Prepared in cooperation with the Miami-Dade Water and Sewer Department

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Scientific Investigations Report 2017–5145

U.S. Department of the Interior
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By Jeffrey N. King and Jeremy D. Decker

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RYAN K. ZINKE, Secretary

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Conversion Factors

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
	Transmissivity*	
square meter per day (m^2/d)	10.76	square foot per day (ft^2/d)
	Specific storage	
inverse meter (1/m)	0.3048	inverse foot (1/ft)
	Pressure	
kilopascal (kPa)	0.1450	pound per square inch (lb/ft^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above or below the vertical datum.

Supplemental Information

*Transmissivity: The standard unit for transmissivity is cubic meter per day per square meter times meter of aquifer thickness [(m^3/d)/m^2]m.

In this report, the mathematically reduced form, meter squared per day (m^2/d), is used for convenience.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or kilograms per cubic meter (kg/m^3).

Abbreviations

BAS	MODFLOW Basic Package
BTN	MT3DMS Basic Transport Package
CFR	Code of Federal Regulations
CHD	MODFLOW Time-Variant, Specified-Head Package
DIS	MODFLOW Discretization File
DRN	MODFLOW Drain Package
DRT	MODFLOW Drains with Return Flow Package
EPA	U.S. Environmental Protection Agency
FDEP	Florida Department of Environmental Protection
PEST	model-independent parameter estimator
SSM	MT3DMS Source/Sink Mixing Package
TDS	total dissolved solids
USDW	Underground Source of Drinking Water
USGS	U.S. Geological Survey
WEL	MODFLOW Well Package

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Abstract

Nonhazardous, secondarily treated, domestic wastewater (effluent) has been injected about 1 kilometer below land surface into the Boulder Zone of the Floridan aquifer system at the North District Wastewater Treatment Plant in southeastern Florida. The Boulder Zone contains saline, nonpotable water. Effluent transport out of the injection zone is a risk of underground effluent injection. At the North District Wastewater Treatment Plant, injected effluent was detected outside the Boulder Zone. The U.S. Geological Survey, in cooperation with the Miami-Dade Water and Sewer Department, investigated effluent transport from the Boulder Zone to overlying permeable zones in the Floridan aquifer system.

One conceptual model is presented to explain the presence of effluent outside of the injection zone in which effluent injected into the Boulder Zone was transported to the Avon Park permeable zone, forced by buoyancy and injection pressure. In this conceptual model, effluent injected primarily into the Boulder Zone reaches a naturally occurring feature (a karst-collapse structure) near an injection well, through which the effluent is transported vertically upward to the uppermost major permeable zone of the Lower Floridan aquifer. The effluent is then transported laterally through the uppermost major permeable zone of the Lower Floridan aquifer to another naturally occurring feature northwest of the North District Wastewater Treatment Plant, through which it is then transported vertically upward into the Avon Park permeable zone. In addition, a leak within a monitoring well, between monitoring zones, allowed interflow between the Avon Park permeable zone and the Upper Floridan aquifer. A groundwater flow and effluent transport simulation of the hydrogeologic system at the North District Wastewater Treatment Plant, based on the hypothesized and non-unique conceptualization of the subsurface hydrogeology and flow system, generally replicated measured effluent constituent concentration trends. The model was calibrated to match observed concentration trends for total ammonium (NH_4^+) and total dissolved solids.

The investigation qualitatively indicates that fractures, karst-collapse structures, faults, or other hydrogeologic features may permit effluent injected into the Boulder Zone to be transported to overlying permeable zones in the Floridan aquifer system. These findings, however, are qualitative because the locations of transport pathways that might exist from the Boulder Zone to the Avon Park permeable zone are largely unknown.

Introduction

Historically, most nonhazardous, secondarily treated, domestic wastewater (effluent) in southeastern Florida was discharged to the Atlantic Ocean before the North District Wastewater Treatment Plant (figs. 1, 2) was constructed in 1970. Effluent from the North District Wastewater Treatment Plant (hereafter referred to as the treatment plant) was discharged to the Atlantic Ocean through an outfall until the mid-1990s. In 2008, environmental impacts of effluent discharge to the ocean led the State of Florida to determine that the elimination of ocean discharge was in the public interest. As a result, the primary means of effluent discharge at the treatment plant is shifting from ocean outfall to underground injection.

The Florida Department of Environmental Protection (FDEP) permits effluent from the treatment plant to be injected into the Boulder Zone through injection wells IW–1 (G–3950), IW–2 (G–3952), IW–3 (G–3805), and IW–4 (G–3954) (figs. 2 and 3; table 1; Cunningham, 2015, pl. 2). Construction of the injection wells began in 1994 for IW–2 and IW–3 and in 1997 for IW–1 and IW–4. Effluent injection to the Boulder Zone commenced in 1997 and monthly average injection rates from June 1997 to April 2012 at the treatment plant ranged from zero (no reported injection) to 2.3 cubic meters per second (m^3/s) (fig. 4). The Boulder Zone is a highly transmissive hydrogeologic unit near the base of the Floridan aquifer system in the early Eocene Oldsmar Formation (fig. 5). At the treatment plant, the Boulder Zone is about -870 to -1,050 meters (m)

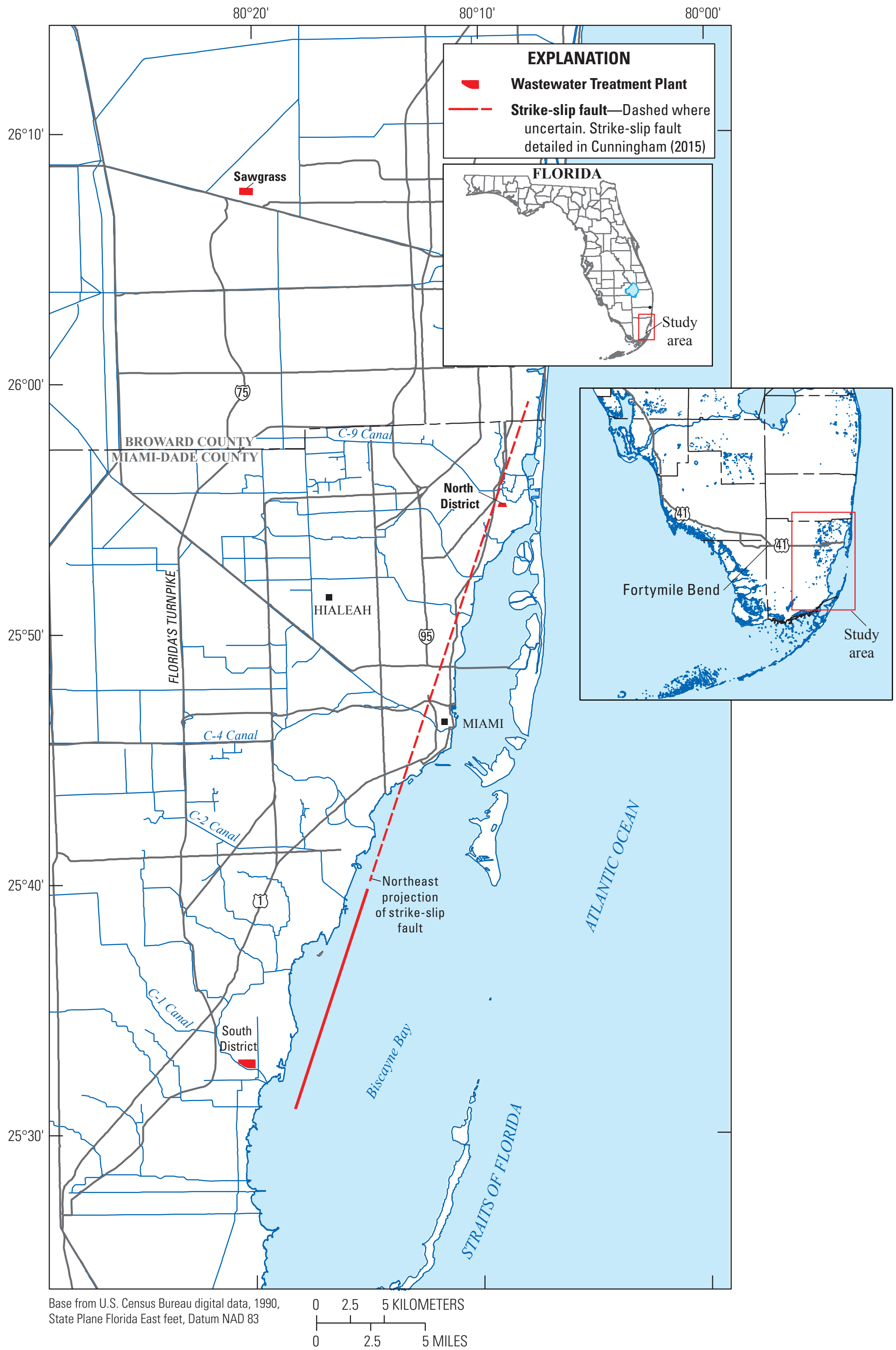


Figure 1. Locations of North and South District Wastewater Treatment Plants and orientation of a strike-slip fault in Miami-Dade County, Florida.

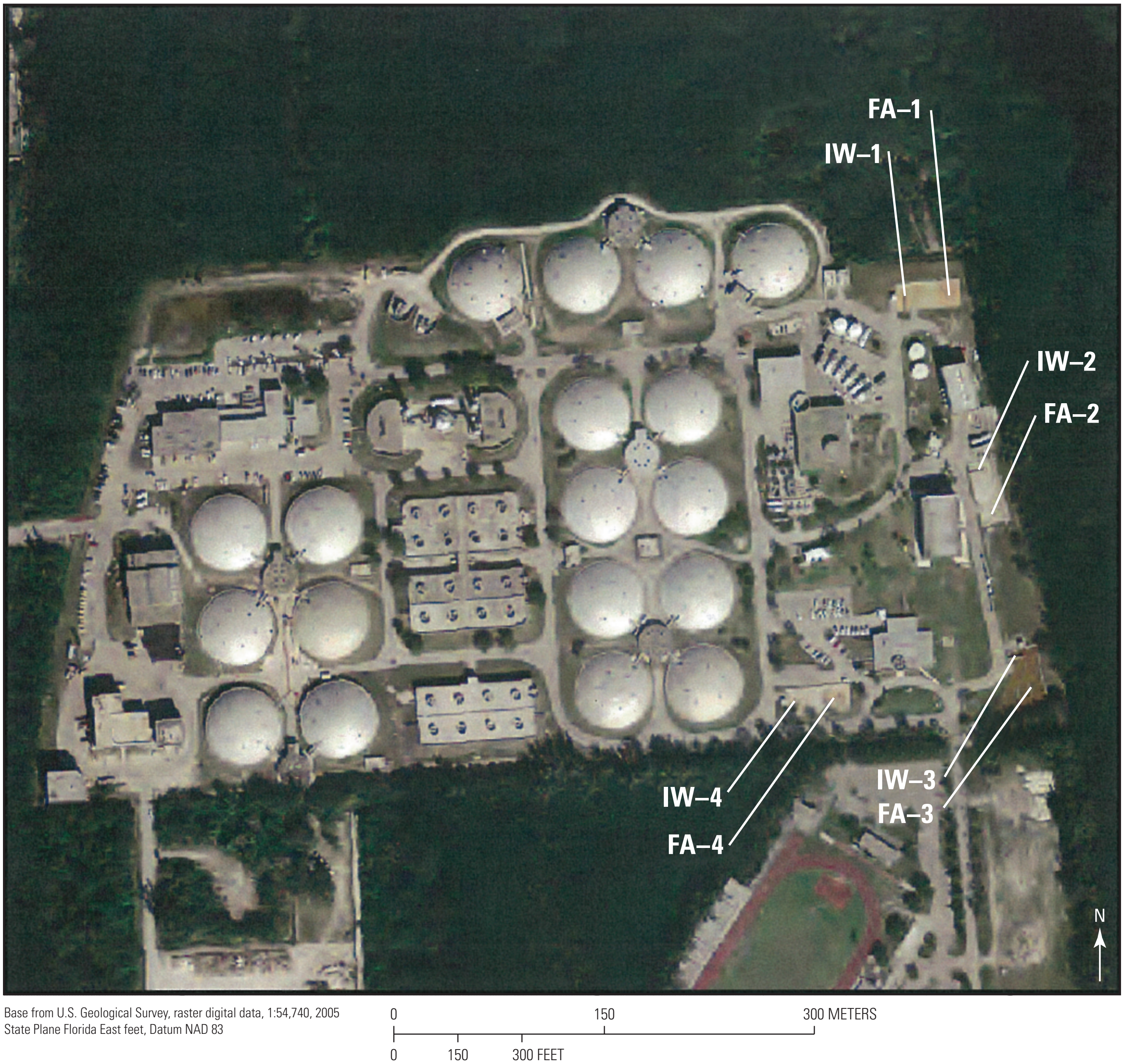


Figure 2. Locations of injection wells IW–1, IW–2, IW–3, and IW–4 and Floridan aquifer system monitoring site locations FA–1, FA–2, FA–3, and FA–4 at the North District Wastewater Treatment Plant, Miami-Dade County, Florida.

with respect to the National Geodetic Vertical Datum of 1929 (NGVD 29) (figs. 3 and 6) and has a total dissolved solids (TDS) concentration of about 35 kilograms per cubic meter (kg/m^3), similar to that of ocean water.

At the treatment plant, dual-zone monitoring wells were installed in the Floridan aquifer system at four sites, FA–1, FA–2, FA–3 and FA–4, to detect potential transport of treated effluent from the deeper Boulder Zone to more shallow permeable zones (figs. 2, 3, and 7). Monitoring wells FA–1U (G–3951B), FA–2U (G–3953B), FA–3U (G–3804B), and FA–4U (G–3955B) monitor the upper zone of the Floridan aquifer system (which corresponds to the lowest part of the Upper Floridan aquifer and uppermost part of the underlying middle confining unit), at sites FA–1, FA–2, FA–3 and FA–4, respectively (figs. 2, 3; table 1). Monitoring wells FA–1L (G–3951A), FA–2L (G–3953A), FA–3L (G–3804A), and FA–4L (G–3955A) monitor the lower zone of the Floridan aquifer system (which corresponds to the Avon Park permeable zone at sites FA–1, FA–2, FA–3 and FA–4, respectively) (figs. 2, 3; table 1). At the treatment plant, the Upper Floridan aquifer is about -270 to -370 m NGVD 29, or about 500 to 600 m above the Boulder Zone (figs. 3 and 6), and has a typical TDS concentration of about 5 kg/m^3 (fig. 8).

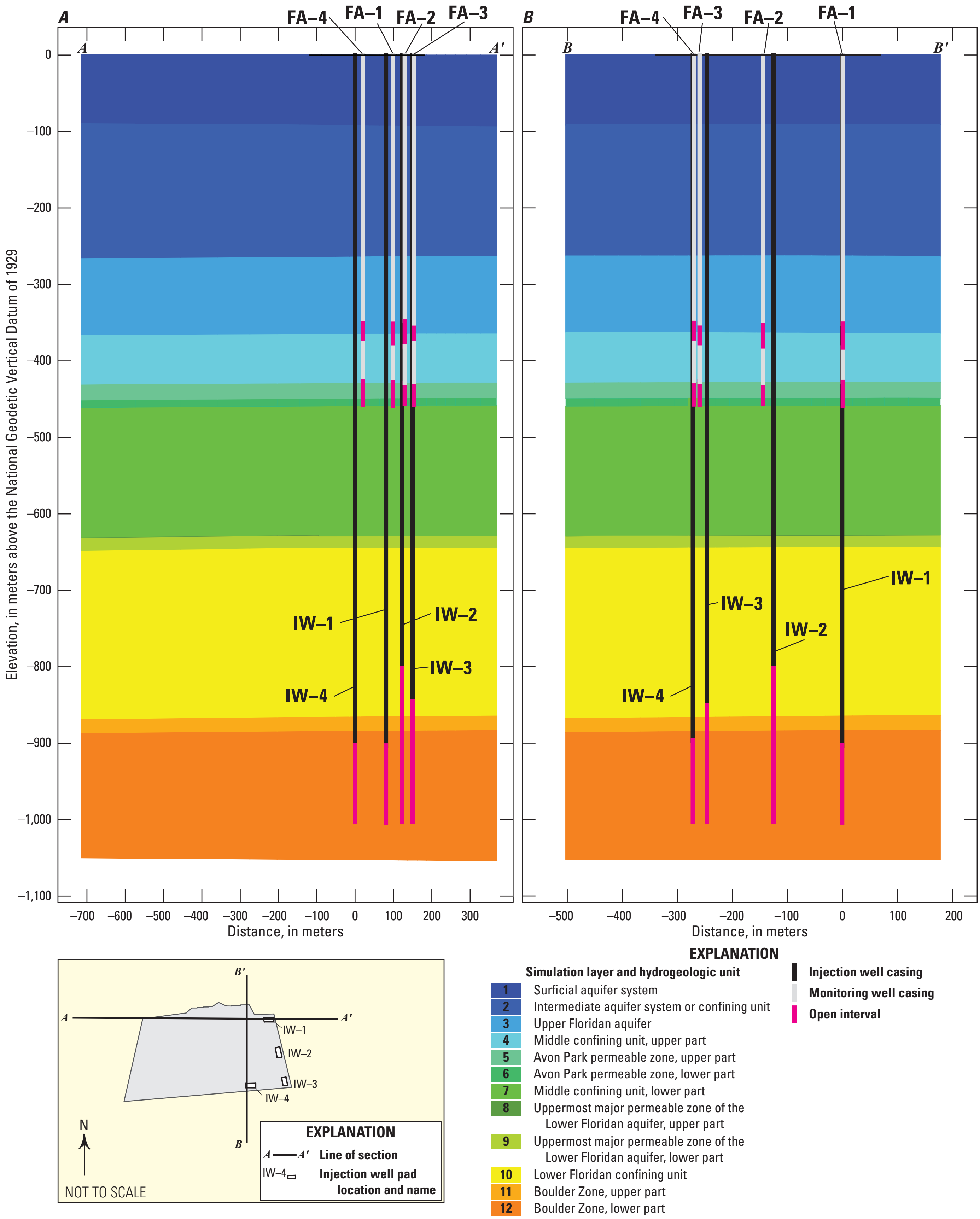


Figure 3. Hydrogeologic framework across the North District Wastewater Treatment Plant, Miami-Dade County, Florida, in the *A*, east-west (section *A*–*A*′) and, *B*, north-south (section *B*–*B*′) directions.

Table 1. Wells in southeastern Florida used in the present investigation.

[Well locations are shown in figures 2, 3, and 7. Depths of open intervals are in meters below ground surface. Open interval lengths and well diameters are in meters. Transducer elevations are in meters, referenced to the National Geodetic Vertical Datum of 1929. USGS, U.S. Geological Survey; --, well data are not available or are not published]

USGS identification		Other well identification	Location	Depth of open interval		Open interval length	Well diameter at top of open interval	Transducer elevation
Local well number	Site identification number			Top	Bottom			
MO–196	243400081474501	KW–MZL	Key West	390.14	402.34	12.19	--	--
MO–130	251548080183801	--	North Key Largo	--	526.39	--	--	--
S–3001	252058080202501	--	Near Card Sound	--	609.60	--	--	--
S–1533	252100080242901	S–1533L, S1533M, S–1533U	Near Card Sound Road	--	702.26	--	--	--
NP–100	252255080361101	ENP–100	Everglades National Park	348.30	388.90	40.60	--	--
S2U	253244080203001	S2U	Near Cutler Bay	300.80	310.90	10.10	--	--
MDS–I12	253256080205101	I12	Near Cutler Bay	--	934.82	--	--	--
SBZ1	253257080195601	SBZ1	Near Cutler Bay	306.32	316.08	9.75	--	--
S3U	253257080204801	S3U	Near Cutler Bay	299.01	320.04	21.03	--	--
G–3234	253648080345801	Coastal Petroleum 11F State No. 1, Lease 340A	Everglades National Park	--	3,510.99	--	--	--
G–3235	253924080461701	Humble 1.1.F. - State 1-10	Everglades National Park	--	25.10	--	--	--
I–1	254134080210301	PU–I1	Near Kendall	--	898.25	--	--	--
G–3239	254540080494301	Commonwealth Oil No. 1	Big Cypress National Preserve	--	3,522.88	--	--	--
G–3240	254548080463001	Gulf Refining State No. 1, Lease 340	Water Conservation Area 3A	--	3,461.61	--	--	--
G–3061	254941080171701	--	Hialeah	--	336.80	--	--	--
C–1240	255336081183401	BICY–MZ2	Ochopee	255.42	298.70	--	--	--
G–3767	255436080280701	DF–5	Near Krome Avenue	347.47	374.90	--	--	--
G–3804B	255505080084901	FA–3 upper monitoring zone, FA–3U	Near North Miami Beach	353.57	379.48	25.91	0.32	4.26
G–3804A	255505080084902	FA–3 lower monitoring zone, FA–3L	Near North Miami Beach	429.77	460.25	30.48	0.17	–19.99
G–3955B	255505080085401	FA–4 upper monitoring zone, FA–4U	Near North Miami Beach	353.57	379.48	25.91	0.32	4.66
G–3955A	255505080085402	FA–4 lower monitoring zone, FA–4L	Near North Miami Beach	429.77	460.25	30.48	0.17	–19.80
G–3954	255505080085501	IW–4	Near North Miami Beach	896.11	1,005.84	109.73	0.61	--
G–3805	255505080085001	IW–3	Near North Miami Beach	850.39	1,005.84	155.45	0.61	--
G–3953B	255509080085001	FA–2 upper monitoring zone, FA–2U	Near North Miami Beach	350.52	383.74	33.22	0.32	4.63
G–3953A	255509080085002	FA–2 lower monitoring zone, FA–2L	Near North Miami Beach	431.29	458.72	27.43	0.17	–19.89
G–3952	255510080085003	IW–2	Near North Miami Beach	798.58	1,005.84	207.26	0.61	--
G–3950	255514080085203	IW–1	Near North Miami Beach	905.26	1,005.84	100.58	0.61	--
G–3951B	255514080085101	FA–1 upper monitoring zone, FA–1U	Near North Miami Beach	353.57	384.66	31.09	0.32	3.92
G–3951A	255514080085102	FA–1 lower monitoring zone, FA–1L	Near North Miami Beach	429.77	461.16	31.39	0.17	–20.56
C–962	255846080533001	Well 1	Raccoon Point	--	1,188.72	--	--	--
G–2964	255934080195601	PBP–I2, MIR–MW1	Pembroke Pines	--	640.08	--	--	--
PBP–I1	255936080195701	--	Pembroke Pines	--	1,097.28	--	--	--

