the breakthrough curve, indicating that the tracers behave analogously within the formation. There is a slight difference, however, between the declining limbs of tracer breakthrough curves approximately 9 h after tracer injection. This difference is likely the result of injecting tracer-free water in G-3773 after the first detection of RWT in the production well, S-3164.

[32] The cumulative mass arrival per injected mass for RWT and ^{2}H is also shown in Figure 7. Natural variability of ^{2}H within the Biscayne aquifer could explain the slight discrepancy in the mass recovery between the RWT and ^{2}H. In general, the mass recovery of RWT and ^{2}H compare favorably, with approximately 60% of the mass of each tracer recovered at the termination of the test approximately 12.75 h after the tracer injection.

7. Results From Temperature Logging

[33] Fluid temperature logging was conducted at observation well, G-3772, following the injection of the tracer and flushing solutions in the injection well, G-3773. The logging consisted of measuring the fluid temperature as a function of depth in the open interval of the well at discrete times. The logging was conducted during the tracer injection at 0930 on 22 April 2003 and at elapsed times of 3.37, 5.05, 6.13, and 7.17 h following the tracer injection. Figure 8 shows the caliper (borehole diameter) log, the digital optical borehole image log, and temperature profiles of observation well G-3772 conducted at different times during the tracer test. Well G-3772 is located between the tracer injection well (G-3773) and the production well (S-3164). Darker sections of the digital borehole image correspond to sections of the borehole that are enlarged and are likely permeable limestone strata having touching-vug porosity [*Cunningham et al.*, 2006b]. The intervals at elevations of approximately

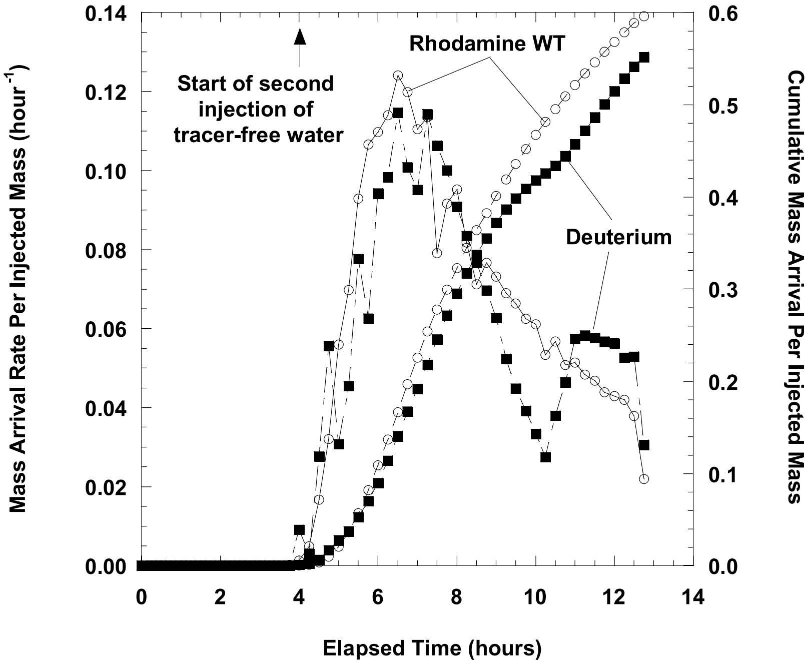

Figure 7. Normalized rate of mass arrival per injected mass and cumulative mass arrival per injected mass for RWT and ^{2}H at production well S-3164 versus elapsed time from the start of the tracer injection.

−9.5 and −10.4 m appear to be the most permeable in the observation well G3772; *Cunningham et al.* [2006b] also identified intervals of touching-vug porosity from −11 m to the bottom of the borehole.