Table 1. Wells in southeastern Florida used in the present investigation.—Continued

[Well locations are shown in figures 2, 3, and 7. Depths of open intervals are in meters below ground surface. Open interval lengths and well diameters are in meters. Transducer elevations are in meters, referenced to the National Geodetic Vertical Datum of 1929. USGS, U.S. Geological Survey; --, well data are not available or are not published]

USGS identification		Other well identification	Location	Depth of open interval		Open interval length	Well diameter at top of open interval	Transducer elevation
Local well number	Site identification number			Top	Bottom			
S–567	260614080085401	Oil Test Well	Fort Lauderdale	--	917.45	--	--	--
PLT–ROI1	260739080160801	RO Reject Injection Well 1	Plantation	--	1,018.03	--	--	--
PLT–I2	260828080140801	--	Plantation	--	1,067.41	--	--	--
C–1239	261010081434901	I75–MZ2	Naples	275.84	320.04	44.20	--	--
G–2296	261016080492601	Alligator Alley Test Well	Water Conservation Area 3A	--	856.79	--	--	--
G–2941	261023080104801	BF–4S	Lauderdale Lakes	332.23	365.76	33.53	--	--
G–2941	261023080104801	BF–4M	Lauderdale Lakes	1,550.00	1,600.00	50.00	--	--
CS–I2	261445080154801	--	Coral Springs	--	1,066.80	--	--	--
BCN–I1	261538080092801	--	Coconut Creek	--	1,070.46	--	--	--
G–2969	261853080072501	BF–6	Deerfield Beach	656.84	676.66	19.81	--	--
PB–1765	262107080174201	PBF–10R	Boca Raton	--	373.38	--	--	--
C–1238	262448081255601	IWSD–MZ2	Immokalee	324.61	353.57	28.96	--	--
PB–1694	264033080060901	PBF–3	West Palm Beach	--	460.25	--	--	--
PB–1144	265800080051301	PBF–1	Tequesta	311.20	316.38	5.18	--	--

At the treatment plant, injected effluent was detected outside the Boulder Zone at four locations in the Avon Park permeable zone (Walsh and Price, 2010) and at two locations in the Upper Floridan aquifer. The injected effluent typically has a TDS concentration of less than 1 kg/m^3 (appendix 1, fig. 1–1), and total ammonium (NH_4^+) concentration of up to 20 milligrams per liter (mg/L) (appendix 1, fig. 1–2). On June 17, 1997, a 28-month-long test of injection wells IW–2 and IW–3 commenced. After 11 months in May 1998, ammonium concentrations increased in the Avon Park permeable zone at four monitoring wells (fig. 9). Effluent transport to the Avon Park permeable zone increased from the native 0.35-mg/L ammonium concentration in the Avon Park permeable zone. At 22 months after the start of the test, decreases in TDS concentrations in the Avon Park permeable zone were measured in April 1999 at the same four locations (fig. 10*A*–*D*). Effluent transport to the Avon Park permeable zone reduced the native 25-kg/m^3 TDS concentration in the Avon Park permeable zone. In May 2009, spikes in ammonium concentrations (fig. 11*B*, *D*) and TDS concentrations (fig. 8*B*, *D*) were measured at two locations in the Upper Floridan aquifer, in upper zones of Floridan aquifer system monitoring wells FA–2U and FA–4U. Corresponding spikes in ammonium concentrations and TDS concentrations were not observed in the other monitoring wells (figs. 8*A*, *C*, 11*A*, *C*).

One risk of injecting effluent underground is the transport of that effluent out of the injection zone and into an Underground Source of Drinking Water (USDW). The U.S. Environmental Protection Agency (EPA) generally defines a USDW as a geologic formation capable of yielding a substantial amount of groundwater that either (1) supplies any public water system or (2) does not currently supply a public water system, but contains a sufficient quantity of groundwater to supply a public water system and has a TDS concentration less than 10 kg/m^3 (Part C of the Safe Drinking Water Act and 40 CFR §144.3). Water from a USDW is not necessarily potable and may require treatment to be potable. In the vicinity of the treatment plant, Upper Floridan aquifer groundwater is not potable and does not currently supply a public water system; however, because the aquifer contains a sufficient quantity of groundwater to supply a public water system and has a TDS concentration less than 10 kg/m^3, it is considered to be a USDW. Conversely, the Avon Park permeable zone and the Boulder Zone are not considered to be USDWs, because these zones do not have TDS concentrations less than 10 kg/m^3 in the vicinity of the treatment plant.

From 2003 to 2005, the Miami-Dade Water and Sewer Department pumped groundwater from the Avon Park permeable zone to reduce concentrations of effluent constituents in the zone. Specifically, from March 2003 to March 2004 and from January 2005 to March 2005, 295,000 cubic meters (m^3) of groundwater were removed from the Avon Park permeable zone through lower monitoring zones of Floridan aquifer system monitoring wells to purge injected effluent constituents from the Avon Park

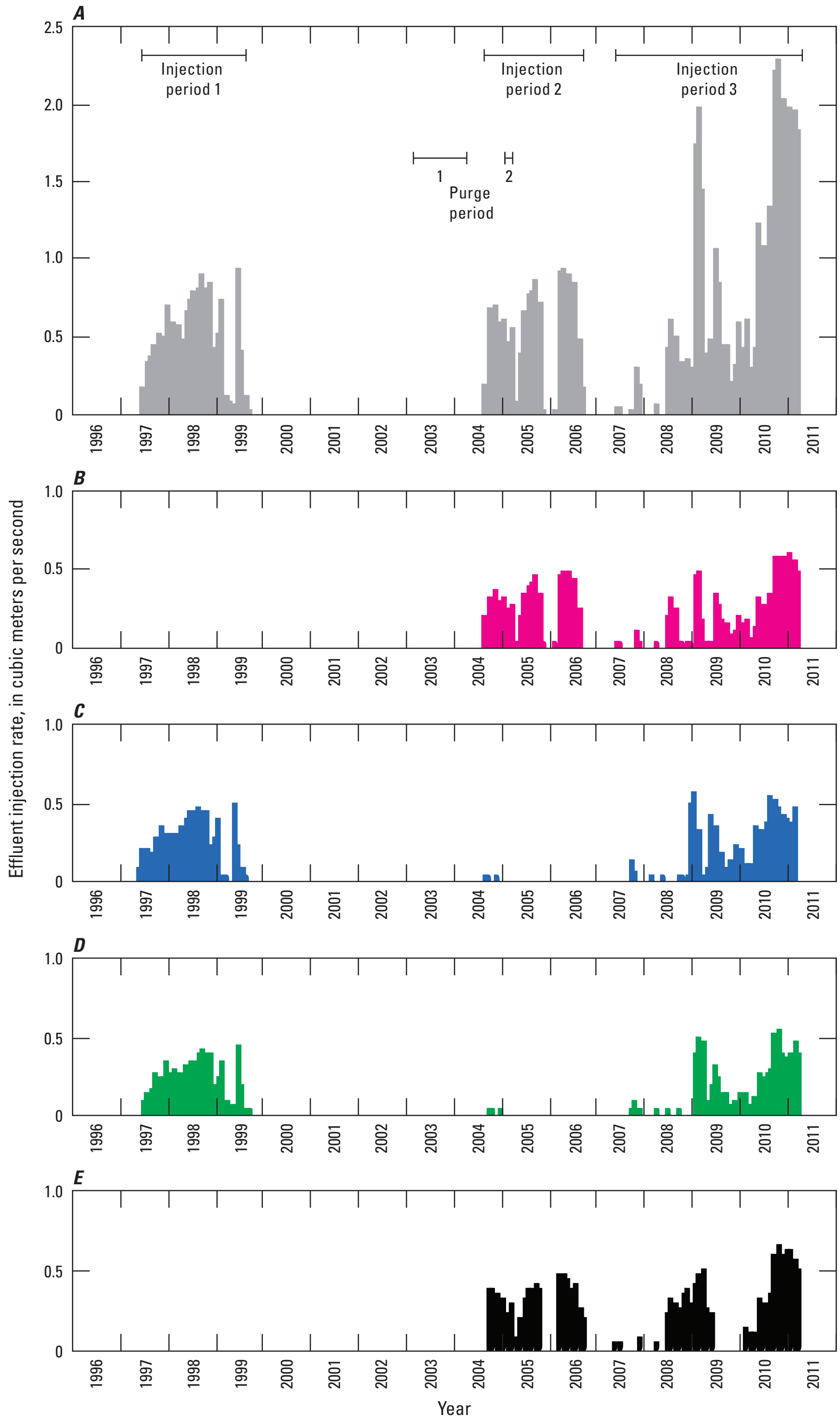


Figure 4. Rate of effluent injection measured from 1996 to 2011 at the North District Wastewater Treatment Plant, Miami-Dade County, Florida through *A*, injection wells IW–1, IW–2, IW–3, and IW–4, *B*, well IW–1, *C*, well IW–2, *D*, well IW–3, and *E*, well IW–4 (Miami-Dade County, 1999a, b; Decker and King, 2018).

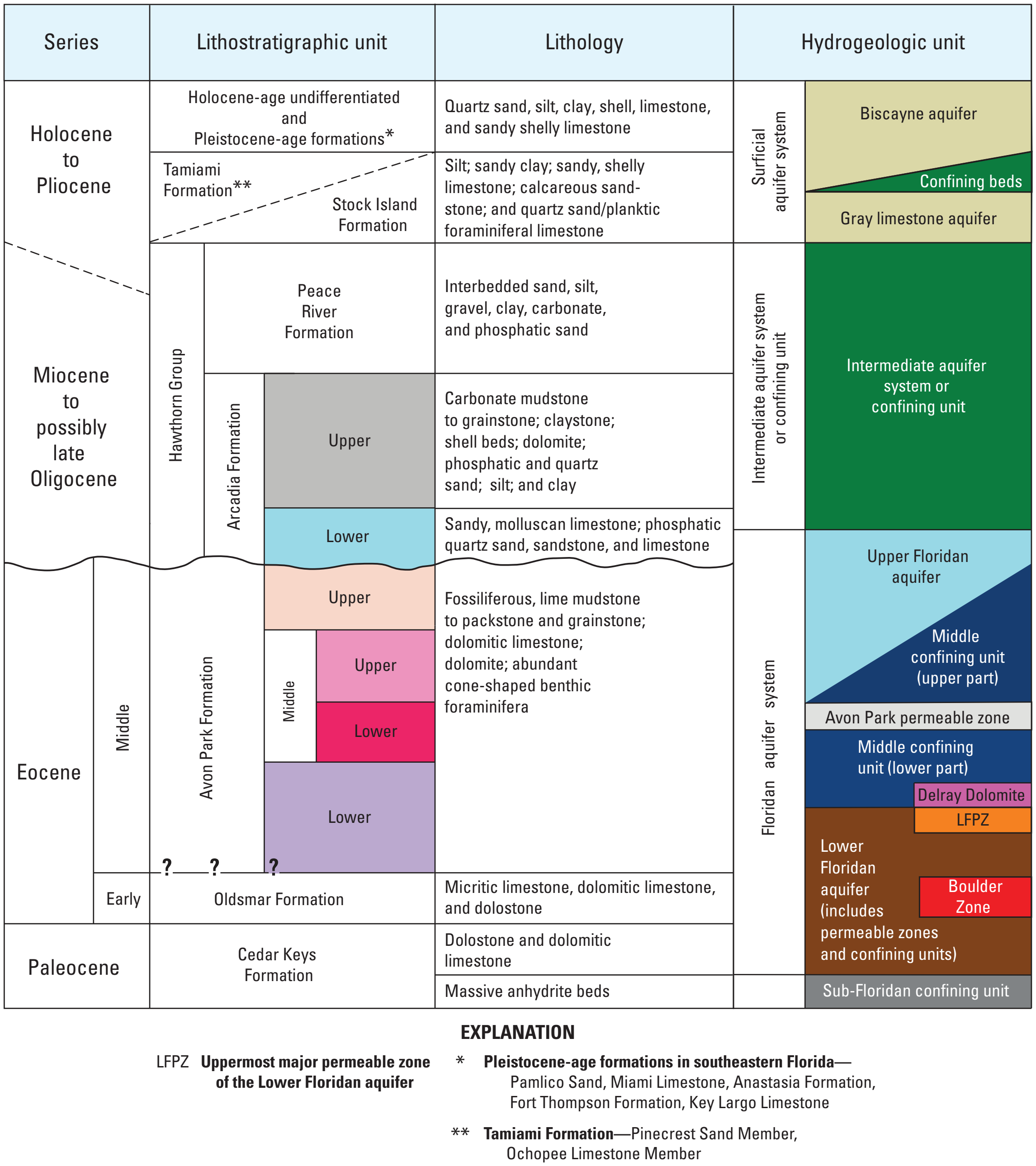


Figure 5. Lithostratigraphic units in the study area, generalized lithologies, and correlation to hydrogeologic units, for the Floridan aquifer system in southeastern Florida. Subdivisions of the Arcadia and Avon Park Formations are defined in this study and are informal (modified from Reese and Cunningham, 2014).

permeable zone, including 1,070 kilograms (kg) of ammonium (Miami-Dade County, 2005, table 2). The purge was suspended from March 2004 to January 2005 to test the mechanical integrity of treatment plant wells.

Although the risk associated with effluent transport out of the injection zone and into the USDW has been recognized, the mechanisms and pathways of transport have remained unclear. As coastal communities in Florida and elsewhere grow, there is an increasing need to find ways to manage wastewater that do not adversely affect potential drinking water supply. To this end, linking hydrogeologic characteristics with groundwater-flow and transport models may provide insights on the suitability of deep aquifers to serve as receptacles for treated wastewater, and possibly serve as tools to test underground injection management scenarios as well. To address the specific issue at the treatment plant, the U.S. Geological Survey (USGS), in cooperation with the Miami-Dade Water and Sewer Department, investigated effluent transport from the Boulder Zone to overlying permeable zones in the Floridan aquifer system. As the need for alternative wastewater treatment processes in coastal communities grows, and as this type of investigation becomes more sophisticated, it may become an increasingly informative approach for management of deep aquifers.

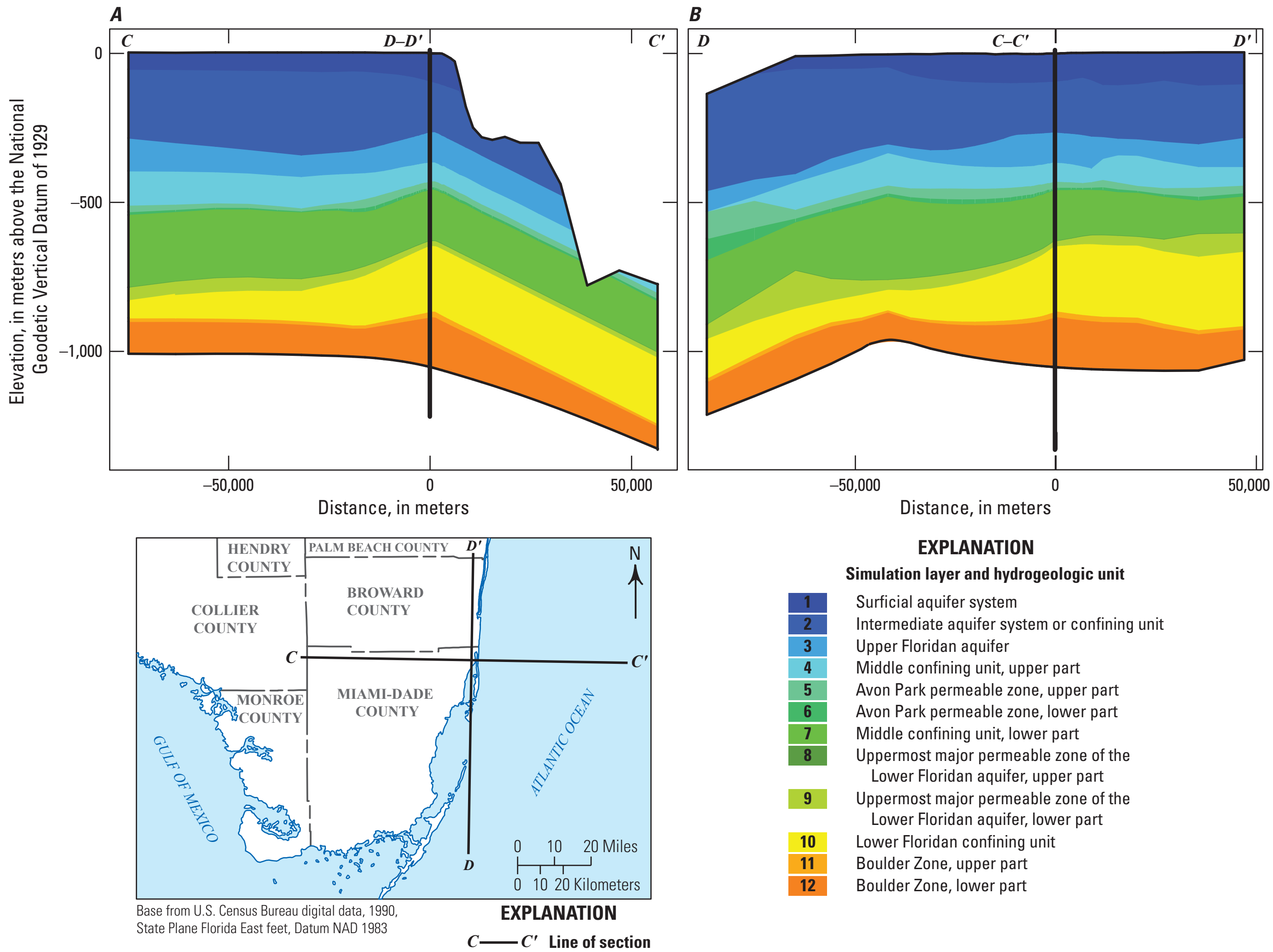


Figure 6. Hydrogeologic framework across parts of southeastern Florida in the *A*, east-west (section *C–C′*) and *B*, north-south (section *D–D′*) directions.

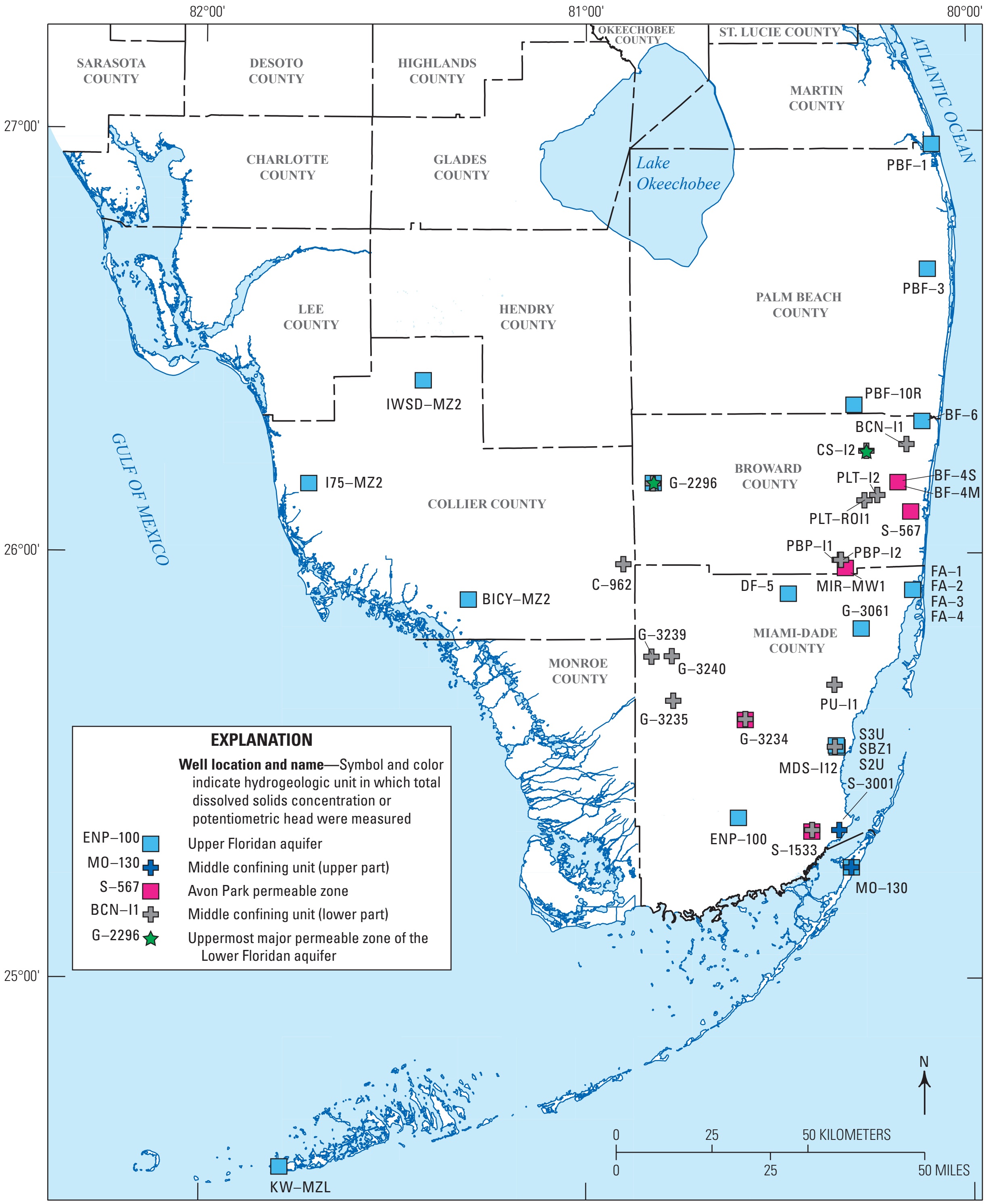
Purpose and Scope

The purpose of this report is to describe an investigation concerning the transport of nonhazardous, secondarily treated, domestic wastewater (effluent) injected into the Boulder Zone at the North District Wastewater Treatment Plant from 1997 to 2011. As part of this investigation, effluent confinement in the Boulder Zone was characterized; a possible preferential transport pathway from the Boulder Zone to the Avon Park permeable zone was characterized; and the extent of the effluent plume in 2011 was estimated based on plausible hydrogeologic system characteristics. A naturally occurring transport path may be a structural feature in a part of rock that is relatively more conductive to groundwater than the surrounding rock, such as a fracture in a relatively impermeable rock formation, or an area of porous medium that preferentially or diffusively transmits groundwater and groundwater constituents. Although simulated, characterization of infrastructure-related transport of effluent between the Avon Park permeable zone and the Upper Floridan aquifer was not a primary objective of this evaluation.

The report is limited to a description of the conceptual model and a simulation of effluent transport from the Boulder Zone to the Avon Park permeable zone based on the model. The conceptual model and simulation are limited to the Upper Floridan aquifer, the Boulder Zone, and the hydrogeologic units between the two, from 1997 to 2011. The simulation domain includes Broward and Miami-Dade Counties, and the Straits of Florida.

Approach

To characterize effluent transport, a conceptual model was simulated using hydraulic and geologic parameters that describe possible transport pathways. Effluent water quality and injection rate data, and water quality and pressure data for the monitoring wells at the treatment plant were obtained from monthly operating and other reports provided by the Miami-Dade Water and Sewer Department to the Florida Department of Environmental Protection



Base from U.S. Census Bureau digital data, 1990,
State Plane Florida East feet, Datum NAD 1983

Figure 7. Locations of wells in southern Florida used in the present investigation (table 1).

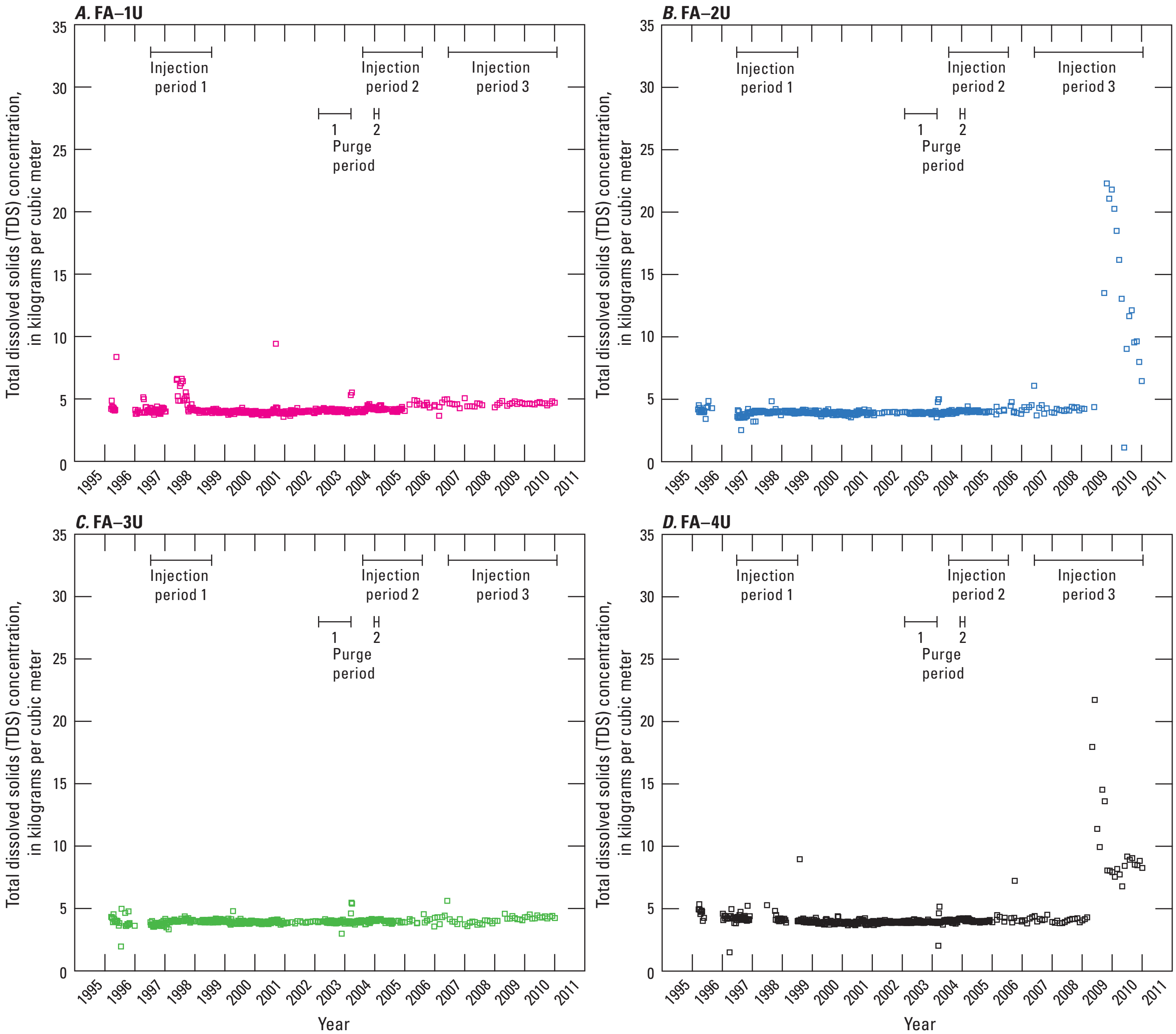


Figure 8. Concentrations of total dissolved solids (TDS) measured from 1995 to 2011 at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, in upper zones of Floridan aquifer system (lowest part of the Upper Floridan aquifer and uppermost part of the underlying middle confining unit) monitoring wells *A*, FA–1U, *B*, FA–2U, *C*, FA–3U, and *D*, FA–4U (Miami-Dade County, 2006; Decker and King, 2018).

(Decker and King, 2018). Potentiometric data for sites outside of the treatment plant were obtained from the South Florida Water Management District database DBHYDRO (appendix 1). Simulation results were compared to measured TDS and ammonium concentrations, and measured pressures and potentiometric heads in the Floridan aquifer system. Hydraulic and geologic parameters were adjusted to locally minimize an objective function that described the fit of simulated potentiometric heads and concentrations to measurements. Simulation output sensitivities to variation in simulation input were quantified and evaluated, and simulation limitations are presented herein.

Hydrogeologic Setting

The Floridan aquifer system consists mostly of permeable carbonate rock and underlies all of Florida and parts of Georgia, Alabama, and South Carolina (Williams and Kuniansky, 2016). Throughout southern Florida, the Floridan aquifer system is overlain by the intermediate aquifer system or confining unit, which is subjacent to a surficial aquifer system (fig. 5). In parts of southern Florida, the Floridan aquifer system is underlain by a low-permeability anhydrite unit in the middle part of the Cedar Keys Formation. The regional continuity and extent of the anhydrite unit is not known.

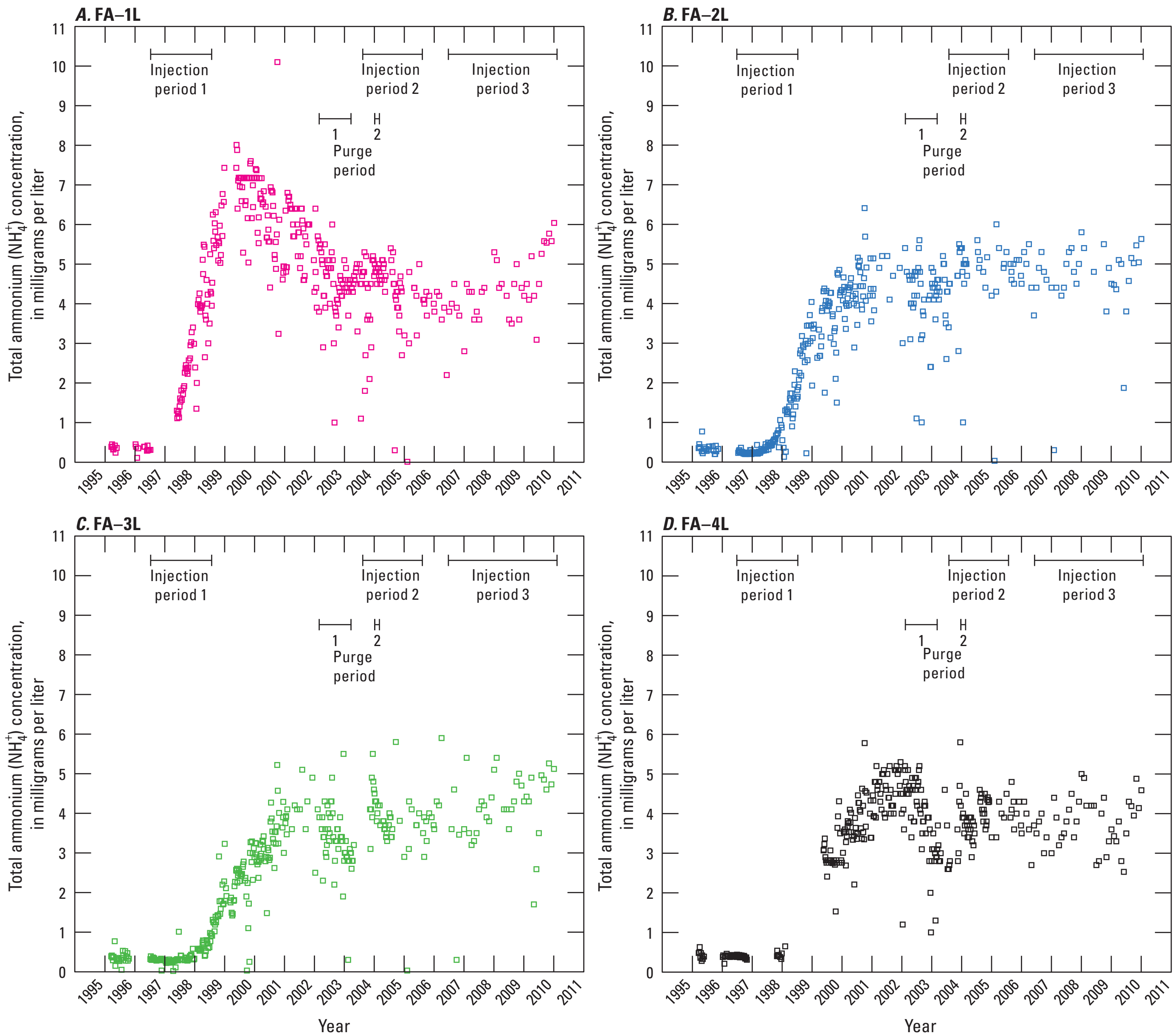


Figure 9. Total ammonium (NH_4^+) concentrations measured from 1995 to 2011 at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, in lower zones of Floridan aquifer system (Avon Park permeable zone) monitoring wells *A*, FA–1L, *B*, FA–2L, *C*, FA–3L, and *D*, FA–4L (Miami-Dade County, 2006; Decker and King, 2018).

In southeastern Florida, the Floridan aquifer system includes the following geologic units, in ascending (oldest to youngest) order: the upper part of the Cedar Keys Formation (Cole, 1944; Vernon, 1951; Winston, 1977; Miller, 1986; Hoenstine and others, 1990; Winston, 1993, 1994; Williams and Kuniansky, 2016), the Oldsmar Formation (Winston, 1977; Hoenstine and others, 1990; Winston, 1993, 1994), the Avon Park Formation (Miller, 1986; Hoenstine and others, 1990; Winston, 1993; Williams and Kuniansky, 2016), and the lower part of the Arcadia Formation in the Hawthorne Group (Dall and Harris, 1892; Freas and Riggs, 1968; Scott, 1988; Cathcart and Botinelly, 1991). These units include rocks of Paleocene, Eocene, Oligocene, and Miocene age.

Hydrogeologic Framework

Miller (1986) described the Floridan aquifer system as being composed of upper and lower aquifers, separated by a middle confining unit. The Upper Floridan aquifer is the upper, major permeable zone of the Floridan aquifer system. The lower part of the aquifer system, designated by Miller (1986) as the Lower Floridan aquifer, includes a highly transmissive dolomite and dolomitic limestone in the Cedar Keys Formation. Oil-well drillers first referred to this highly transmissive region of the Lower Floridan aquifer as the Boulder Zone, because “fractured dolomite breaks off in boulder-sized chunks” where drilled, causing rock to

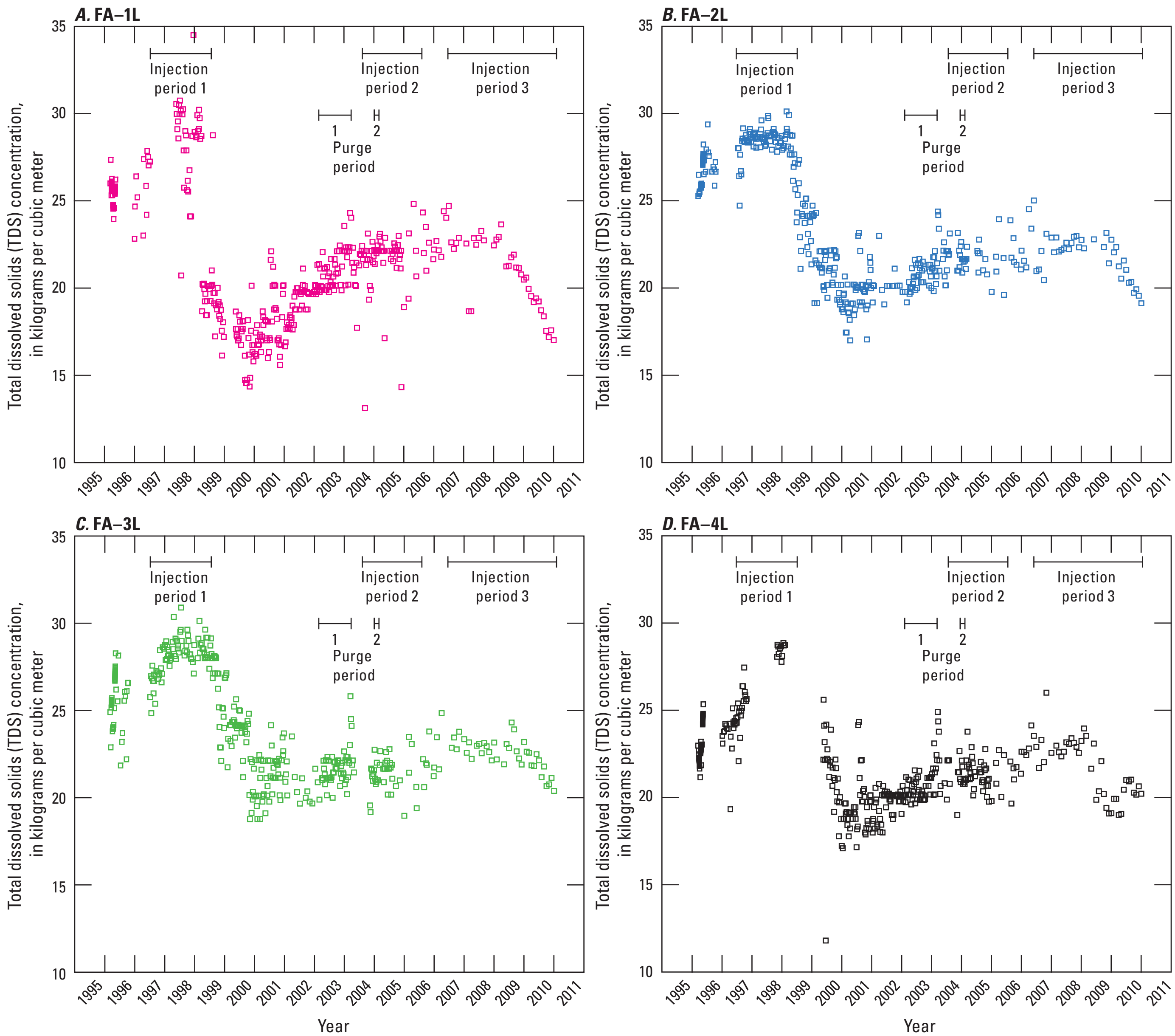


Figure 10. Concentrations of total dissolved solids (TDS) measured from 1995 to 2011 at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, in lower zones of Floridan aquifer system (Avon Park permeable zone) monitoring wells *A*, FA–1L, *B*, FA–2L, *C*, FA–3L, and *D*, FA–4L (Miami-Dade County, 2006; Decker and King, 2018).

“fall under and around the bit,” such that “the action of the bit [is similar to] drilling through boulders” (Kohout, 1965). Large cavities formed by paleokarst-generating processes in the Lower Floridan aquifer give the Boulder Zone its high transmissivity (Miller, 1986).

Reese and Richardson (2008) synthesized hydrogeologic data to construct a framework for the Floridan aquifer system in central and southern Florida. Reese and Cunningham (2014) and Cunningham (2014) refined the framework in Broward County. Reese and Richardson (2008), Reese and Cunningham (2014), and Cunningham (2014) detailed the following hydrogeologic units, in descending order (figs. 3–5): the surficial aquifer system; the intermediate confining unit (or intermediate aquifer system in the south-central and southwestern part of the peninsula); the Upper Floridan aquifer; the middle confining unit 1 of the Floridan aquifer system of Miller (1986), which includes the Avon Park permeable zone; the uppermost major permeable zone of the Lower Floridan aquifer, the Lower Floridan aquifer confining unit, and the Boulder Zone. Reese and Richardson (2008) delineated the Avon Park permeable zone throughout central and southern Florida. The Avon Park permeable zone is a hydrogeologic unit that is not coincident, everywhere, with the Avon Park Formation. The Avon Park permeable zone is within the middle confining unit 1 of Miller (1986) and is referred to as the Middle Floridan aquifer

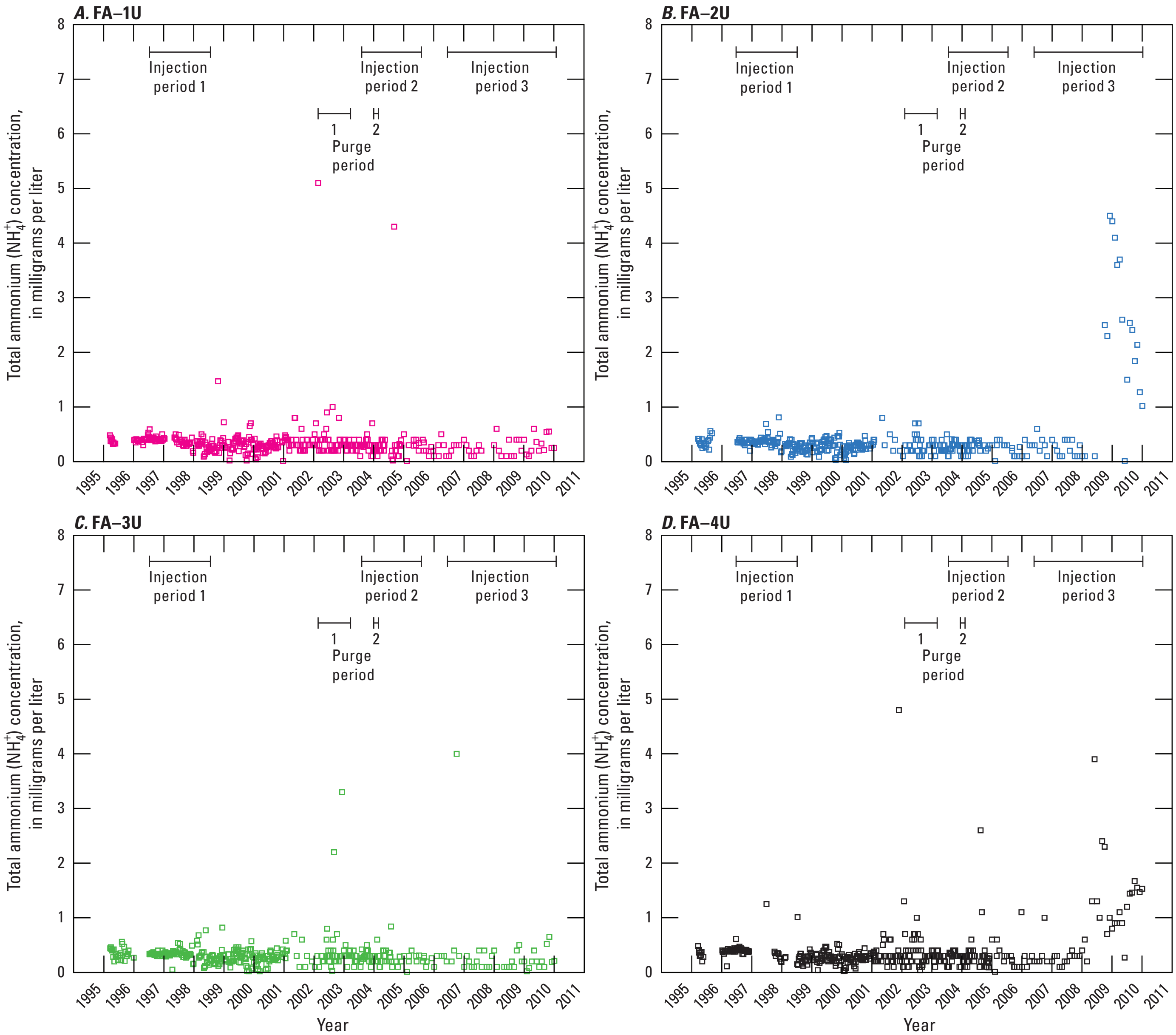


Figure 11. Total ammonium (NH_4^+) concentrations measured from 1995 to 2011 at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, in upper zones of Floridan aquifer system monitoring wells *A*, FA–1U, *B*, FA–2U, *C*, FA–3U, and *D*, FA–4U (Miami-Dade County, 2006; Decker and King, 2018).

in some previous studies (Bennett and Rectenwald, 2003; Lukasiewicz, 2003a, b; Bennett and Rectenwald, 2004). Reese and Richardson (2008) renamed the middle Floridan aquifer unit the “Avon Park permeable zone,” bounded by overlying and underlying semiconfining leaky units they respectively called middle confining unit 1 (upper part herein) and middle confining unit 2 (lower part herein).