[34] The temperature logging performed at 0930 on 22 April 2003 was conducted before the tracer injection and represents the ambient temperature profile under pumping conditions in S-3164. The temperature profile at 0930 shows a constant temperature from the top of the open interval of the well to an elevation of about −10 m, followed by a sharp increase in the temperature at that elevation. Immediately below the interval of touching-vug porosity at −10 m there is a short interval of constant temperature that extends to the next interval of touching-vug porosity at about −11 m. This is then followed by a monotonic increase in the temperature with depth in the well. The increasing temperature with depth is most likely an artifact of the source of recharge water to the Biscayne aquifer. The sharp increase in temperature at approximately −10 m is most likely the result of warmer water in the formation that is migrating through the highly permeable touching-vug porosity at this elevation.

[35] The fluid temperature log conducted in the observation borehole at 1252 shows an increase of approximately 0.8°C at the interval of touching-vug porosity at −10 m (Figure 9). There is also a slight increase in the temperature (approximately 0.1°C with depth at 1252 as compared to the fluid temperature log at 0930. The sharp increase in temperature in the observation well at approximately −10 m is attributed to the tracer injection and the subsequent flushing of the injection well with tracer-free water. The injection solution and the tracer-free water were stored in tanks at land surface overnight and equilibrated with the ambient air temperature, which was approximately 26°C, whereas the temperature of the groundwater ranged from 22.5 to 23.5°C. The temperature log at 1252 shows that an increase in the temperature at −10 m in the observation well occurred prior to the first detection of RWT in the production well. A continuous temporal history of borehole fluid temperature in the G-3772 observation well was not collected; therefore, the travel time of the thermal pulse associated with the fluid injected into G-3773 cannot be calculated.

[36] The results of Figure 9 imply that the fluid migration from the injection well to production well is primarily along the touching-vug flow zone at approximately −10 m. The constant increase in temperature below this interval is attributed to warmer water migrating through more deeply buried touching-vug flow zones intersected by both the injection and observation wells. Groundwater with an increased temperature at −10 m in G-3772 did not migrate downward implying there is little vertical flow in the open interval of the observation well.

[37] The temperature profile in G-3772 at 1433 is similar in shape to the temperature profile prior to the tracer injection (Figure 8). There is, however, a slight increase in temperature below −10 m in the observation borehole at 1433 in comparison to the temperature log conducted at 0930. The temperature measured at 0930 at −10 m is nearly the same as the temperature measured at 1433. The warmer tracer solution has likely migrated past the observation well in the interval of touching-vug porosity at −10 m, but it is still being transported through the deeper touching-vug flow zones. Thus, it appears that the bedded touching-vug pore system that lies below −10 m has a lower transmissivity compared to the flow zone at −10 m. The formation hydraulic properties described here can produce an elongated breakthrough tail, as the tracer migrated rapidly through the touching-vug flow zone at −10 m and more slowly within the deeper touching-vug flow zones. The production well, S-3164, was constructed using surface casing that extends to an approximate elevation of