Williams and Kuniansky (2016) recently revised the hydrogeologic framework of the Floridan aquifer system at regional and subregional scale. A fundamental change in the Floridan aquifer system hydrogeologic framework introduced by Williams and Kuniansky (2016), is the renaming, abandoning, or reassigning of the discontinuous numbered middle “confining” units of Miller (1986). Instead, “composite” units are identified to subdivide the Floridan aquifer system into the Upper and Lower Floridan aquifers or to subregional, less-permeable zones within the Upper or Lower Floridan aquifers. This revised characterization is in recognition that these lithostratigraphic units are not confining over their identified subregional extents, and rather may be semiconfining, leaky, or have hydraulic properties similar to adjacent aquifer properties. Additionally, while some of these “confining” units of Reese and Richardson (2008) have hydraulic conductivities that range from 1 to 100 feet per day (0.3 to 30 meters per day), those units are still relatively less permeable than units that have large dissolution features,

Table 2. Purge start date, end date, rate, volume, fluid total ammonium (NH_4^+) concentration, and ammonium mass extracted from the Avon Park permeable zone from 2003 to 2005 through the lower zone of Floridan aquifer system monitoring wells FA–1L, FA–2L, FA–3L, and FA–4L at the North District Wastewater Treatment Plant, Miami-Dade County, Florida (Miami-Dade County, 2005).

[NA, not applicable; m^3/d, cubic meter per day; m^3, cubic meter; mg/L, milligram per liter; kg, kilogram. Purge rates and purge concentrations are from Miami-Dade County (2005). Purge volumes and purge masses are computed. Mechanical integrity of injection wells was tested between March 2004 and December 2004, during which time the Avon Park permeable zone was not purged]

Well	Date		Rate (m^3/d)	Volume (m^3)	Concentration (mg/L)	Mass (kg)
	Start	End				
FA–1L	3/17/2003	3/22/2004	380	140,000	4.1	580
FA–2L	11/24/2003	3/22/2004	260	30,000	3.7	110
FA–3L	11/24/2003	3/22/2004	380	45,000	2.8	120
FA–4L	11/24/2003	3/22/2004	360	43,000	2.5	110
FA–1L	1/3/2005	3/30/2005	120	11,000	4.4	50
FA–2L	1/3/2005	3/30/2005	100	9,000	4.3	40
FA–3L	1/3/2005	3/30/2005	70	6,000	3.8	20
FA–4L	1/3/2005	3/30/2005	130	11,000	3.4	40
Total	NA	NA	NA	295,000	NA	1,070

such as the Avon Park permeable zone. As most of the analysis presented in this report occurred before the release of Williams and Kuniansky (2016), the hydrogeologic unit naming conventions from Reese and Richardson (2008), which retained the term “middle confining unit” are used here. Additionally, this local study divides the system into more vertical units than Williams and Kuniansky (2016). The middle confining unit, upper part or middle confining unit 1 of Reese and Richardson (2008) is named the “Ocala-Avon Park lower permeability zone of the Upper Floridan aquifer” in Williams and Kuniansky (2016). The Avon Park permeable zone is the same unit for both Reese and Richardson (2008) and Williams and Kuniansky (2016). The middle confining unit 2 of Reese and Richardson (2008) or middle confining unit, lower part, in this report is named the “middle Avon Park composite unit” by Williams and Kuniansky (2016). Reese and Richardson (2008) subdivided the lower Avon Park Formation more than Williams and Kuniansky (2016). A schematic comparison of hydrogeologic nomenclature from Reese and Richardson (2008) and William and Kuniansky (2016) is provided in figure 29 in Williams and Kuniansky (2016).

Structural Features

At some locations in southeastern Florida, structural features—such as fractures and faults related to tectonic activity, or buried karst-collapse structures—cut across relatively less permeable units in the Floridan aquifer system (Reese and Cunningham, 2014). These structural features may form vertical groundwater transport paths across low-permeability, carbonate strata that separate zones of regionally extensive, high-permeability rock (Cunningham, 2014, 2015). Cunningham (2015) described structural features of the Floridan aquifer system at Miami-Dade County’s North and South District Wastewater Treatment Plants. Hickey and Vecchioli (1986) showed how distal faults or abandoned wells may permit injectate to be transported from an injection zone to a superjacent permeable zone or USDW, through preferential pathways where the injection zone is locally confined at the site scale (fig. 12).

Several investigators have measured or described apparent, natural transport paths through geologic units typically characterized as confining; for example, Cunningham (2014) used water-based, multichannel, high-resolution, seismic-reflection surveys to image tectonic faults and karst-collapse systems that breach confining units in the Floridan aquifer system. Maliva and others (2007) stated that “seismic reflection profiles and stratigraphic data indicate that folding of likely tectonic origin is widespread in the subsurface of Florida.”

Cunningham and Walker (2009), Cunningham and others (2012), Cunningham (2013, 2015), and Reese and Cunningham (2014) used seismic reflection profiles and other stratigraphic data to characterize karst-collapse structures and tectonic faults in the Floridan aquifer system in southeastern Florida. At the City of Sunrise Sawgrass wastewater treatment facility (fig. 1) in Broward County, Montgomery Watson (1996) indicated that effluent injected into the Boulder Zone was detected in the uppermost major permeable zone of the Lower Floridan aquifer because of a lack of confinement between the permeable zones. Cunningham (2014) indicated that the lack of confinement between these zones may be associated with a locally identified karst-collapse feature.

Cunningham (2015) identified a karst-collapse structural feature at North District Wastewater Treatment Plant injection well IW–2 through the upper part of the Boulder Zone, Lower Floridan confining unit, Lower Floridan permeable zone, and lower part of the middle confining unit. Cunningham (2015) also identified a fault that may extend northwest of the treatment plant (fig. 1). Faults are associated with karst-collapse structural features, common in carbonate rocks (McDonnell and others, 2007), and may serve as potential transport pathways between the Boulder Zone and other units.

Maliva and others (2007) investigated the transport of effluent injected into the subsurface in southern Florida, documenting effluent transport from the injection zone to a USDW at the South District Wastewater Treatment Plant and at the Seacoast Utilities effluent injection facility in Palm Beach County. Maliva and others (2007) also documented effluent transport from the injection zone to permeable hydrogeologic units below a USDW at the following seven effluent injection facilities in southeastern Florida: GT Lohmeyer facility in Broward County, City of Sunrise facility in Broward County, City of Plantation facility in Broward County, City of Margate facility in Broward County, Broward North Regional facility, Palm Beach County System 3 facility, and Palm Beach County Southern Region facility.

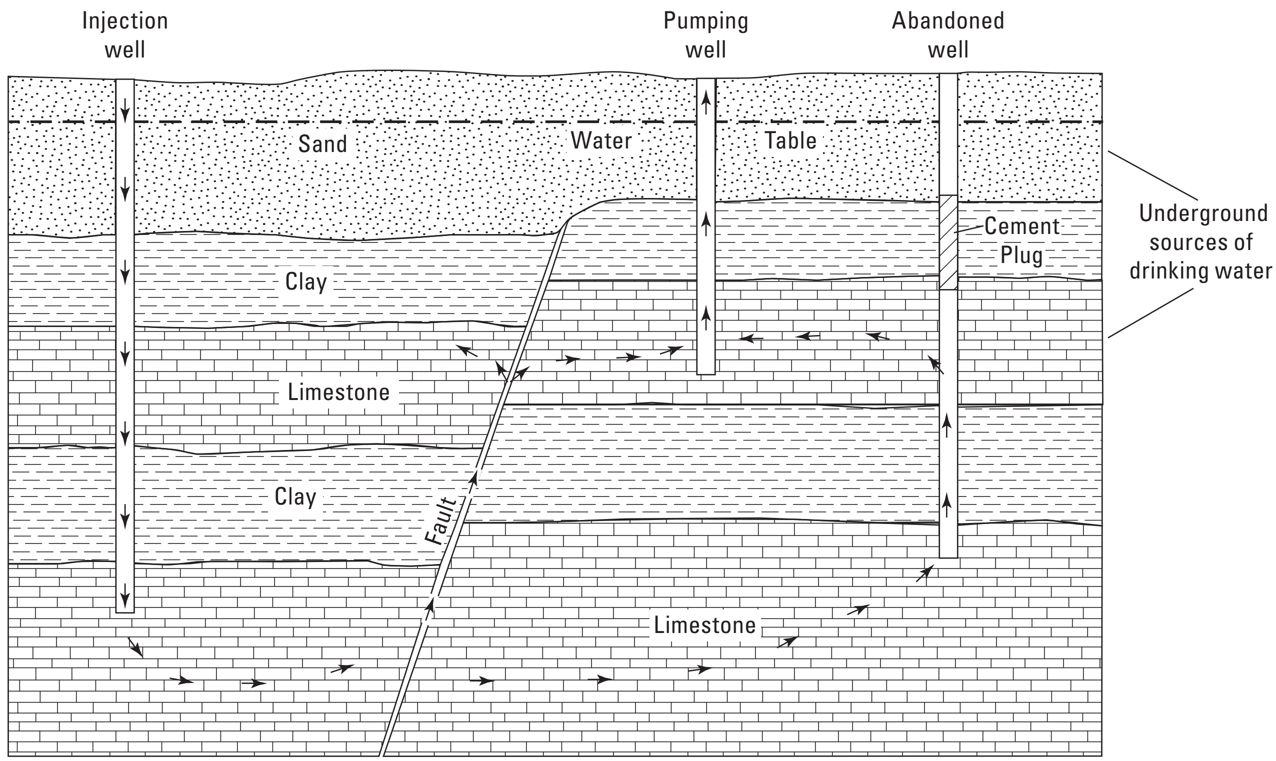


Figure 12. Conceptual model of possible consequences of transport of subsurface injectate through preferential pathways. From Hickey and Vecchioli (1986).

Flow and Transport System Characteristics

The Floridan aquifer system in southern Florida is largely recharged by precipitation in central Florida. In the Upper Floridan aquifer, groundwater flows from regions of higher potentiometric head in central Florida to regions of lower potentiometric head in southern Florida (Stringfield, 1936; Parker and others, 1955; Bush and Johnston, 1988). In southeastern Florida, groundwater in the Upper Floridan aquifer generally moves eastward from a groundwater divide in the center of the peninsula toward the Straits of Florida.

Meyer (1989) used isotope, temperature, and salinity anomalies to show that upwelling groundwater originating in the Lower Floridan aquifer was probably the source of salinity in the Upper Floridan aquifer and that circulating, younger seawater was more likely to be the source of salinity in the Floridan aquifer system than connate seawater. Meyer (1989) speculated that transport paths, such as fractures and relict sinkholes, may intersect or span confining units and permit vertical flow and transport across confining units (as in fig. 12). Meyer (1989) stated that a region of anomalies in temperature and TDS concentration is oriented from the northwest to the southeast of peninsular Florida and that the anomalies "seem to originate from sinkholes or vertical solution pipes that are aligned with the major system of fractures or joints in the Tertiary limestone."

Kohout (1965) described geothermal heating that drives a cyclic, convective, westward flow of saltwater from the Atlantic Ocean into the Boulder Zone. Kohout (1965) estimated an average water column temperature of 17 degrees Celsius (°C) and an average chloride concentration of 20 kg/m^3 in the Straits of Florida beneath which the Boulder Zone is postulated to crop out, and 24 °C water temperature and 19 kg/m^3 chloride concentration in an inland well at Fortymile Bend, at a depth of about 600 m below mean sea level. Kohout (1965) postulated that the increase in temperature between the Atlantic Ocean and groundwater at Fortymile Bend was caused by geothermal heating of the Boulder Zone by deeper units. A temperature of about 110 °C was measured at about 3,500 m below sea level at Fortymile Bend. The density gradient between the outcrop and Fortymile Bend forces ocean water westward. Groundwater then flows upward by convection and into contact with fresher groundwater flowing seaward in superjacent units in the Floridan aquifer system. Meyer (1989) stated that "opposing views [on the circulation hypothesis] were expressed by Vernon (1970) who suggested that the temperature anomaly was due only to heat conduction, and Sproul (1977), who concluded that existing data were insufficient to support either hypothesis."

Meyer (1989) also described the subsurface hydrologic circulation and how it might affect the subsurface storage of effluent in the Floridan aquifer system in southern Florida. Meyer (1989) indicated that "injected liquid waste will ultimately conform to the regional groundwater circulation system. The injected waste, thus, will move with the inland and upward flow of seawater from the Florida Straits," although "the time involved in the circulation is short by geologic standards but extremely long by man's standards" (Meyer, 1989).

Conceptual Model of Effluent Transport From the Boulder Zone

The conceptual model simulated in this investigation transports injectate vertically through structural features and leaky multizone monitoring wells, and laterally through more permeable zones in the Floridan aquifer system, in stages (fig. 13), similar to the conceptual model presented in Hickey and Vecchioli (1986) (fig. 12). At the beginning of the simulated period, some of the effluent injected into the Boulder Zone reaches a structural feature near IW–2 (representing a karst-collapse feature) and is transported vertically upward to the uppermost major permeable zone of the Lower Floridan aquifer. It should be noted that IW–2 injects effluent into both the Boulder Zone and the lower part of the overlying confining unit within the Lower Floridan aquifer. Effluent reaching the uppermost major permeable zone of the Lower Floridan aquifer is then transported laterally through this zone. Effluent in the uppermost major permeable zone of the Lower Floridan aquifer reaching a simulated structural feature (representing a fault) northwest of the treatment plant is then transported vertically upward into the Avon Park permeable zone. The fluids reaching this zone are then transported laterally southeastward toward the lower monitoring wells at the treatment plant. Toward the end of the simulated period, leaks between monitoring wells allowed interflow between the lower monitored zone (in the Avon Park permeable zone) and the upper monitored zone (in the Upper Floridan aquifer). It is important to note that the conceptual model presented herein is not the only hypothesis describing effluent transport in the vicinity of the treatment plant. Other conceptual models may also explain effluent transport from the Boulder Zone to the Avon Park permeable zone, but it was not within the scope of the present investigation to simulate all possible transport paths.

The model represents effluent transport from the Boulder Zone to the Avon Park permeable zone from June 17, 1997, to January 31, 2011. Effluent was injected into the subsurface during the following three distinct injection periods at the treatment plant (fig. 4):

- June 1997 to September 1999: into injection wells IW–2 and IW–3;
- August 2004 to September 2006: primarily into injection wells IW–1 and IW–4; and
- May 2007 to the end of the simulation in February 2011: into injection wells IW–1, IW–2, IW–3, and IW–4.

Visual inspection of the injection time series at the four injection wells (fig. 4), and the observed concentrations at the lower monitoring zones (figs. 9, 10) indicate that the strongest responses in all the monitoring wells were in the lower monitoring zone during and following injection period 1, when injection wells 2 and 3 were operating. Figure 10 shows an initial increase in TDS concentration, followed by a rapid freshening, in response to injection period 1. The initial increase in TDS concentration was probably a result of more saline water being displaced from the point of injection, moving in front of the injectate. Figure 9 shows a distinct increase in ammonium concentration during and following injection period 1. During injection period 2, when injection wells 1 and 4 were operating, observed ammonium concentrations at all monitoring wells were nonresponsive. During injection period 3, when all injection wells were operating, there was an apparent response in TDS concentration in all four monitoring wells, and an apparent response in ammonium concentration in the lower monitoring zones (figs. 9 and 10). Total ammonium and TDS concentration time series in lower zones of Floridan aquifer system monitoring wells were more responsive to injection periods 1 and 3 than to injection period 2 (figs. 4, 9, and 10). Injection into wells IW–2 and IW–3 may influence flow and transport from the Boulder Zone to the Avon Park permeable zone more than injection into wells IW–1 and IW–4. To simulate this influence, the conceptual model included a heterogeneous representation of hydraulic conductivity in the Boulder Zone that favored transport to the Avon Park permeable zone of effluent injected through wells IW–2 and IW–3, and not through wells IW–1 and IW–4.

Visual inspection of the observed concentrations in the lower monitoring zones (figs. 9, 10), indicates that the effluent plume arrived first at monitoring well FA–1L. The magnitudes of change in TDS and ammonium concentrations were also greatest at monitoring well FA–1L. This result indicates effluent was transported along a preferential pathway from the Boulder Zone, near injections wells IW–2 and IW–3, to the Avon Park permeable zone, closer to monitoring well FA–1L than to the other monitoring wells. For this conceptual model, effluent injected into the Boulder Zone is transported radially in preferred directions. Preferential flow in the Boulder Zone is heterogeneous. Effluent injected into wells IW–1 and IW–4 is preferentially transported in high-conductivity zones, away from the postulated vertical transport path near injection well IW–2. The conceptual model simulated here is consistent with the observed data but does not confirm the hypothesized transport path.

Visual inspection of the observed concentrations in the upper monitoring zones (figs. 8, 11), showed increasing concentrations of TDS and ammonium at monitoring wells FA–2U and FA–4U beginning around 2009, during injection period 3. These trends correspond to observed breaches between upper and lower zones in monitoring wells FA–2L and FA–2U, and FA–4L and FA–4U. A breach was observed at a depth of about 1,092 feet (332.8 m) during a video observation of a differential purge test of well FA–4U that was conducted April 16–20, 2010. During part of the test, the upper monitoring zone well FA–4U was purged, and the lower monitoring zone well FA–4L was not purged. The differential purge created a potentiometric-head gradient across breaches

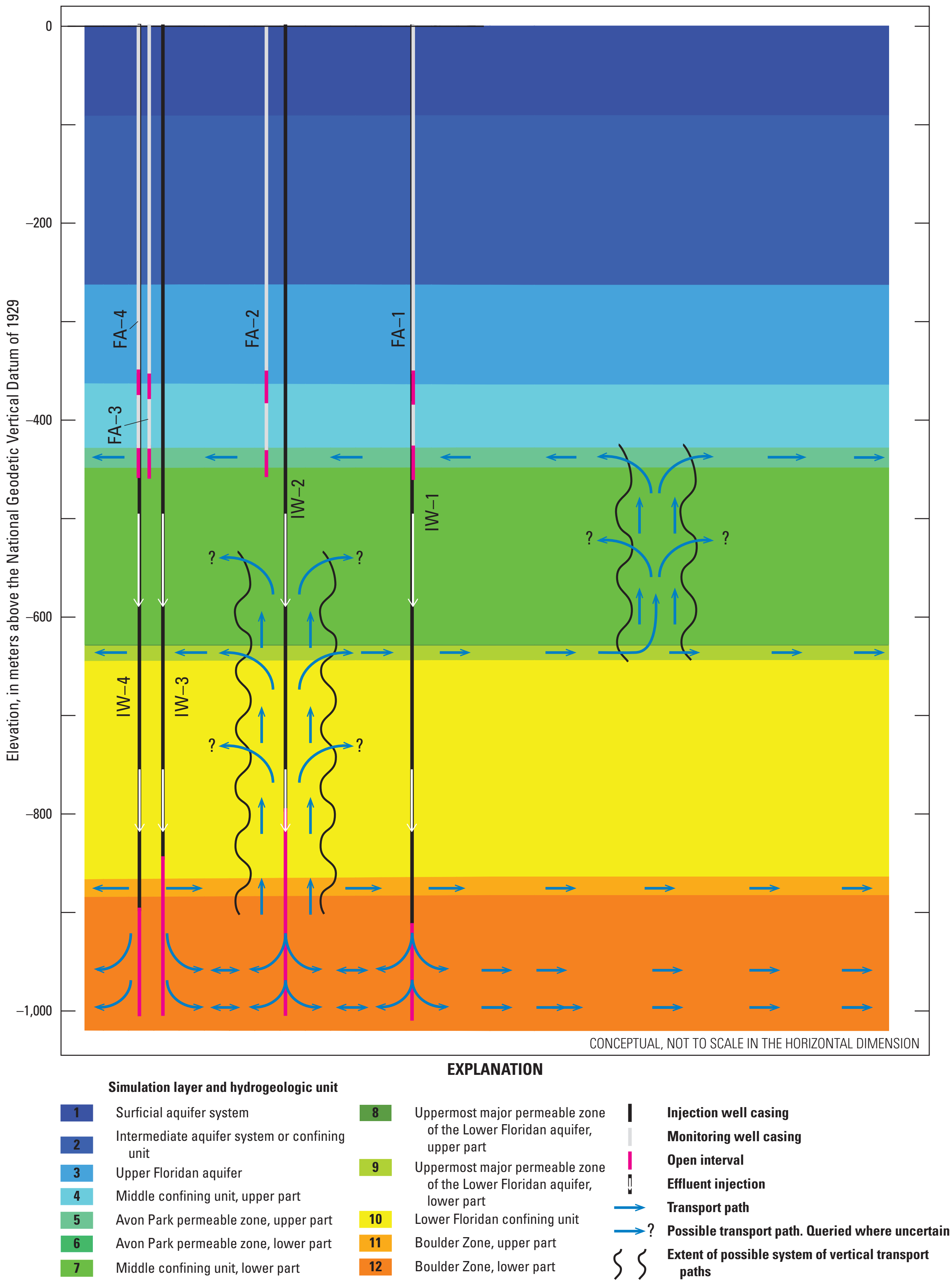


Figure 13. Conceptual model of effluent transport at the North District Wastewater Treatment Plant, Miami-Dade County, Florida.

in the well casing that separates FA–4U from FA–4L. Video observation indicated that floating particulate matter inside the lower monitoring zone was transported into the upper monitoring zone through a breach in the separation between the upper and lower zones. It was also confirmed that when neither the lower nor upper monitoring zone was purged, the velocity of floating particulate matter in the lower zone was less than when the imposed potentiometric-head gradient existed. Thus the resulting conceptual model included a preferential pathway from the Avon Park permeable zone to the Upper Floridan aquifer monitoring zone at monitoring sites FA–2 and FA–4.

Monitoring wells drilled in the Floridan aquifer system were purged prior to measuring water-quality constituents to ensure that samples represented groundwater recently present in the monitoring zone. After about 2008, routine monthly presample purges of the upper sampling zone may have forced groundwater from the lower zones of wells FA–2L and FA–4L through breaches in separation between the upper and lower monitoring zones, and vice versa. This could result in elevated TDS and ammonium concentrations measured in the upper zone sample from wells FA–2U and FA–4U that are representative of a mixture of water from the upper zone and lower zone and not representative of the water quality outside of the monitoring zone. Likewise, TDS and ammonium concentrations measured in the lower monitoring zone from wells FA–2L and FA–4L may not be representative of water quality outside of the monitoring zone. The model, however, was not designed to capture short-duration events such as presampling purges. In the model, the transport of TDS and ammonium between upper and lower monitoring zones at sites FA–2 and FA–4 is strictly forced by the ambient potentiometric-head gradient between these zones.

Simulation of Effluent Transport

The numerical model SEAWAT (Guo and Bennett, 1998; Guo and Langevin, 2002) was used to simulate effluent injection into the Boulder Zone, transport to the Avon Park permeable zone through the stepwise path, and transport to the Upper Floridan aquifer through breaches in monitoring wells (Decker and King, 2018). SEAWAT is a model of variable-density groundwater flow and dual-domain constituent transport in a porous medium, built from MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and others, 2000) and MT3DMS (Zheng and Wang, 1999; Zheng and others, 2001)—models for flow and transport in a porous medium, respectively. Equation 37 of Guo and Langevin (2002) was solved for potentiometric head using a preconditioned conjugate gradient solver. Equation 1 of Zheng and Wang (1999) was solved for TDS and ammonium concentrations using a general conjugate gradient solver. TDS and ammonium were considered nonreactive species and therefore conservative. The model was calibrated to best replicate measured ammonium and TDS concentration trends, and potentiometric heads were estimated from pressure and TDS concentration data. Some hydraulic and geologic parameters were estimated using the model-independent parameter estimator PEST (Doherty, 2010). Hydraulic and geologic parameters from literature (Decker and King, 2018) were used to determine initial parameter values in PEST. A drain-return flow analog was used to simulate fluid movement along vertical transport paths that connect the Boulder Zone to the uppermost major permeable zone of the Lower Floridan aquifer, the Lower Floridan aquifer to the Avon Park permeable zone, and the Avon Park permeable zone to the Upper Floridan aquifer (appendix 1). Flow through these vertical paths was calculated as the product of an estimated transport path conductance value and the difference in total hydraulic head values between path endpoints. This calculation is similar to the finite-difference flow calculation between two simulation grid cells.

The simulation was forced by the injection of effluent from the treatment plant into the ambient hydraulic head field of the Boulder Zone from June 1997 to February 2011. The purge of the Avon Park permeable zone through lower zones of Floridan aquifer system monitoring wells from 2003 to 2005 (table 2) also forced the simulation. The 19,120-square-kilometer (km^2) simulation domain was discretized into rectilinear cells composing 79 columns, 78 rows, and 12 layers. The simulation represented conditions from June 1977 to February 2011 with 177 varied-duration stress periods. Most stress periods were 1 month in duration. Initial potentiometric head and TDS concentrations were based on measurements and values from literature. Boundary conditions were specified at select locations on the basis of literature values. A preliminary simulation ensured that initial potentiometric head and TDS concentrations were in a state of dynamic equilibrium. Details about the stress history, spatial and temporal discretization, initial and boundary conditions, other simulation inputs, model construction, calibration, and sensitivity are detailed in appendix 1 and Decker and King (2018).

Simulated Concentrations of TDS and Total Ammonium (NH_4^+) and Potentiometric Head

Simulated TDS concentrations qualitatively fit measured TDS concentrations for lower zones of Floridan aquifer system monitoring wells (fig. 14) forced by all three injection periods (fig. 4), the purge period (table 2), and intervals between injection periods. Quantitatively, differences between measured, weighted TDS concentrations and simulated TDS concentrations accounted for 2 percent of an objective function valuation at each of the four lower zone monitoring wells, for a total contribution of 8 percent.

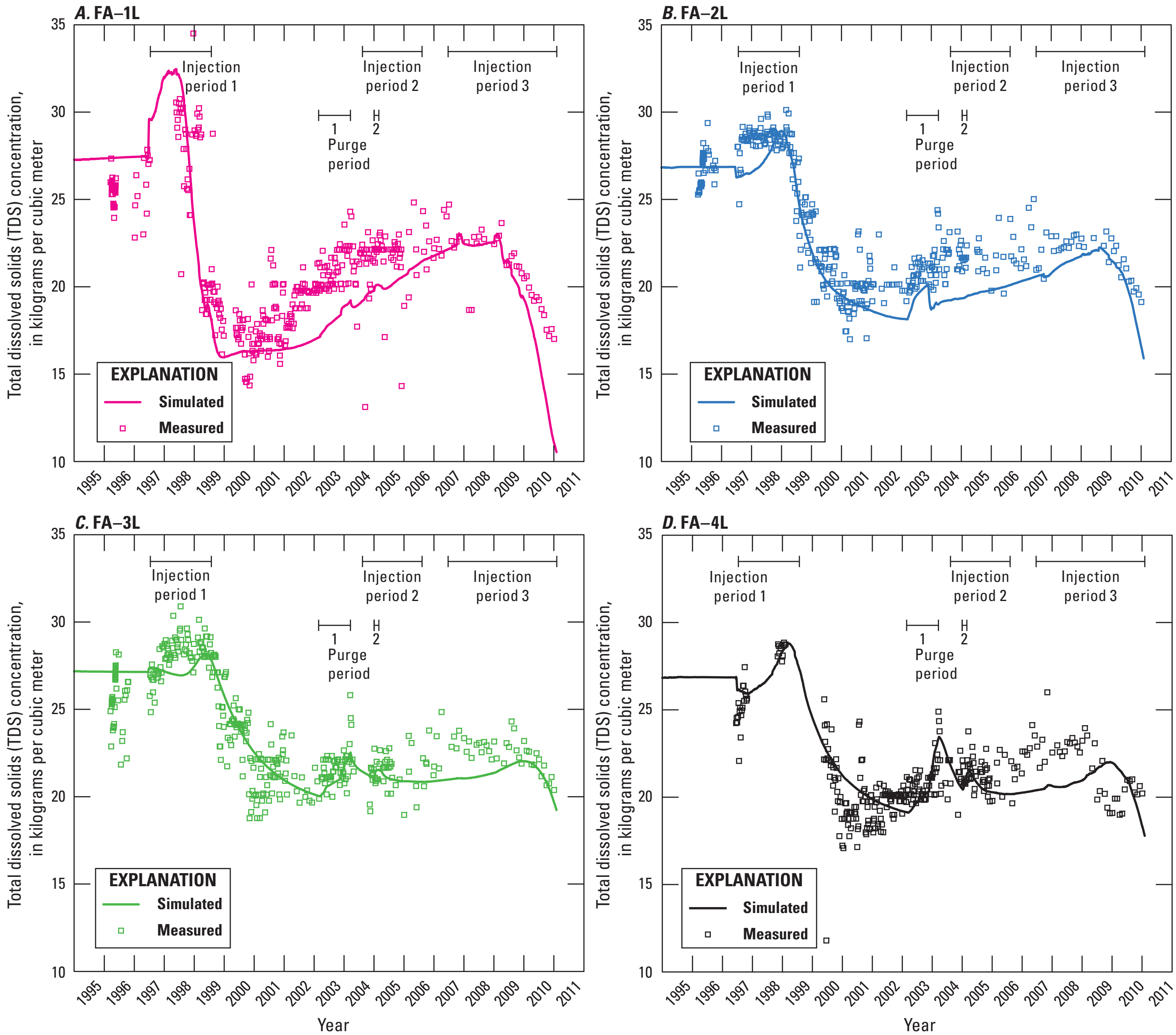


Figure 14. Concentrations of total dissolved solids (TDS), simulated and measured, at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, from 1995 to 2011, for lower zones of Floridan aquifer system monitoring wells *A*, FA–1L, *B*, FA–2L, *C*, FA–3L, and *D*, FA–4L.

Simulated ammonium concentrations qualitatively fit measured concentrations for lower zones of Floridan aquifer system monitoring wells (fig. 15). Simulated arrival times for ammonium matched measured arrival times. Simulated ammonium concentrations also qualitatively fit measured ammonium concentrations forced by the purge. Quantitatively, differences between measured, weighted ammonium concentrations and simulated ammonium concentrations accounted for 10 percent of an objective function valuation at each of the four lower zone monitoring wells, for a total contribution of 40 percent. Measured ammonium concentrations in these wells were weighted to make a greater contribution to the valuation than other kinds of measurements, because characterizing the effluent plume is one objective of the present investigation.

Simulated ammonium concentrations qualitatively fit measured concentrations for upper zones of Floridan aquifer system monitoring wells FA–1U and FA–3U (fig. 16*A*, *C*). Simulated ammonium concentrations qualitatively fit measured concentrations for FA–2U and FA–4U (fig. 16*B*, *D*) until about 2009. Observed discrepancies at wells FA–2U and FA–4U after 2009 could be related to the sampling purges, which are not accounted for in the model. Quantitatively, differences between measured, weighted ammonium concentrations and simulated ammonium concentrations accounted for 2.5 percent of an objective function valuation

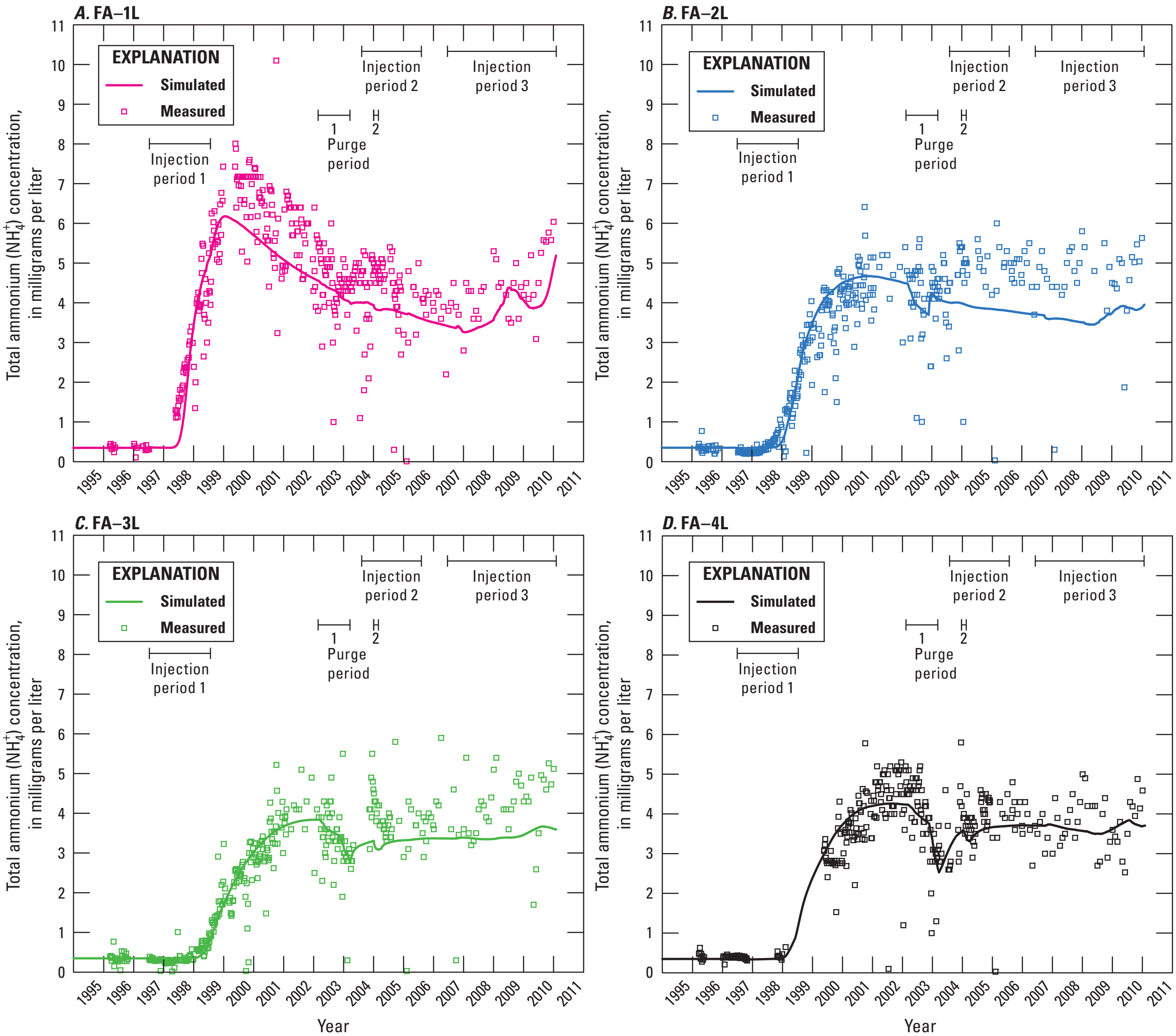


Figure 15. Total ammonium (NH_4^+) concentration, simulated and measured, at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, from 1995 to 2011, for lower zones of Floridan aquifer system monitoring wells *A*, FA–1L, *B*, FA–2L, *C*, FA–3L, and *D*, FA–4L.

at each of the four upper zone monitoring wells, for a total contribution of 10 percent.

Simulated TDS concentrations were about 1 part per thousand greater than measured concentrations for upper zones of Floridan aquifer system monitoring wells FA–1U and FA–3U; and for upper zones of Floridan aquifer system monitoring wells FA–2U and FA–4U before about 2009 (fig. 17). Observed discrepancies at wells FA–2U and FA–4U after 2009 could be related to the sampling purges, which are not accounted for in the model. Quantitatively, differences between measured, weighted TDS concentrations and simulated TDS concentrations accounted for 2 percent of an objective function valuation at each of the four upper zone monitoring wells, for a total contribution of 8 percent.

Simulated potentiometric heads outside of the treatment plant were qualitatively similar to measured potentiometric heads at the following monitoring wells in the Upper Floridan aquifer: G–3061, DF–5 (G–3767), BF–4S (G–2941), BF–6 (G–2969), PBF–10R (PB–1765) and ENP–100 (NP–100) (table 1, figs. 7, 18, 19). Simulated potentiometric heads also qualitatively fit measured potentiometric heads at the following monitoring wells in the Avon Park permeable zone: DF–5, BF–4M, and MIR–MW1 (G–2964, PBP–I2) in Pembroke Pines (table 1, figs. 7, 20). Quantitatively, differences between measured, weighted potentiometric heads and simulated potentiometric heads accounted for 2 percent of an objective function valuation at each offsite monitoring well, for a total contribution of 18 percent.

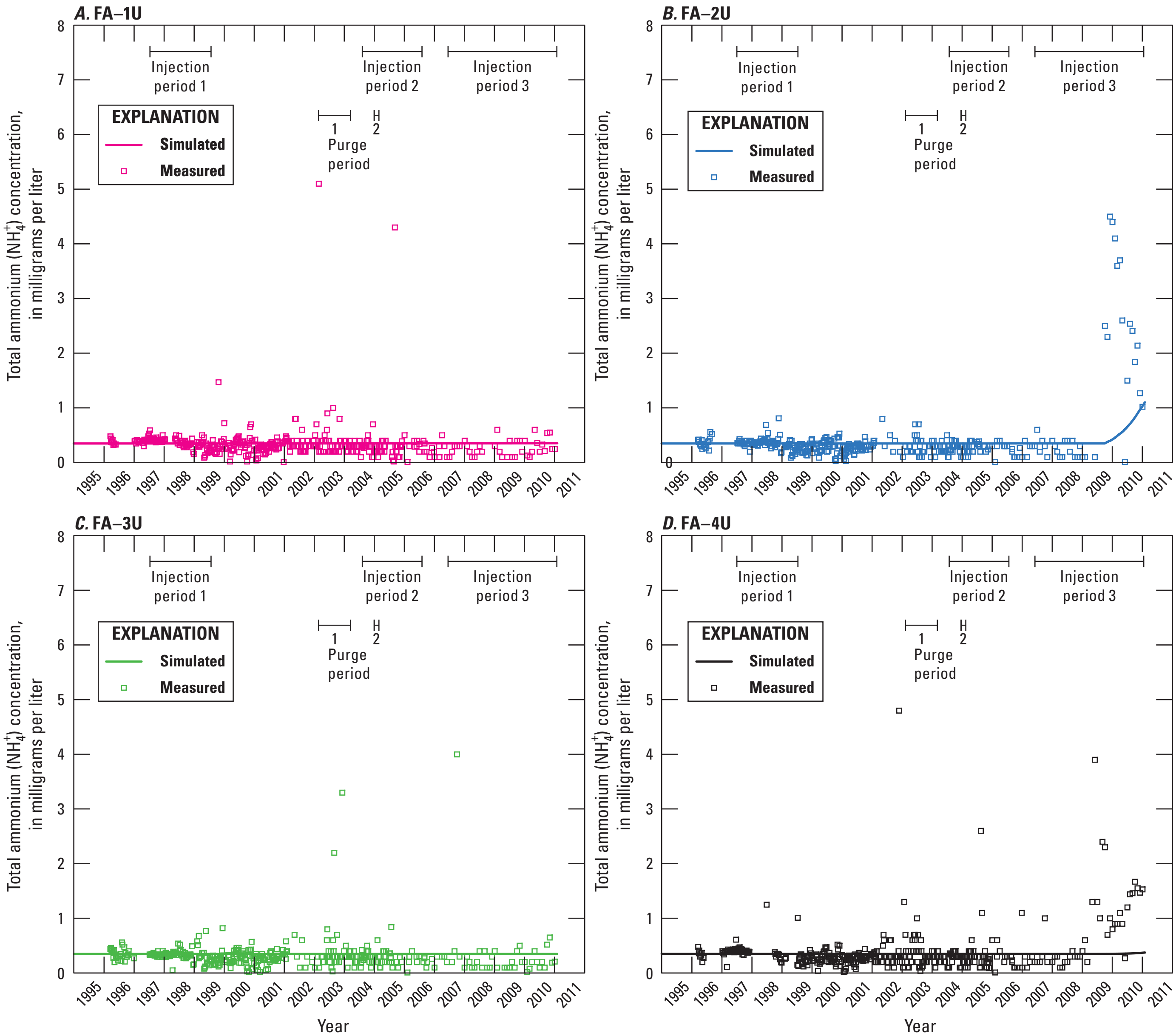


Figure 16. Total ammonium (NH_4^+) concentration, simulated and measured, at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, from 1995 to 2011, for upper zones of Floridan aquifer system monitoring wells *A*, FA–1U, *B*, FA–2U, *C*, FA–3U, and *D*, FA–4U.

Within the treatment plant, simulated potentiometric head was about 0.6 m higher, 0.4 m lower, 0.6 m higher, and 0.2 m lower than a generalized mean computed potentiometric head in upper zones of monitoring well FA–1U, before about 2005 in wells FA–2U and FA–3U, and before about 2008 in well FA–4U, respectively (fig. 21). Simulated potentiometric head did not qualitatively fit major deviations from the generalized mean computed potentiometric head in upper zones of Floridan aquifer system monitoring well FA–2U after about 2005 and in well FA–4U after about 2008 (fig. 21*B*, *D*). Quantitatively, differences between computed, weighted potentiometric head and simulated potentiometric head accounted for 2 percent of an objective function valuation at each of the four upper zone monitoring wells, for a total contribution of 8 percent.