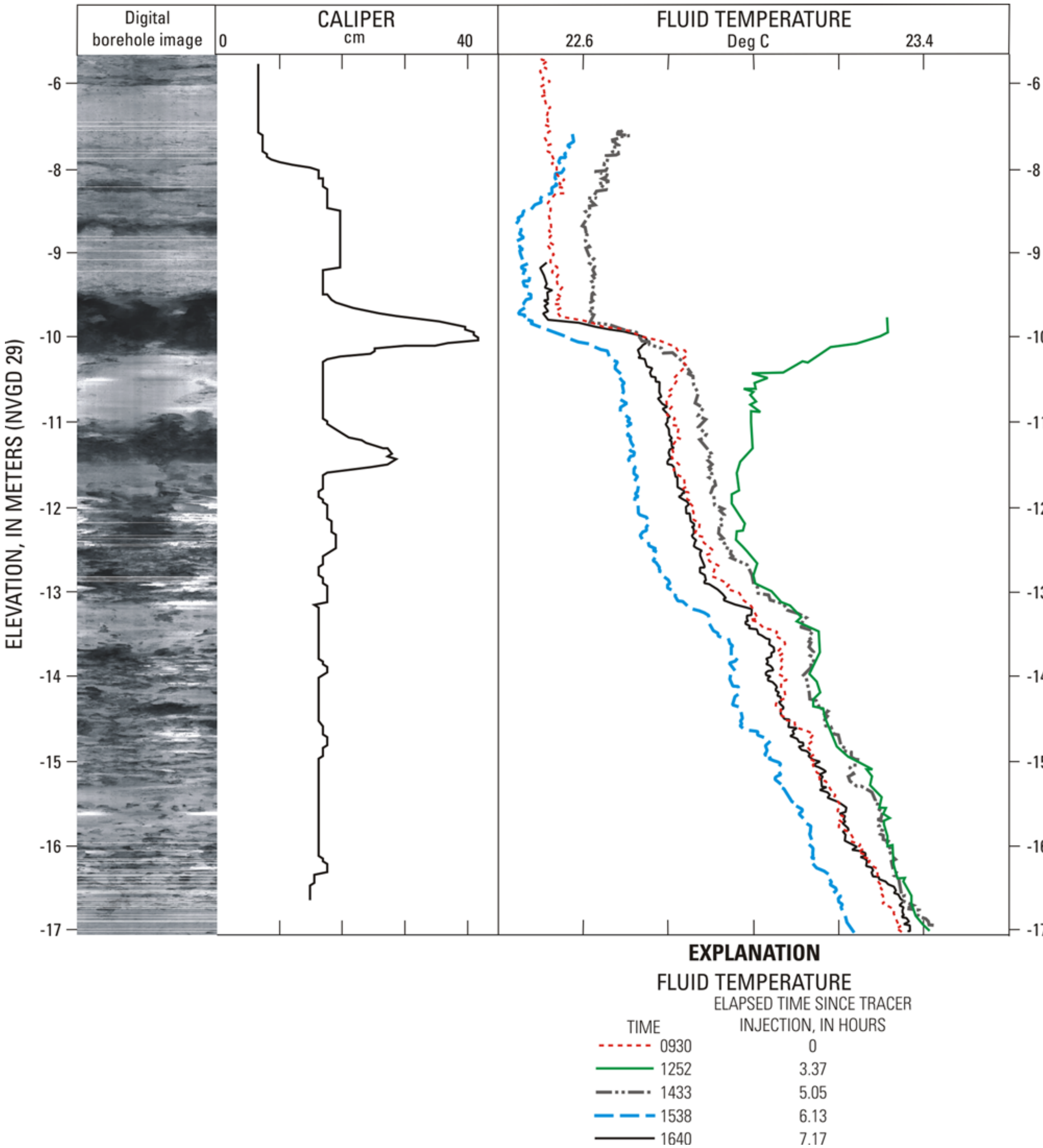

Figure 8. Open and oriented view of borehole wall image from digital optical borehole image (OBI) log, caliper log, and fluid temperature versus depth for discrete times in observation well G-3772.

−10.6 m. Thus, touching-vug flow zones from −10 m to the bottom of the injection well are likely to contribute to the waters withdrawn from the production well.

8. Hydrogeologic Conceptual Model

[38] The outcome of April 2003 aquifer and tracer tests conducted at the NWWF confirms the value of a highly resolved, lithostratigraphic framework and definition of the pore space of the Biscayne aquifer. Earlier tracer tests conducted in the Biscayne aquifer were qualitative in nature, and focused more on establishing travel time connection from point to point. No effort was made to delineate flow zone connectivity. *Cunningham et al.* [2006b] were able to infer patterns of porosity and permeability related to the major carbonate lithofacies by integrating a detailed analysis of core samples with borehole geophysical and optical logs, and cyclostratigraphy. As a result, they were able to provide for a tightly constrained correlation of preferred flow zones mappable over distances of kilometers or more.