Simulated potentiometric heads qualitatively fit computed potentiometric heads after about 2003 in the lower zone of Floridan aquifer system monitoring well FA–1L (fig. 22*A*). Simulated potentiometric head qualitatively fit computed potentiometric head in well FA–2L before about 2006 and at the end of the simulation in 2011 (fig. 22*B*). Simulated potentiometric head was a maximum of about 1.5 m lower than computed potentiometric head in well FA–2L between 2006 and 2011. Simulated potentiometric head qualitatively fit computed potentiometric head in well FA–3 before about 2010 (fig. 22*C*). Simulated potentiometric head was about 1 m lower than computed potentiometric head in well FA–3L after about 2010. Simulated potentiometric head was about 3 m lower than computed potentiometric head in well FA–4L

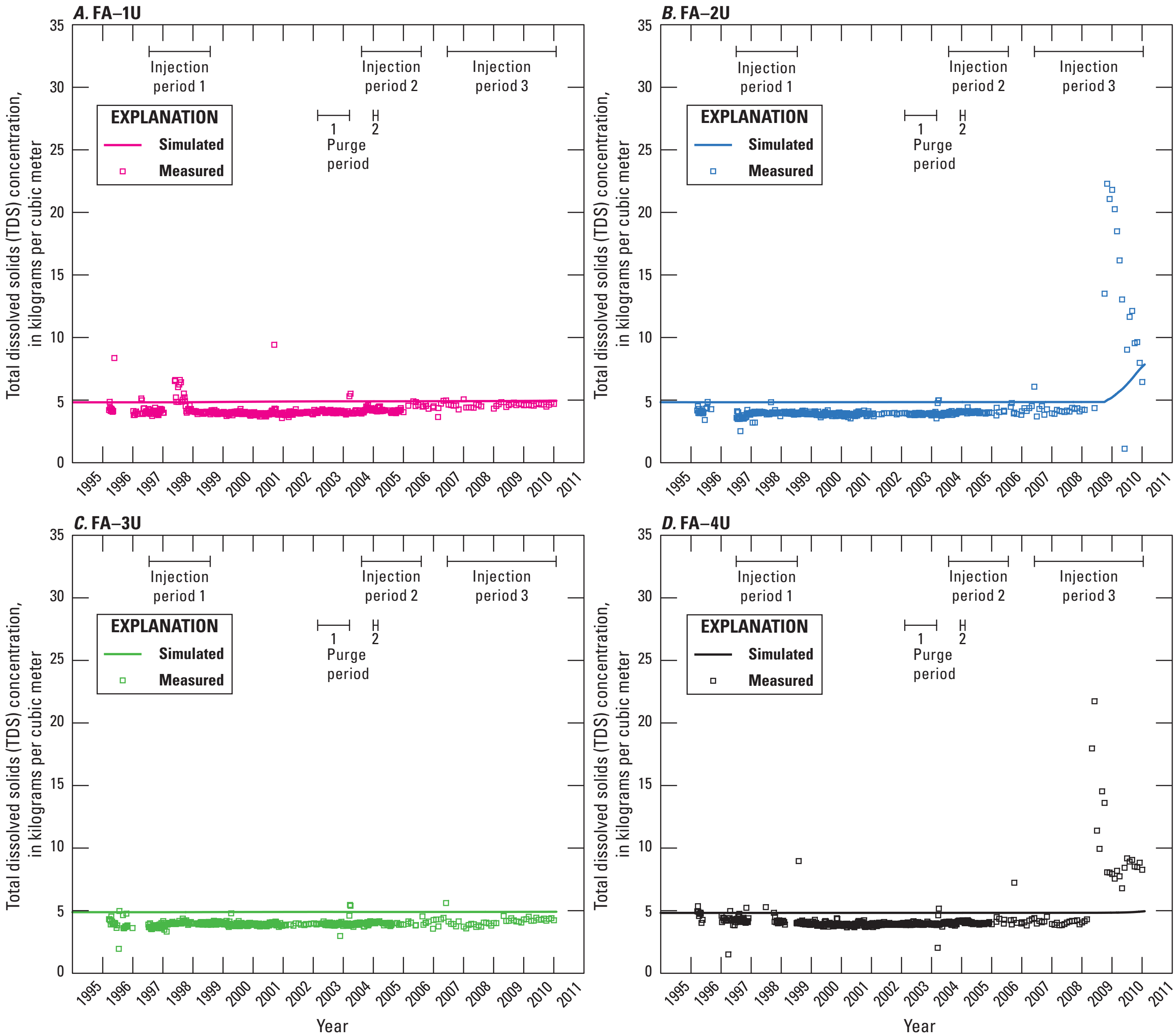


Figure 17. Concentrations of total dissolved solids (TDS), simulated and measured, at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, from 1995 to 2011, for upper zones of Floridan aquifer system monitoring wells *A*, FA–1U, *B*, FA–2U, *C*, FA–3U, and *D*, FA–4U.

before about 2003 and up to about 3 m lower after about 2009 (fig. 22*D*). Quantitatively, differences between computed, weighted potentiometric head and simulated potentiometric head accounted for 2 percent of an objective function valuation at each of the four lower zone monitoring wells, for a total contribution of 8 percent. Weighted differences between measured or computed values and simulated values detailed thus far in this section sum to a total contribution to the valuation of the objective function of 100 percent.

The discrepancy between simulated and observed potentiometric head in the upper and lower monitoring zones at the treatment plant could be due to error in the model conceptualization or in the computation of heads used as observation values. Uncertainty existed in the transducer-recorded pressure on which potentiometric head was computed for Floridan aquifer system monitoring wells at the treatment plant. Pressure transducers installed on Floridan aquifer system monitoring wells were inspected once on July 28, 2009, when a maximum pressure deviation of 0.95 pound per square inch (lb/in^2) (6,550 kilograms per meter per second squared or 6.55 kilopascals) was indicated for pressure transducers that monitored upper zones of Floridan aquifer system monitoring wells, and a maximum potentiometric-head deviation of 1.6 m was computed from the reading of the pressure transducers that monitored lower zones of Floridan aquifer system monitoring wells. Potentiometric head was computed from measured pressures in monitoring wells, postulated density of the water column

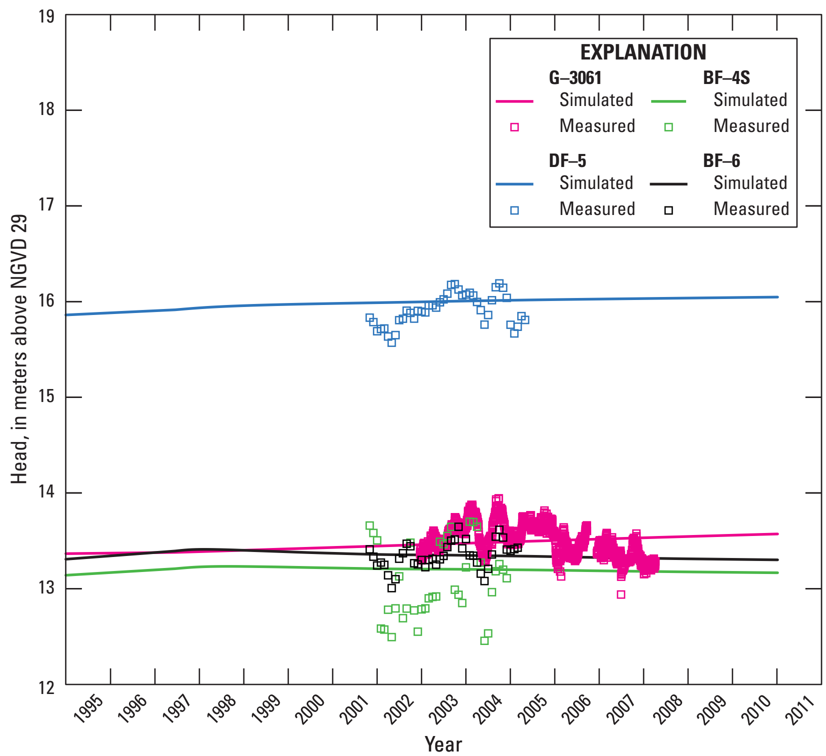


Figure 18. Potentiometric head, simulated and measured, from 1995 to 2011, in selected monitoring wells in the Upper Floridan aquifer, in Broward and Miami-Dade Counties, Florida.

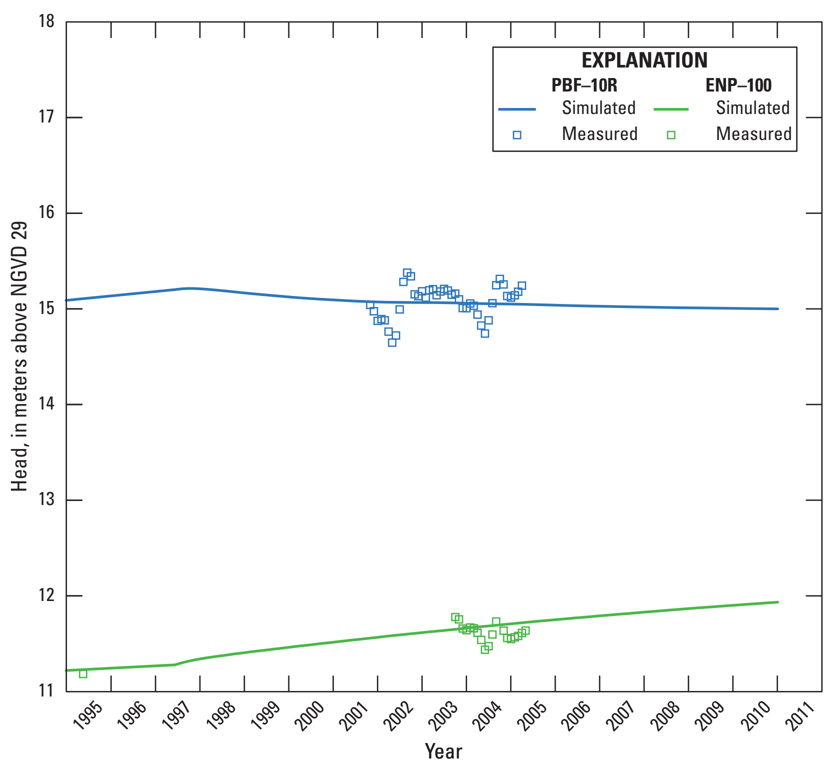


Figure 19. Potentiometric head, simulated and measured, from 1995 to 2011, in selected monitoring wells in the Upper Floridan aquifer, in Miami-Dade and Palm Beach Counties, Florida.

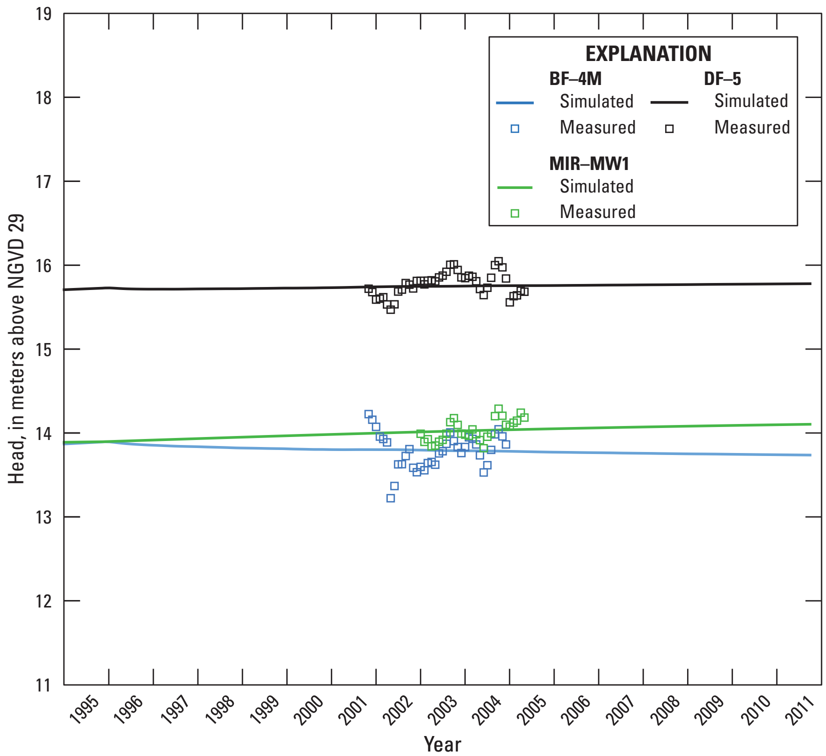


Figure 20. Potentiometric head, simulated and measured, from 1995 to 2011, in selected monitoring wells in the Avon Park permeable zone, in Broward and Miami-Dade Counties, Florida.

above points at which pressure was measured, and elevations of points. Each component of the potentiometric-head calculation had associated unknown error or uncertainty, which introduced error or uncertainty into the associated potentiometric-head calculation. It is not known whether 0.95-lb/in^2 and 1.6-m deviations are typical or atypical. The computed heads would also indicate a consistent, generally downward potentiometric gradient between the upper and lower monitoring zones during the simulation period, except after 2010 at monitoring sites FA–2 and FA–4, and it is not known with certainty whether this generally downward gradient exists between the Upper Floridan aquifer and the Avon Park permeable zone (figs. 21, 22). Computed potentiometric head in Floridan aquifer system monitoring wells at the treatment plant are, therefore, weighted less in parameter estimation analyses than TDS and ammonium concentration measurements.

Boulder Zone Confinement

Results of the simulations were used to characterize confinement of the Boulder Zone. Measured TDS and ammonium concentrations in the lower zones of Floridan aquifer system monitoring wells, which primarily sample the Avon Park permeable zone, indicate that effluent injected primarily into the Boulder Zone can be transported out and above the Boulder Zone. Results of simulations of the conceptual model indicate that the possibility of effluent transport out of the injection zone by naturally occurring transport paths cannot be rejected. If a naturally occurring transport path acts as a conduit for effluent flow out of the Boulder Zone and into the Avon Park permeable zone at the treatment plant, then hydrologic units above the Boulder Zone may not completely confine injected effluent.

Geologic structures in the deeper parts of the Floridan aquifer system that may provide a hydraulic connection between units have been identified in Florida (Cunningham, 2015; Reese and Cunningham, 2014; Spechler, 2001). The karst-collapse feature near IW–2 is a proximal structure that could connect the Boulder Zone to the Avon Park permeable zone. Other features may be associated with the regional fault system identified west of the treatment plant and provide conduits for fluid transport. Results of the present investigation indicate the potential importance of naturally occurring conduits in facilitating the transport of injected effluent in southeastern Florida. Maliva and others (2007) stated that the "distribution and cause of the development of fractures, and possibly other flow conduits, in the Floridan [a]quifer [s]ystem, is important for understanding vertical fluid migration" and that the "focus of confinement analyses should . . . be on the extent and distribution of fracturing rather than analyses of the properties of the rock matrix." It is important to characterize the extent and distribution of these potential naturally occurring transport

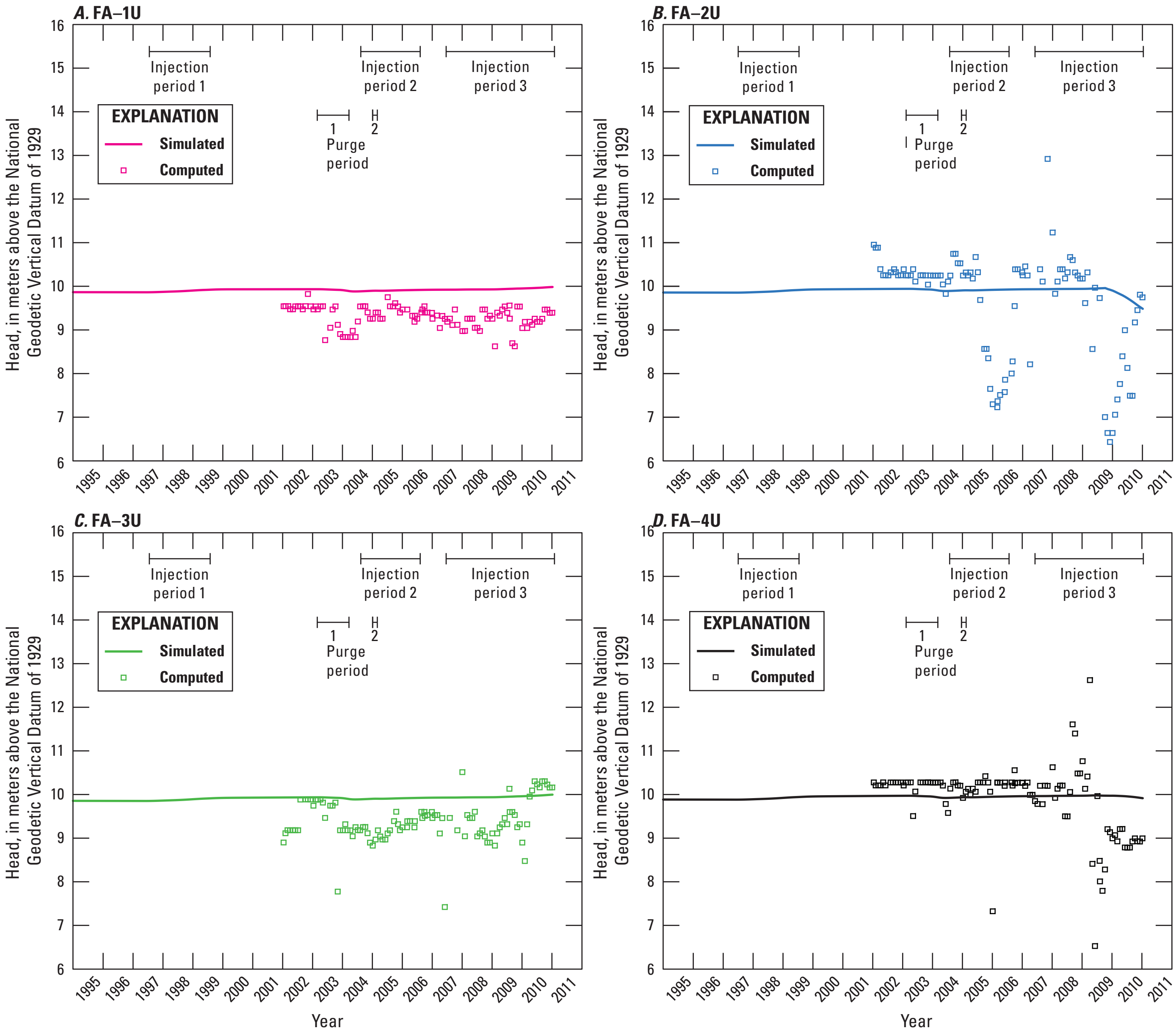


Figure 21. Potentiometric head, simulated and computed, from 1995 to 2011, in upper zones of Floridan aquifer system monitoring wells *A*, FA–1U, *B*, FA–2U, *C*, FA–3U, and *D*, FA–4U.

pathways, such as collapse features and faults, to evaluate the efficacy of confinement of injectate within targeted zones in the subsurface.

Confinement could potentially be further compromised by a lack of well integrity. The potential for vertical transport between permeable zones via breaches in monitoring zones is indicated by the ammonium and TDS concentration data in upper zones of Floridan aquifer system monitoring wells FA–2U and FA–4U after 2009. Although the breaches can provide conduits for effluent transport from the Boulder Zone into zones where samples were collected in Upper Floridan aquifer monitoring wells, the computed and simulated heads indicate a downward flow gradient between the Upper Floridan aquifer and the Avon Park permeable zone at the treatment plant.

Simulated Extent of the Effluent Plume in 2011

Results of the simulation were used to estimate the extent of effluent outside of the monitoring wells for the conditions represented by the conceptual model. The simulated extent of the plume is a function of hydrogeologic parameters and a postulated transport path, which may not reflect the actual location of a path or the existence of more than one path.

The simulated extent of the effluent plume in the Avon Park permeable zone and Boulder Zone on February 28, 2011, is shown in figures 23 and 24. The spatial distribution of simulated elevated ammonium concentration indicates the plume in the Avon Park permeable zone extends over

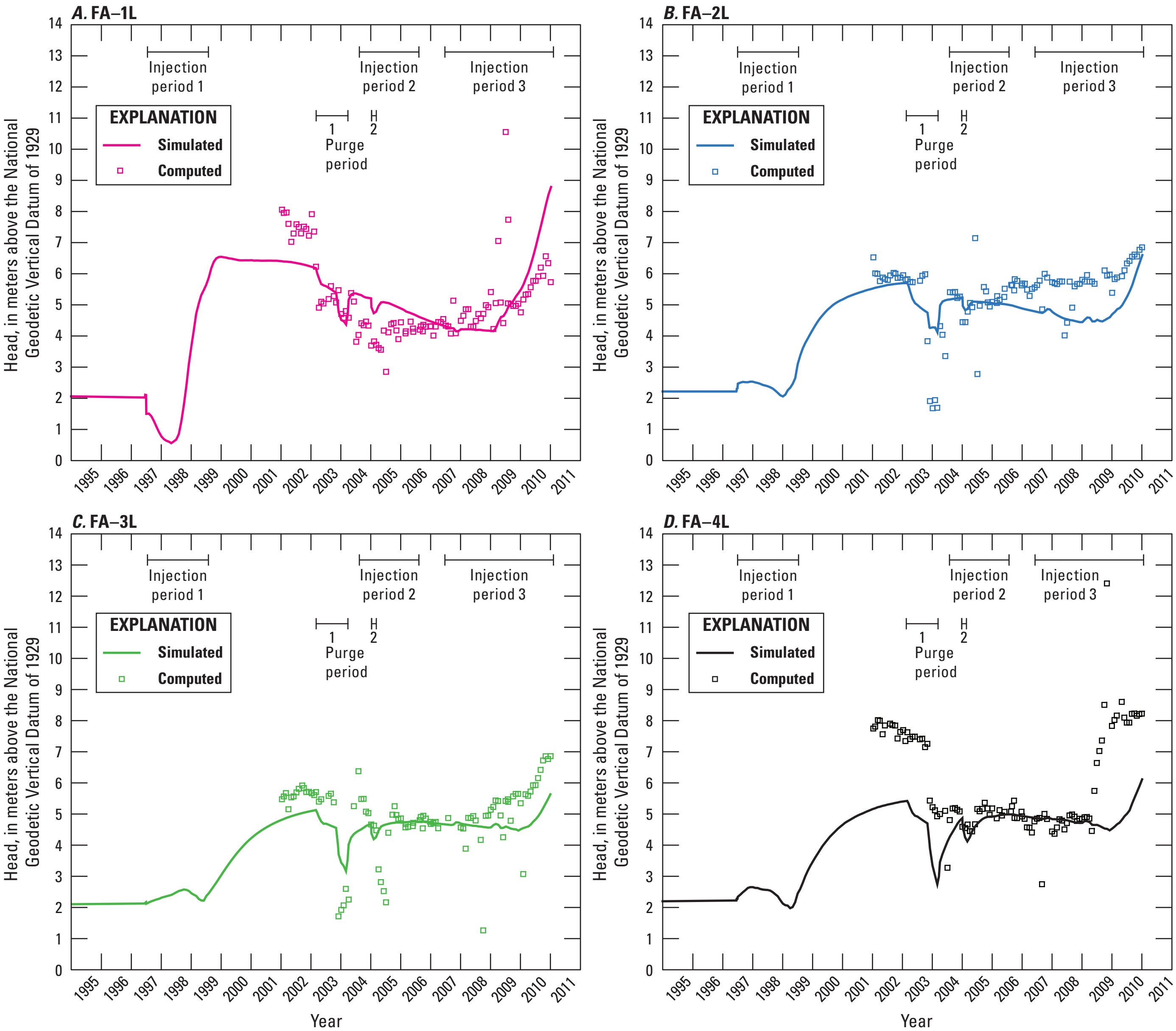


Figure 22. Potentiometric head, simulated and computed, from 1995 to 2011, in lower zones of Floridan aquifer system monitoring wells *A*, FA–1L, *B*, FA–2L, *C*, FA–3L, and *D*, FA–4L.

1 kilometer (km) beyond the treatment plant. The simulated extent is a generalized representation that indicates one possible plume size and constituent distribution. Other estimates of the plume extent and constituent distribution could be simulated with other conceptual models that fit the observations equally well. The present investigation does not confirm that the simulated extent of the effluent plume (figs. 23, 24) is the only possible extent.

The lower zone of Floridan aquifer system monitoring well FA–1L was purged from March 2003 to March 2004, the lower zones of Floridan aquifer system monitoring wells FA–2L, FA–3L, and FA–4L were purged from November 2003 to March 2004, and the lower zones of all four wells were purged from January 2005 to March 2005 (table 2; appendix 1). The effects of a purge are evident where and when constituent concentrations change with time toward background concentrations. The influence of a purge on time series for ammonium and TDS concentrations is a function of the size and location of the effluent plume. An effluent purge decreases ammonium concentrations and increases TDS concentrations more for a smaller plume than for a larger plume in the Avon Park permeable zone at the treatment plant. A purge decreases ammonium concentrations and increases TDS concentrations more in monitoring wells that are on the edge of the plume than in monitoring wells in the center of the plume, in the Avon Park permeable zone at the treatment plant.

Floridan aquifer system monitoring wells FA–1L and FA–2L are probably not on the edge of the plume, whereas Floridan aquifer system monitoring wells FA–3L and FA–4L may be on the edge of the plume, based on measured,

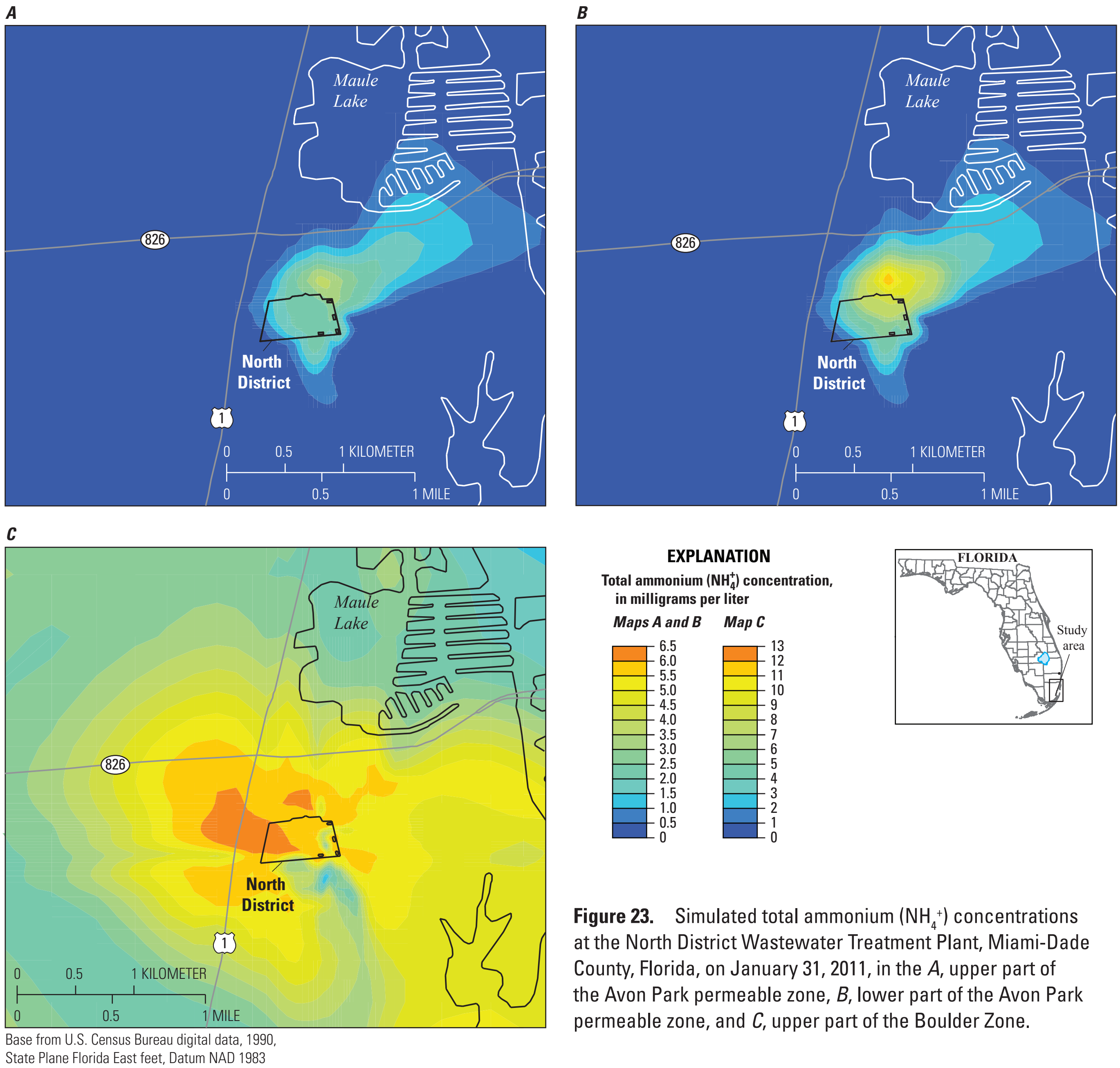
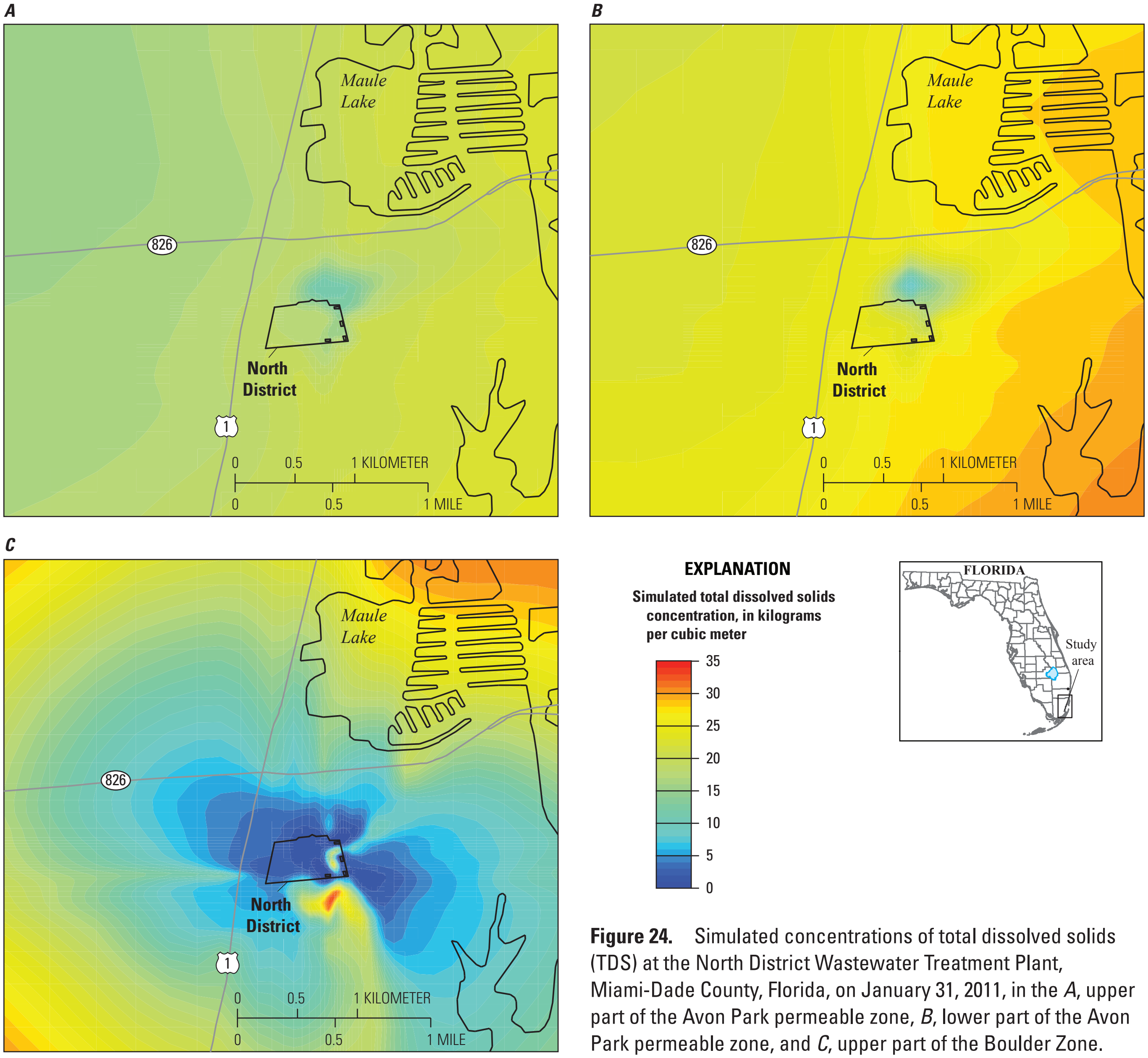


Figure 23. Simulated total ammonium (NH_4^+) concentrations at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, on January 31, 2011, in the *A*, upper part of the Avon Park permeable zone, *B*, lower part of the Avon Park permeable zone, and *C*, upper part of the Boulder Zone.

generalized rates of ammonium concentration change in these wells during the first purge period, when FA–1L was purged for a longer duration than all of the other purged wells (table 2; fig. 9). The simulation did not exhibit a change in the rate of ammonium concentration decrease at well FA–1L, in general agreement with the measured concentration time series (fig. 15*A*). The simulation exhibited a change in the rate of ammonium concentration decrease at wells FA–3L and FA–4L, also in general agreement with the measured concentration time series (fig. 15*C*, *D*). The simulation exhibited a change in the rate of ammonium concentration decrease at well FA–2L, which was not in general agreement with the measured concentration time series at that well (fig. 15*B*), and suggests that the effluent plume may be larger near well FA–2L than the simulated plume. Measured and simulated rates of ammonium concentration change are consistent with, but do not confirm, the interpretation that the location of the intersection of the transport path and the Avon Park permeable zone is northwest of injection well IW–1. The influence of the purge was equally evident in measured (fig. 10) and simulated (fig. 14) TDS concentrations during the first purge period. Similarly, the response to the purge is more evident in the observed TDS concentrations in the lower monitoring zones of wells FA–3L and FA–4L, and the simulation represents this response. The purge is less evident in observed TDS concentrations at in the lower monitoring zones of wells FA–1L and FA–2L, but the simulation results show the effect of the purge at well FA–2L.



Base from U.S. Census Bureau digital data, 1990,
State Plane Florida East feet, Datum NAD 1983

Figure 24. Simulated concentrations of total dissolved solids (TDS) at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, on January 31, 2011, in the *A*, upper part of the Avon Park permeable zone, *B*, lower part of the Avon Park permeable zone, and *C*, upper part of the Boulder Zone.

Limitations

Results of the numerical flow and transport model should be interpreted in consideration of the assumptions and uncertainties inherent to the model. The greatest sources of uncertainty in this model are associated with the conceptual model that describes the transport of effluent from the Boulder Zone to the Avon Park permeable zone, including the location, configuration, and efficacy of preferential pathways. A karst-collapse feature has been identified near IW–2, and the conceptual model hypothesis is that this feature allows fluid transport between the Boulder Zone and uppermost major permeable zone of the Lower Floridan aquifer. The extent of this feature is unknown, however, as well as its ability to transmit fluids between the Boulder Zone and uppermost major permeable zone of the Lower Floridan aquifer. A regional fault has been inferred near the treatment plant, and the conceptual model hypothesis is that this or a related feature allows transport of fluids between the uppermost major permeable zone of the Lower Floridan aquifer and the Avon Park permeable zone at a location north of the treatment plant. The location and extent of the fault, however, as well as its ability to transmit fluids are unknown.

The distribution, magnitude, and variability assigned to transport parameters in the model are not definitive and do not necessarily represent actual properties or conditions. Although many parameters are estimated to effect a reasonable match of simulated to observed concentrations and heads, calibrated values are predicated on the conceptual model and postulated transport pathways. Additionally, there is uncertainty in characterizing the transport system, even under an assumed correct conceptual model, related to the non-uniqueness of hydraulic/transport parameter estimation.

Simulated transport was most sensitive to the hydraulic conductivity of the Boulder Zone. For the upper part of the Boulder Zone, the simulation used homogeneous mobile zone porosity and heterogeneous hydraulic conductivity, which ranged over six orders of magnitude. This heterogeneous hydraulic conductivity was used to simulate the relatively more substantial influence of injection wells IW–2 and IW–3 on effluent transport from the Boulder Zone to the Avon Park permeable zone compared to that of injection wells IW–1 and IW–4. The complex heterogeneity near the treatment plant is utilitarian in replicating observed data but does not imply a detailed understanding of the distribution of hydraulic conductivity. Boulder Zone porosity was assumed to be uniform; it is not known whether, or to what degree, simulation of heterogeneous porosity would reduce the orders of magnitude range of heterogeneity in hydraulic conductivity required to fit simulated to observed potentiometric heads and concentrations. It is also not known if, or to what degree, other combinations of values for transport path conductance and distributions of hydraulic conductivity of overlying units would reduce the range of heterogeneity in hydraulic conductivity.

All of the hydraulic parameters controlling transport along the conceptualized transport path, including hydraulic conductivities of the uppermost major permeable zone of the Lower Floridan aquifer and the Avon Park permeable zone, and conductance values of the preferential vertical and lateral transport paths, are estimated or assigned to best replicate observed data, but are not definitively known. The estimation of all hydraulic parameters is subject to non-uniqueness, and the value estimated for each parameter is dependent on the estimated and assigned distribution of all the other parameters and variables.

Total dissolved solids and ammonium species are assumed to be conservative—nonreactive and transported at mean pore water velocity. The validity of this conservative assumption was not evaluated. The geochemical status of injectate is likely not at equilibrium with the geologic strata into which it is injected, possibly resulting in chemical reactivity between injectate constituents and subsurface rock. Additionally, ammonium, as a nutrient, may be subject to decay through microbial assimilation or may be microbially produced from more complex nitrogen-containing organic compounds in the injected wastewater.

Fluid density is dependent on TDS concentration and temperature. The dependence of density on TDS concentration was quantitatively incorporated within the simulation. However, the simulation did not account for the impact of temperature on density. Natural subsurface temperature gradients or differences between the temperature of injectate and ambient groundwater may affect fluid density and, therefore, groundwater flow and constituent transport in ways that are not considered in the simulation.

Both conceptualization of the flow system and flow model simulations of constituent transport are limited by uncertainties in the data upon which they are based. Potentiometric head data are computed rather than directly measured and are subject to error associated with transducers used to measure groundwater pressure and to error in the inferred density of the water column within a monitoring well. Multizone wells are subject to flaws that allow interflow between zones, obscuring the true water quality of an aquifer within a particular depth interval.

The model simulation domain includes the Floridan aquifer system, but the overlying intermediate confining unit and Biscayne aquifer are not simulated. Although substantial stresses are primarily applied to the Biscayne aquifer in the surficial aquifer system, these stresses were not represented in the simulation. This seemed reasonable, because it was assumed that the extremely high transmissivity of the Biscayne aquifer (Fish and Stewart, 1991), the relatively lower hydraulic conductivity of the intermediate aquifer system and confining unit (Miller, 1986; Williams and Kuniansky, 2016), and the negligible and distal stresses in the Upper Floridan aquifer would minimally affect injectate movement in the zones of concern at the treatment plant.

Initial conditions for potentiometric head in the Upper Floridan aquifer and Avon Park permeable zone, in the northwestern and southwestern corners of the simulation domain, were assumed at the inception of the simulation. A range of transient boundary conditions for potentiometric heads in the Upper Floridan aquifer and Avon Park permeable zone were postulated on the basis of literature values (appendix 1, table 1–1) in the northwestern and southwestern corners of the model domain, for the duration of the simulation. Potentiometric boundary head was an estimable parameter in the simulation, varying within these ranges in literature values, in response to the minimization of an objective function. The value of the objective function was relatively insensitive to these boundary conditions (appendix 1).

Whereas some parts of this investigation were quantitative, interpretations were qualitative. The investigation qualitatively indicates that fractures, karst-collapse structures, faults, or other hydrogeologic features may permit effluent injected into the Boulder Zone to be transported to overlying permeable zones in the Floridan aquifer system. Findings are qualitative, however, because the locations of transport paths that might exist from the Boulder Zone to the Avon Park permeable zone are largely unknown. Although the quantitative nature of the investigation may suggest to some readers precise, deterministic, quantitative findings, the findings of the investigation described in this report are qualitative.

Summary and Conclusions

The primary means of nonhazardous, secondarily treated, domestic wastewater (effluent) discharge at the North District Wastewater Treatment Plant (herein referred to as the treatment plant) plant is transitioning from an existing ocean outfall to underground injection. Since 1997, effluent from the treatment plant has been injected into the Boulder Zone, a highly transmissive hydrogeologic unit about 1 kilometer below land surface at the base of the Floridan aquifer system. Data collected from monitoring wells at the treatment plant indicate effluent has moved from the Boulder Zone upward into the Avon Park permeable zone at four monitoring wells after 1997. At two monitoring wells in the Upper Floridan aquifer, effluent was detected after 2009. Though not potable, groundwater in the Upper Floridan aquifer in the vicinity of the treatment plant is categorized by the U.S. Environmental Protection Agency as an Underground Source of Drinking Water, because it contains a sufficient quantity of groundwater to supply a public water system and has a total dissolved solids (TDS) concentration less than 10 kilograms per cubic meter. Effluent transport out of an injection zone into an Underground Source of Drinking Water is a risk of underground effluent injection.

Detection of constituents outside of the Boulder Zone indicates a lack of confinement of injected effluent in the Boulder Zone. Possible naturally occurring transport paths include a karst-collapse feature identified near injection well IW–2, and with less certainty, a possible fault structure north of the treatment plant. In addition, a leak within a monitoring well, between monitoring zones, allowed interflow between the Avon Park permeable zone and the Upper Floridan aquifer. It is important to characterize the extent and distribution of potential naturally occurring transport pathways to evaluate the efficacy of confinement of injectate within injection zones in the subsurface. Although a leak within a monitoring well was simulated, characterization of such infrastructure-related transport of effluent out of the targeted zones was not a primary objective of this evaluation.

The U.S. Geological Survey, in cooperation with the Miami-Dade Water and Sewer Department, investigated effluent transport from the Boulder Zone to overlying permeable zones in the Floridan aquifer system. Effluent injection into the Boulder Zone was simulated from 1997 to 2011. To represent the conceptual model of naturally occurring pathways that could transport effluent out of the Boulder Zone, one hypothetical effluent transport path from the Boulder Zone to the Avon Park permeable zone was characterized as follows. Effluent injected primarily into the Boulder Zone reaches a structural feature (a karst-collapse feature) near injection well IW–2 and is transported vertically upward through the feature to the uppermost major permeable zone of the Lower Floridan aquifer. The effluent is then transported laterally through the uppermost major permeable zone of the Lower Floridan aquifer to a structural feature (representing a fault or related structure) northwest of the treatment plant, and transported vertically upward through the feature into the Avon Park permeable zone. Leaks in monitoring wells between monitoring zones allowed interflow between the Avon Park permeable zone and the Upper Floridan aquifer. The model was calibrated to match observed concentration trends for total ammonium (NH_4^+) and TDS in Floridan aquifer system monitoring wells. The model generally replicated measured effluent constituent concentration trends, based on the hypothesized and non-unique conceptualization of the subsurface hydrogeology and flow system.

The extent of the effluent plume was estimated for 2011 using the simulated distribution of effluent constituents TDS and ammonium. In the Avon Park permeable zone, the simulated effluent plume was centered where the postulated transport path connected to the Avon Park permeable zone. The simulated effluent plume in 2011 was estimated to extend laterally over 1 kilometer from the treatment plant, in the Avon Park permeable zone. Measured and simulated rates of ammonium and TDS concentration change are consistent with, but do not confirm, that the location of the intersection of the transport path and the Avon Park permeable zone is northwest of injection well IW–1.

Simulation results should be interpreted in light of limitations in the model. The greatest source of uncertainty in the model is the conceptualization of the transport flow path from the Boulder Zone to the Avon Park permeable zone. Other limitations include uncertainty in the distribution, magnitude, and variability assigned to aquifer, confining unit, and transport parameters; the assumption of TDS and ammonium as conservative constituents; neglect of the temperature effects on water density and thus transport of the effluent; and uncertainty in hydraulic, geologic and water chemistry data upon which conceptualization of the flow system and flow model simulations is based. The investigation qualitatively indicates that fractures, karst-collapse structures, faults, or other hydrogeologic features may permit effluent injected into the Boulder Zone to be transported to overlying permeable zones in the Floridan aquifer system; findings are qualitative because the locations of transport paths that might exist from the Boulder Zone to the Avon Park permeable zone are largely unknown.

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Appendix 1. Summary of Simulation of Transport Duration and Path

A numerical model of groundwater flow and solute transport was constructed to simulate the conceptual model of the effluent transport system at the North District Wastewater Treatment Plant (herein referred to as the treatment plant), using a modified version of SEAWAT Version 4 (Langevin and others, 2007). SEAWAT Version 4 is a numerical model of variable-density groundwater flow and solute transport in a porous medium, built from MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and others, 2000) and MT3DMS (Zheng and Wang, 1999; Zheng and others, 2001) models for flow and transport, respectively. The model described here (Decker and King, 2018) represents injection of variable-density fluid, bearing a specified composition of total dissolved solids (TDS) and total ammonium (NH_4^+), into the Boulder Zone, and transport via the proposed conceptual model into the Avon Park permeable zone and into the upper monitoring zone at two monitoring wells. As implemented in the SEAWAT model, a zone of lower hydraulic conductivity is simulated between wells IW–3 and IW–4, and between wells IW–1 and IW–2. The low-conductivity zone forces transport of much of the effluent injected into wells IW–2 and IW–3 through the postulated vertical transport path near well IW–2 and provides a barrier to transport of effluent injected into wells IW–1 and IW–4 to the postulated vertical transport path. Model construction and calibration are described, including data used to simulate injection, boundary conditions, transport properties, and calibration data. The model was calibrated in stages using an automated parameter estimation approach in which objective functions of the difference between simulated and observed ammonium concentrations, TDS concentrations, and potentiometric heads were minimized (Doherty, 2010). Concentration measurements and computed heads from pressure data were subjectively weighted.