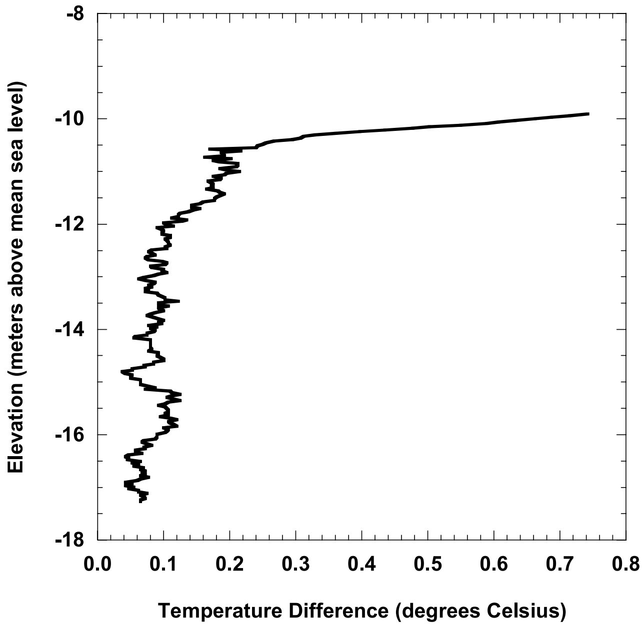

Figure 9. Recorded difference in fluid temperature between 0930 and 1252 in observation well G-3772.

8.1. Geologic Controls on Groundwater Flow

[39] Transmissivity associated with the entire thickness of the lower part of the Biscayne aquifer (Fort Thompson Formation) was estimated to be approximately 3 m^2/s. In addition, the time-varying drawdown response is symptomatic of a dual-porosity system. *Cunningham et al.* [2006b] observed that two principal pore systems could be defined within the Biscayne aquifer rock lithofacies. Groundwater can be transmitted through an interparticle pore network that includes separate vugs (matrix porosity) or through interconnected contact (touching) of vugs with each other. The separate vug and microscopic pore features are embedded within the limestone matrix that supplies water from storage. Touching vugs that form interconnected pore space within the Biscayne aquifer function as the preferred flow zones. Unfortunately, the aquifer test could not distinguish vertical variability in the permeability of the individual zones of touching-vug porosity.

[40] The results of the tracer testing and temperature logging, however, suggest that only one of the touching-vug flow zones observed over the thickness of the Fort Thompson Formation dominated the flow regime, and resulted in the rapid breakthrough of the tracers at the production well. Thus, although there are multiple touching-vug flow zones over the depth of the Biscayne aquifer, a single, areally extensive feature appears to control most of the groundwater flow and chemical transport. The thickness of this zone is estimated from borehole image logs to be approximately 0.9 m.

[41] The tracer test demonstrated continuity of the touching-vug flow zones and their ability to transport dissolved chemical constituents rapidly over a distance of approximately 100 m in the Biscayne aquifer. Lithostratigraphic mapping suggests flow zone continuity within the Biscayne aquifer extends over dimensions that are much larger than the distance between the tracer injection and production wells, likely encompassing the entire well field and adjoining areas [*Cunningham et al.*, 2006a, 2006b]. The results of the aquifer test suggest that these preferred touching-vug flow zones are capable of transporting dissolved chemical constituents over much larger distances than that considered in this investigation. Rapid water-level changes recorded in monitoring wells in response to pumping and changes in canal stage suggest that touching-vug flow zones are not hydraulically constricted over distances of hundreds of meters to kilometers. Although the Biscayne aquifer is an eogenetic karst aquifer undergoing early, shallow-burial diagenesis, the methods and outcome in this investigation are of significance to telogenetic karst aquifers having large conduit and dissolution-enlarged fracture porosity that have formed along bedding planes and fractures.

[42] There are many well-documented examples in the literature of consolidated and recrystallized karst aquifers in which groundwater flow is concentrated within conduits, solution-enlarged fractures and bedding planes [*White*, 2002]. And in recent years, greater attention has been made to document transfer of water between the aquifer matrix and surrounding fractures and conduit flow regimes [*Martin et al.*, 2006]. Void space of the limestone of the Biscayne aquifer is dramatically different from the characteristics of other karst settings. Large diameter conduits systems are not observed in the Biscayne aquifer near the NWWF. Instead, the principal pathways for groundwater flow in this area of the Biscayne aquifer are lithostratigraphically controlled. Flow zones are separated by limestone characterized by matrix porosity containing interparticle pores and separate vugs. In both types of karst settings, zones of enhanced porosity are the primary mechanism of groundwater movement and chemical migration. In addition, individual features can control the majority of groundwater flow and chemical transport. In the Biscayne aquifer, low hydraulic gradients and a low-lying topography conceal evidence for concentrated rather than diffuse groundwater flow, recharge or discharge. In other karst settings, a single solution-enlarged conduit (out of many conduits) may dominate groundwater flow and chemical migration. Preferential flow zones formed by touching-vug porosity can yield transmissivity that is similar in magnitude to that of conduit features observed in other highly permeable karst settings. For example, estimates of the transmissivity from the aquifer test conducted in the Biscayne aquifer are similar in magnitude to the estimates of transmissivity reported for the limestone of the Edwards, Floridan and Madison aquifers. *Palmer* [2002, p. 89] observed that whereas the magnitude of hydraulic conductivity of the Edwards and Floridan are similar, both appear to be 4 orders of magnitude greater than Paleozoic karst aquifers in Virginia, New York, Pennsylvania, and Kentucky. Detailed mapping of enhanced dissolution features combined with a lithostratigraphic understanding of their repetitive nature and areal extent could prove instrumental for developing conceptual hydrogeologic models for groundwater flow and chemical transport. The interpretation of aquifer tests coupled with tracer experiments enhance and clarify these conceptual models.

8.2. Formation Properties

[43] It is difficult to perform a quantitative interpretation of the tracer breakthrough curves at the production well because flushing of the injection well with a tracer-free solution did not force the tracer solution completely into the

formation at the onset of the test. In addition, the tracer injection well was flushed a second time approximately 4 h after the initial tracer injection. Nevertheless, bounds on formation properties can be ascertained from simplified interpretations of the breakthrough curves. Under the assumption of steady state radially converging flow to the production well in the absence of a regional hydraulic gradient, an estimate of the transport porosity can be made from the following expression:

$$Bn = \frac{Q\tau}{\pi R^2} \tag{1}$$

where Q is the pumping rate, B is the formation thickness, n is the transport porosity, and τ is the travel time from the radial distance R to the pumped well [*Javandel et al.*, 1984]. In general, the product of the porosity and the formation thickness cannot be separated, unless independent estimates of one of parameters are available. The product Bn represents the void space of the formation over the thickness of the aquifer under consideration.

[44] In estimating the transport porosity, τ is commonly taken as the mean arrival time of the breakthrough curve. Because the tracer test was terminated prior to the complete recovery of the injected mass, the mean arrival time of the tracer cannot be estimated. An estimate of the porosity, however, can be made using the travel time associated with the peak concentration of the breakthrough curve. Using the mean pumping rate of 501 L/s, the distance between the injection and production wells of 100 m, and 6.5 h as the time of the peak concentration, the quantity Bn is equal to 0.37.

[45] The results from the temperature logging in the observation well during the tracer test strongly suggest that the touching-vug flow zone at −9.5 m is the dominant hydraulic connection between the injection and production wells and is also responsible for the migration of the majority of the tracer mass. The temperature logging also indicates that RWT and ^2H may have also migrated through the intervals of touching-vug porosity at greater depths in the formation, but the arrival of the tracer through these intervals may be delayed relative to the transport through the interval at −9.5 m.

[46] If it is assumed that the majority of the tracer mass and the peak concentration associated with the breakthrough curve is attributed solely to the 0.9 m-thick touching-vug flow zone at the −9.5 m depth, the transport porosity is estimated to be 0.41. This estimate of the porosity is consistent with the range of the porosity in the touching-vug intervals reported by *Cunningham et al.* [2006b] from inspection of cores and borehole image logs. In contrast, if it is assumed that all touching-vug flow zones within the open-hole interval of the injection well contributed to tracer migration and the time of the peak concentration, the porosity estimate is reduced by an order of magnitude to 0.04. Under this assumption, the cumulative thickness of all touching-vug porosity is approximately 9 m. This estimate should be considered a lower bound because the total mass of the tracer was not recovered, which would have resulted in a much larger mean arrival time. A larger mean arrival time when accompanied by a larger formation thickness in equation (1) would result in a larger estimate of the porosity.

[47] Estimates of dispersion can also be made from the tracer breakthrough curves at the production well. In the interpretation of these breakthrough curves, dispersion may not necessarily encompass the classical definition of dispersion that has been used in unconsolidated porous media [e.g., *Bear*, 1979]. In the Biscayne aquifer, the large pumping rate at the production well is likely to have induced turbulent conditions in the formation. Thus, the dispersion associated with the breakthrough curves could be as a result of turbulent mixing along flow paths in the formation. In addition, the transport is likely to have occurred within several subhorizontal limestone beds characterized by touching-vug porosity between the injection and production wells. The breakthrough curves at the production well shows the cumulative effect of the transport through multiple flow zones, and therefore, the dispersion as estimated from the breakthrough curves could also be attributed to this mechanism of transport.

[48] The solution for transport in a radially converging flow regime described by *Moench* [1989] was used to estimate the dispersion associated with the RWT breakthrough curve. The solution considers mixing in the injection and pumped boreholes and a Dirac (instantaneous) injection of the tracer mass. Only the rising limb and peak of the RWT breakthrough curve were used in estimating the dispersion, because the injection of a second pulse of tracer-free water produced a perturbation in the declining limb of the breakthrough curve, and the complete history of the declining limb of the breakthrough curves was not recorded because the tracer test was terminated after approximately 12.75 h. A large Peclet number (Pe), which is the ratio of advective to dispersive transport, was needed to reproduce the abrupt rising limb of the breakthrough curve (Figure 10). In a radially converging flow regime, the Peclet number reduces to the ratio of the radial distance between the injection and pumped wells, R, and the longitudinal dispersivity, α_L, of the formation [*Moench*, 1989],

$$Pe = \frac{R}{\alpha_L} \tag{2}$$

[49] When mixing in the injection and pumping wells are considered, a Peclet number of between 40 and 50 reproduces the rising limb and the time of the maximum rate of mass arrival per injected mass (Figure 10). The analytical solutions are calculated using the thickness of the dominant touching-vug flow zone (0.9 m) as the thickness of the aquifer subject to the chemical transport. It is assumed that the dominant touching-vug flow zone is responsible for the first detection and rising limb of the breakthrough curve, and thus, the large Peclet number is assumed to be representative of this feature. Furthermore, the analytical solution is scaled by multiplying the rate of mass arrival by a factor so that the maximum rates of mass arrival of the measured and modeled curves are approximately the same. The scaling of the analytical solution is applied for the purpose of comparing the abrupt rising limbs of the modeled and measured curves in estimating the Peclet number. The scaling is conducted arbitrarily because the injection procedure was not a true Dirac input of the tracer mass and other manipulations of the tracer injection make it difficult to estimate the exact mass of the tracer that was injected into the formation.

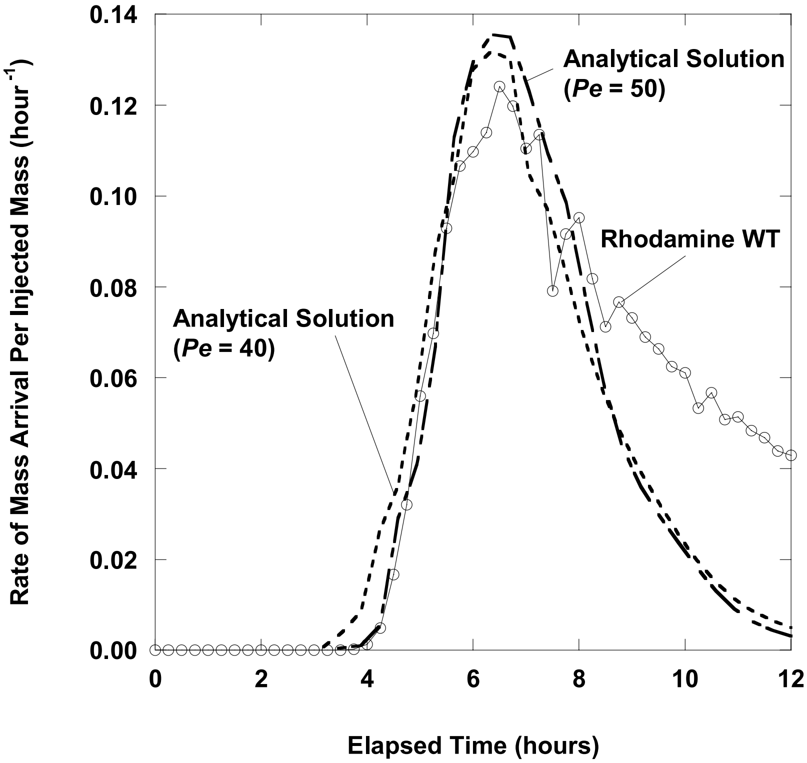

Figure 10. Comparison of rate of mass arrival per injected mass versus elapsed time for RWT and analytical solutions for different Peclet numbers for radially converging chemical transport from an injection well to a pumped well.

[50] Using the distance of 100 m between the injection and production well, α_L is estimated to be between 2 and 2.5 m. This estimate of the longitudinal dispersivity is small relative to the travel distance of the tracer, indicating that dispersion is not dominating the chemical transport responsible for the initial breakthrough of the tracer at the production well. If the mass arrival at the production well associated with the sharp rising limb and peak breakthrough is attributed only to touching-vug limestone porosity that occurs at −9.5 m, as implied by the temperature logging, then it is likely that preferential flow paths contained within this single touching-vug flow zone may account for the dominance of advection in the breakthrough curve. The touching-vug porosity (Figure 3) is seen as being a highly interconnected areally continuous feature; however, the dominance of advection would imply that preferential flow paths within this void space may be dominating the chemical migration. Under such conditions, dispersion may primarily be the result of turbulent processes occurring along these preferential flow paths.

[51] The early termination of the tracer test prohibited more extensive interpretation of the declining limb of the breakthrough curves for RWT and ^{2}H. On the basis of the temperature profiles collected in the observation well, it is likely that the tracers migrating in the touching-vug flow zones at greater depth than the interval at −9.5 m would result in an extended breakthrough tail. The characteristics of the declining limb of the breakthrough curve can identify the significance of advection, dispersion, and diffusion in the transport of dissolved constituents [*Becker and Shapiro*, 2000]. *Shapiro et al.* [2008] interpret a tracer test conducted in the Biscayne aquifer in 2004, where the declining limb of the breakthrough curve provides evidence of the role of advection and diffusion on chemical transport in the Biscayne aquifer.

8.3. Implications for Water Resources Management

[52] The results of the April 2003 aquifer and tracer tests conducted in the NWWF also have implications for well field operations. For example, the results of temperature logging indicate that the touching-vug flow zone at −9.5 m functions as a principal pathway for tracer migration. This touching-vug flow zone occurs near or is slightly shallower than the permitted depth for extractive mining under current regulatory restrictions. Therefore, mine expansion could enhance hydraulic communication between the borrow pit lakes near existing NWWF production wells and permeable strata that form the major producing zone in the NWWF.

[53] The tracer dilution that occurred between the injection and production wells also provides insight for water resources management of the NWWF. The initial tracer concentration that was injected into the formation can be estimated as the mass of RWT injected into the formation divided by the sum of the fluid volume in the water column of the injection well and the initial volume of tracer-free water used as a "chaser." From this estimate, the initial concentration of RWT injected into the formation is approximately 7.4×10^3 mg/L. In comparison, the peak concentration of RWT measured at the production well was approximately 3.5 mg/L. Consequently, there is an approximate dilution of 2×10^3 associated with the peak concentration measured at the production well. The relatively small dispersivity for the travel distance from the injection to the production well implies that dilution may be

largely the result of the mixing of the tracer solution drawn from the injection well with groundwater drawn to the production well from other locations in the formation. The small dispersivity also suggests that over larger transport distances, additional dilution of the tracer may not occur.

[54] The multiporous nature of the Biscayne aquifer similarly presents significant water management implications as it relates to an inadvertent release of a contaminant within the well field protection area. Although touching-vug flow zones would function as the primary pathway for flow and chemical migration, "removing" much of the contaminant that entered the system, a dissolved constituent would likely diffuse into the low-transmissivity, matrix pore space and be held in storage. Chemical constituents would then be released from the matrix pore space back into the flow system at concentrations lower than the original pulse.

[55] The potential for rapid chemical transport in the touching-vug flow zones also raises questions regarding the potential for the transport of pathogens and colloidal particles through the formation from surface water in the vicinity of the NWWF. Stratigraphic mapping in the NWWF area indicates that discrete touching-vug flow zones intersect both the production wells and the borrow pit lakes constructed from mining operations. The results of the tracer test demonstrate the dissolved chemical constituents can migrate with minimal dilution. *Harvey et al.* [2008] investigates the potential for pathogen transport in the Biscayne aquifer using a series of laboratory and field-scale tracer tests.

9. Conclusion

[56] An aquifer test and a tracer test using RWT and ^{2}H were conducted in the Northwest well field (NWWF) in Miami-Dade County, Florida. The NWWF is Florida's largest municipal well field that supplies water from the karst limestone of the Biscayne aquifer to over two million residents of south Florida. The tests were conducted to assess the continuity of permeable features in the formation and their ability to transport dissolved constituents to production wells. This investigation was initiated to address concerns regarding the potential for chemical and pathogen transport from surface-mining lakes to the production wells of the NWWF. Companion articles investigate in more detail the processes affecting the migration of dissolved chemical constituents and pathogen-size colloidal material in the Biscayne aquifer [*Shapiro et al.*, 2008; *Harvey et al.*, 2008].

[57] The Biscayne aquifer is an eogenetic karst limestone. Flow within the Biscayne is lithostratigraphically controlled, and occurs within highly transmissive, touching-vug pore space that form stratiform flow zones capable of transporting contaminants hundreds of meters to kilometers. The void space of the Biscayne aquifer differs dramatically from that of other karst systems that concentrate flow-through conduits and solution-enlarged pathways.

[58] Interpretations of drawdown from the aquifer test conducted at the NWWF indicate that the karst limestone behaves as a dual-porosity aquifer. The touching-vug flow zones are the principal paths of fluid movement and water is released from storage from limestone units characterized by matrix porosity that separate the touching-vug flow zones.

[59] Tracer movement in the Biscayne aquifer is characterized by rapid breakthrough, similar to results in other karst settings. The tracer test conducted in the NWWF also showed a high mass recovery. Analysis of RWT and ^{2}H breakthrough curves indicated that chemical transport in the fastest flow paths in the formation are dominated by advection. The results of temperature logging in observations wells during the tracer test showed that a single, 0.9-m-thick interval of touching-vug porosity was responsible for the rapid tracer breakthrough at the production well. Companion articles by *Shapiro et al.* [2008] and *Harvey et al.* [2008] investigate the role that the void space of the Biscayne limestone has on the retention of chemical constituents and the migration of pathogen size particles.

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