Stress History

Reported values of monthly injected effluent volume and effluent constituent concentrations reported by Miami-Dade County to the Florida Department of Environmental Protection (Miami-Dade County, 1999a, b, 2006; Decker and King, 2018), from June 1997 to September 1999, August 2004 to September 2006, and May 2007 to the end of the simulation in February 2011, were used in the model (figs. 4, 1–1, 1–2). Injection stress was specified at injection wells IW–1, IW–2, IW–3, and IW–4 during each time step, with the MODFLOW Well (WEL) Package. Injected effluent TDS and ammonium concentrations were specified at wells IW–1, IW–2, IW–3, and IW–4 during each time step, using the MT3DMS Source/Sink Mixing (SSM) Package.

Spatial Discretization

The model domain was discretized with MODFLOW Basic Input (BAS) Package, including the MODFLOW discretization (DIS) file, and the MT3DMS Basic Transport (BTN) Package. The simulated, 19,120-square-kilometer (km^2) region of southeastern Florida (fig. 1–3) was discretized into 6,162 cells, composing 79 columns in the east-west direction and 78 rows in the north-south direction. This discretization was sufficiently coarse in resolution to conduct hundreds to thousands of simulation runs to estimate parameters, and sufficiently fine in resolution to fit simulated to measured concentrations and potentiometric heads. The simulation domain was rectangular, extending 143 kilometers (km) in the east-west direction and 134 km in the north-south direction. Column and row dimensions graded from larger spatial dimensions at the domain corners to smaller spatial dimensions at the treatment plant. Maximum column width was 11.7 km along the western part of the simulation domain and maximum row width was 11.8 km along the southern part. Minimum column and row width were both 25 meters (m) near the eastern side of the treatment plant. Minimum column and row dimensions satisfied a resolution balance between simulation run time and simulation fit to measurements. Maximum cross-sectional area for a cell in the horizontal plane was 140 km^2 in the southeastern corner of the domain; minimum cross-sectional area was 625 square meters (m^2) near the eastern side of the treatment plant. The maximum increase in column width was 1.2; the maximum increase in row width was 1.3.

The simulation domain was discretized as 12 layers in the vertical dimension representing the following 10 hydrogeologic units, in descending order and as described herein (fig. 3): the surficial aquifer system (layer 1), the intermediate aquifer system or confining unit (layer 2), the Upper Floridan aquifer (layer 3), the upper part of the middle confining unit (layer 4), the Avon Park permeable zone (layers 5 and 6), the lower part of the middle confining unit (layer 7), the uppermost major permeable zone of the Lower Floridan aquifer (layers 8 and 9), the Lower Floridan confining unit (layer 10), and the Boulder Zone (layers 11 and 12). Layers 1, 2, 7, 8, and 10 were inactive. The number of layers and the choice of limiting the vertical resolution in the Avon Park permeable zone and Boulder Zone satisfied a resolution balance between simulation run time and simulation fit to measurements. The Avon Park permeable zone was split such that the upper part represented about two-thirds of the full unit thickness at any given location, and the lower part represented the remaining third. The Boulder Zone was split such that the upper part represented about one-tenth of the full unit thickness at any given location, and the lower part represented the remaining nine-tenths.

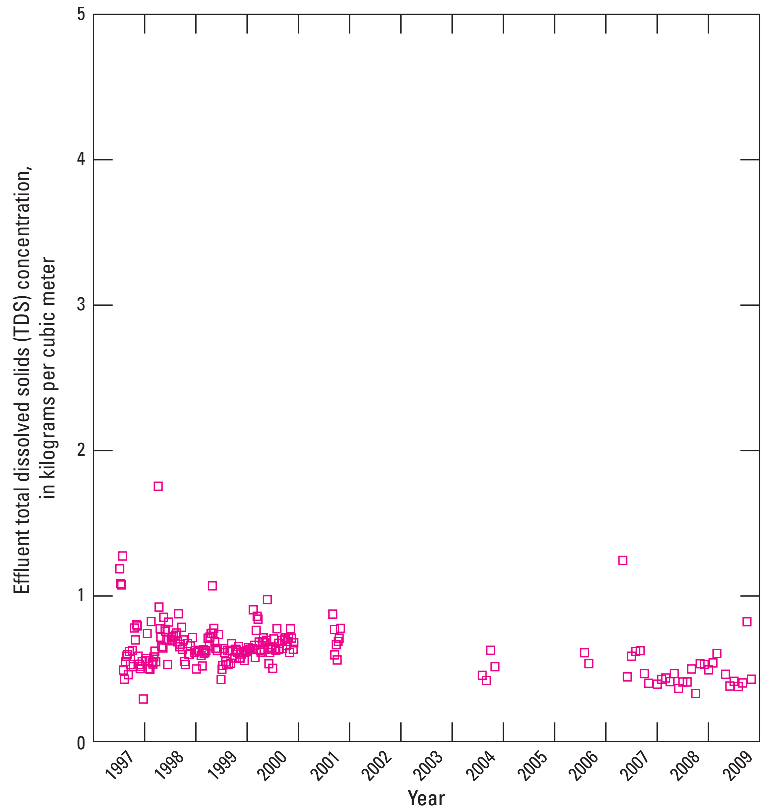

Figure 1–1. Measured, instantaneous effluent total dissolved-solids (TDS) concentrations from 1997 to 2009 at the North District Wastewater Treatment Plant, Miami-Dade County, Florida (Miami-Dade County, 2006; Decker and King, 2018).

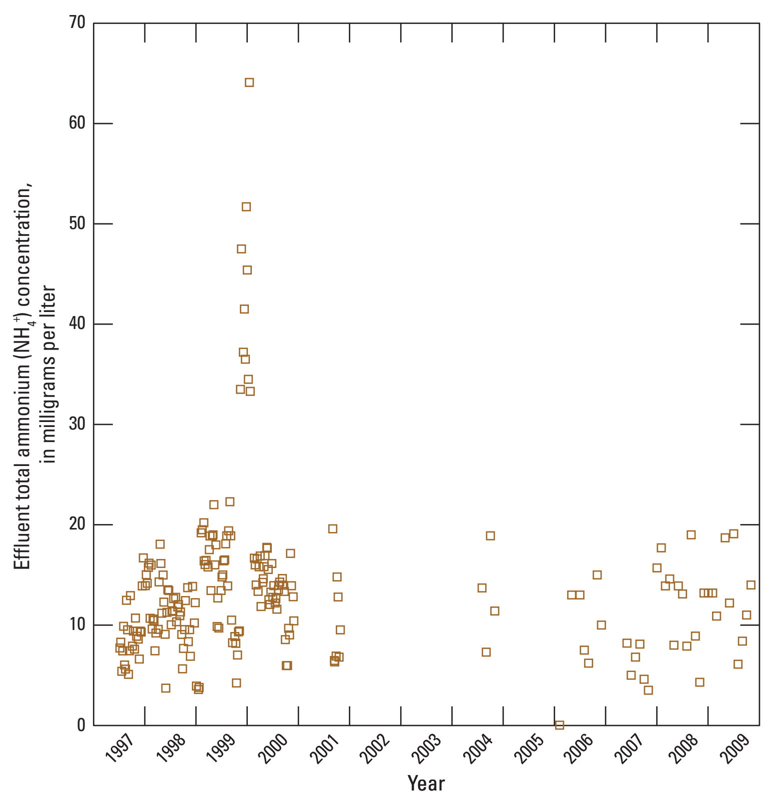

Figure 1–2. Measured, instantaneous effluent total ammonium (NH_4^+) concentrations from 1997 to 2009 at the North District Wastewater Treatment Plant, Miami-Dade County, Florida (Miami-Dade County, 2006; Decker and King, 2018).

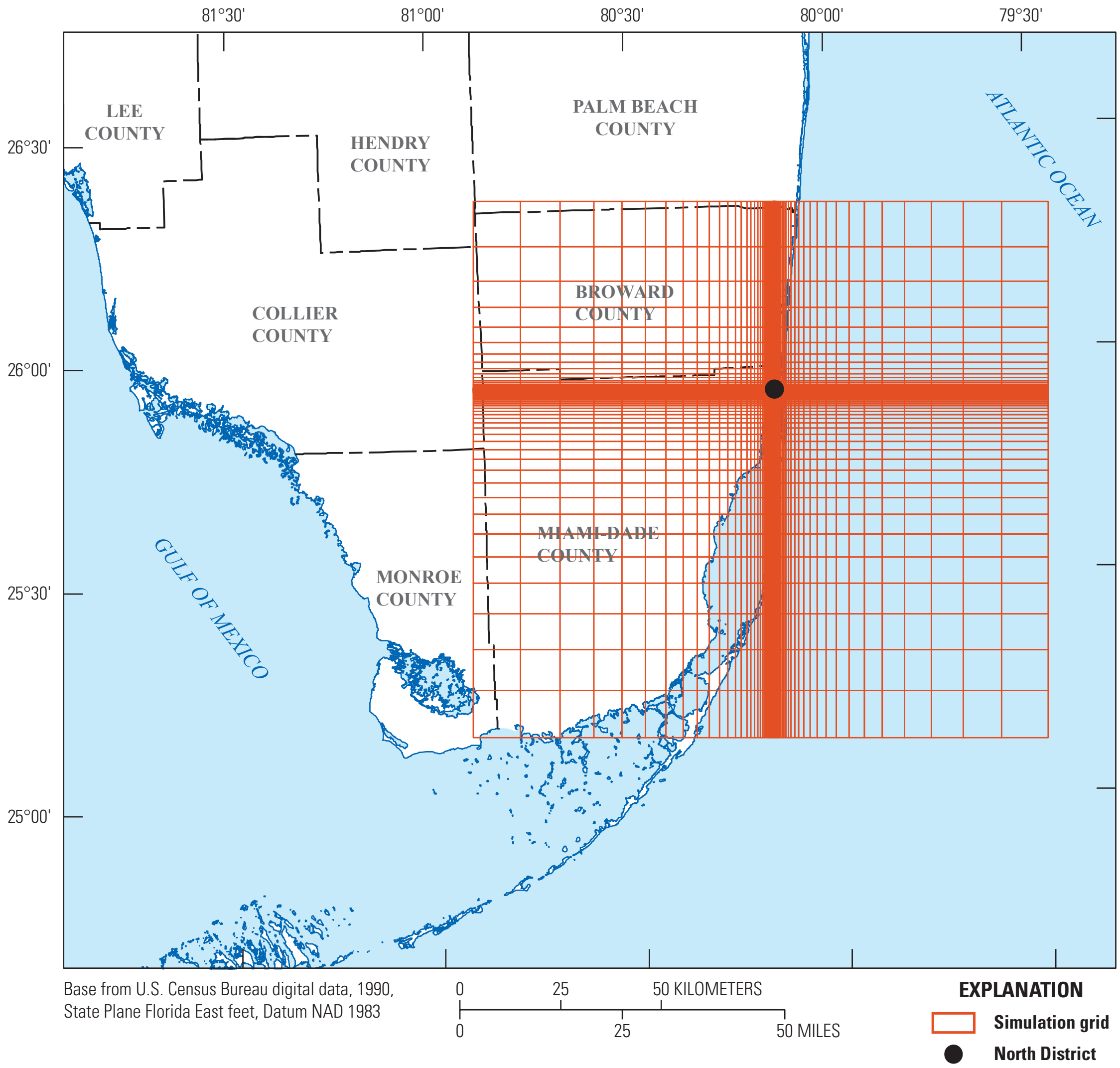

Figure 1–3. Simulation grid that covers Miami-Dade and Broward Counties, Florida.

Temporal Discretization

Time was discretized with the BTN Package and DIS file. The simulation detailed the period from June 14, 1977, to February 28, 2011. Stress was discretized into 177 periods, ranging from 1 day to 20 years, and the duration of most stress periods was 1 month. The initial transport step duration in each stress period was 1 day. A maximum transport step duration of 30 days was then used for all subsequent transport steps.

The first stress period was steady state with respect to groundwater flow. The steady-state condition was assigned to June 14, 1977. The second stress period detailed 20 years, from June 15, 1977, to June 15, 1997, during which time the simulation domain was forced by transient boundary conditions. June 15, 1997, was 2 days prior to initial effluent injection at the treatment plant on June 17. Seven 1-day, transient stress periods detailed the period from June 15 through June 21, 1997. One 9-day, transient stress period detailed the remainder of June 1997. From July 1997 through February 2003, the simulation used 68 monthly, transient stress periods from 28 to 31 days in duration. The months of March 2003, November 2003, March 2004, and January 2005 were each split into two stress periods (for a total of eight stress periods) that accounted for stresses associated with the purge of the Avon Park permeable zone (see “Introduction,” table 2). Monthly stress periods from 28 to 31 days in duration represented the remainder of April 2003 to December 2004 (19 stress periods) and February 2005 to February 2011 (72 stress periods).

Initial and Boundary Conditions

Constant or time-varying, specified potentiometric-head conditions were set for 1,054 cells using the MODFLOW IBOUND array (fig. 1–4). Of those cells, 548 were maintained at the initial values. Time-varying potentiometric head was specified on domain boundaries for the remaining 506 cells, during each time step, with the MODFLOW Time-Variant, Specified Head (CHD) Package (fig. 1–4). Potentiometric head was specified in domain corners for selected units and in

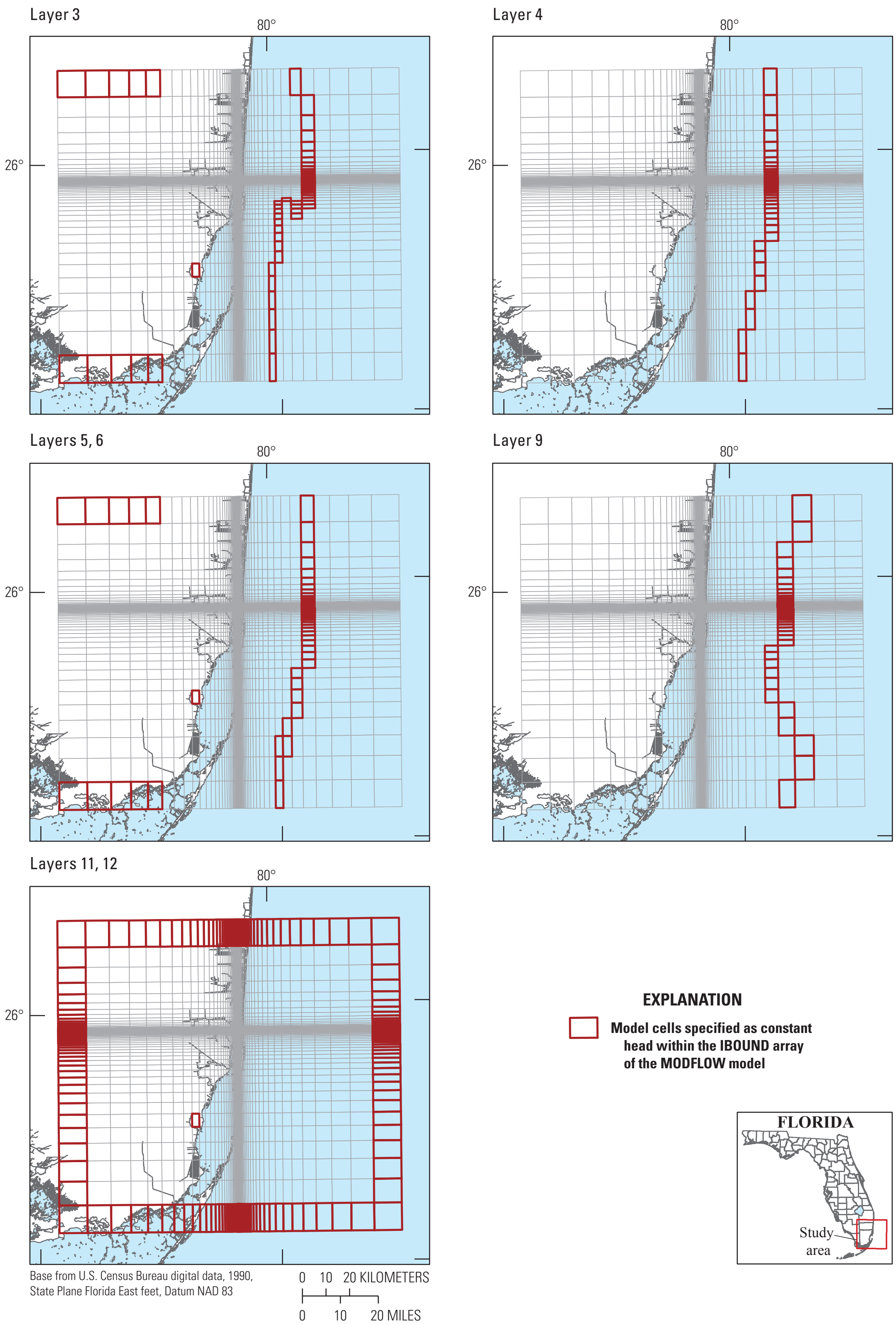

Figure 1–4. Model cells specified as constant head within the IBOUND array of the MODFLOW model.

cells that intersect the floor of the Atlantic Ocean for selected units. Potentiometric head was specified within the domain at one location representing the conditions at the treatment plant. For some boundary cells, potentiometric head was an adjustable parameter estimated using the model-independent parameter estimator (PEST; Doherty, 2010); for other cells, potentiometric head was not adjustable. Layers 1 and 2 (representing the surficial aquifer system and the intermediate aquifer system, respectively), layer 7 (representing the middle confining unit), and layer 10, (representing the Lower Floridan confining unit) were inactive, and thus represent no-flow boundary conditions.

In layer 3 (representing the Upper Floridan aquifer) and in layers 5 and 6 (upper and lower layers, respectively, representing the Avon Park permeable zone), time-varying potentiometric head was specified in cells indicated in figure 1–5 (table 1–1) with CHD heads as estimable parameters in domain corners, specifically, in the northernmost and southernmost rows, in the westernmost five cells. These specified potentiometric-head cells were near the northwestern and southwestern corners of the simulation domain (fig. 1–3). A total of 30 specified potentiometric-head cells represented western domain corners in the Upper Floridan aquifer and Avon Park permeable zone. Preferred values for parameter estimation analyses were obtained from the literature (Decker and King, 2018). In the westernmost five cells on the north side of the domain, potentiometric head was permitted to vary from 14 to 20 m, referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29); in the westernmost five cells on the southern side of the domain, potentiometric head was permitted to vary from 6 to 13 m NGVD 29.

Near where hydrogeologic units extend into the Atlantic Ocean, the potentiometric head in the unit is approximately equivalent to the water-surface elevation or sea level. Potentiometric head was specified with CHD for 314 cells on boundaries that extend into the Atlantic Ocean.

Generalized distributions of regional TDS concentrations (fig. 1–6) were contoured with measurements of TDS, salinity, and electrical conductivity. Reese (1994) investigated the distribution of dissolved solids in the Floridan aquifer system in southeastern Florida using borehole geophysical measurements and water-quality information. Reese (1994) identified 1 to 10 kilograms per cubic meter (kg/m^3) TDS concentrations as brackish groundwater, greater than 10 to 35 kg/m^3 TDS concentrations as slightly saline groundwater, and TDS concentrations greater than 35 kg/m^3 as saline groundwater. Ocean water is assigned a TDS concentration of 35 kg/m^3. Additional TDS concentrations shown in figure 1–6 were from the South Florida Water Management District (2011) and Dausman and others (2010).

Initial conditions for TDS concentrations (fig. 1–6) were specified in the BTN file. Initial TDS concentrations were specified to range from 34 to 35 kg/m^3 throughout the uppermost major permeable zone of the Lower Floridan aquifer and as 35 kg/m^3 throughout the Lower Floridan confining unit and Boulder Zone. In hydrogeologic units superjacent to the uppermost major permeable zone of the Lower Floridan aquifer, initial TDS concentrations were specified as 35 kg/m^3 near where the units extend to the Atlantic Ocean and less than 35 kg/m^3 to the west.

For each stress period, the following boundary conditions for TDS concentration were specified in the SSM file for specified potentiometric-head cells as follows: from 2 to 5 kg/m^3 in layer 3 (representing the Upper Floridan aquifer) in the northernmost rows for the westernmost five cells; from 4 to 6 kg/m^3 in layer 3, in the southernmost rows for the westernmost five cells; from 4 to 6 kg/m^3 in layers 5 and 6 (representing the Avon Park permeable zone), in the northernmost rows for the westernmost five cells; and from 19 to 24 kg/m^3 in layers 5 and 6 in the southernmost rows for the westernmost five cells. TDS concentrations were not specified at any other boundary location in the simulation domain.

The Florida Department of Environmental Protection required measurements to characterize effluent injection into the Boulder Zone and the confinement of injected effluent (Florida Department of Environmental Protection Operation Permit 0057792-009-UO). Some of these data defined an initial potentiometric-head condition in the Upper Floridan aquifer and Avon Park permeable zone. Specifically, for Floridan aquifer system monitoring wells at the treatment plant, TDS concentrations (figs. 8, 10; Decker and King, 2018) and gage pressure (figs. 1–7, 1–8) were measured. The initial potentiometric-head condition at the treatment plant was constructed from these TDS concentration and pressure time series.

Fluid density ρ in each monitoring zone was computed with the following equation of state:

$$\rho = \rho_f + (\rho_o - \rho_f)\frac{TDS - TDS_f}{TDS_o - TDS_f} \qquad (1\text{–}1)$$

where

ρ_f is freshwater density, in units of mass per cubic length;

ρ_o is canonical ocean-water density, in units of mass per cubic length;

TDS is measured TDS concentration, in units of mass per cubic length;

TDS_f is canonical freshwater TDS concentration, in units of mass per cubic length; and

TDS_o is canonical ocean-water TDS concentration, in units of mass per cubic length.

For the present investigation, the equation of state reduced to $\rho = 997.044\text{kg/m}^3 + 856 * TDS$, for which the result of the calculation is density in kilograms per cubic meter. Potentiometric head, in units of length, was computed for Floridan aquifer system monitoring wells (see “Results,” figs. 22, 23) using equation 2 of Guo and Langevin (2002).

The initial condition for potentiometric head was specified in the BAS file from a quasi-steady-state potentiometric-head distribution built specifically for this simulation. The initial condition for potentiometric head

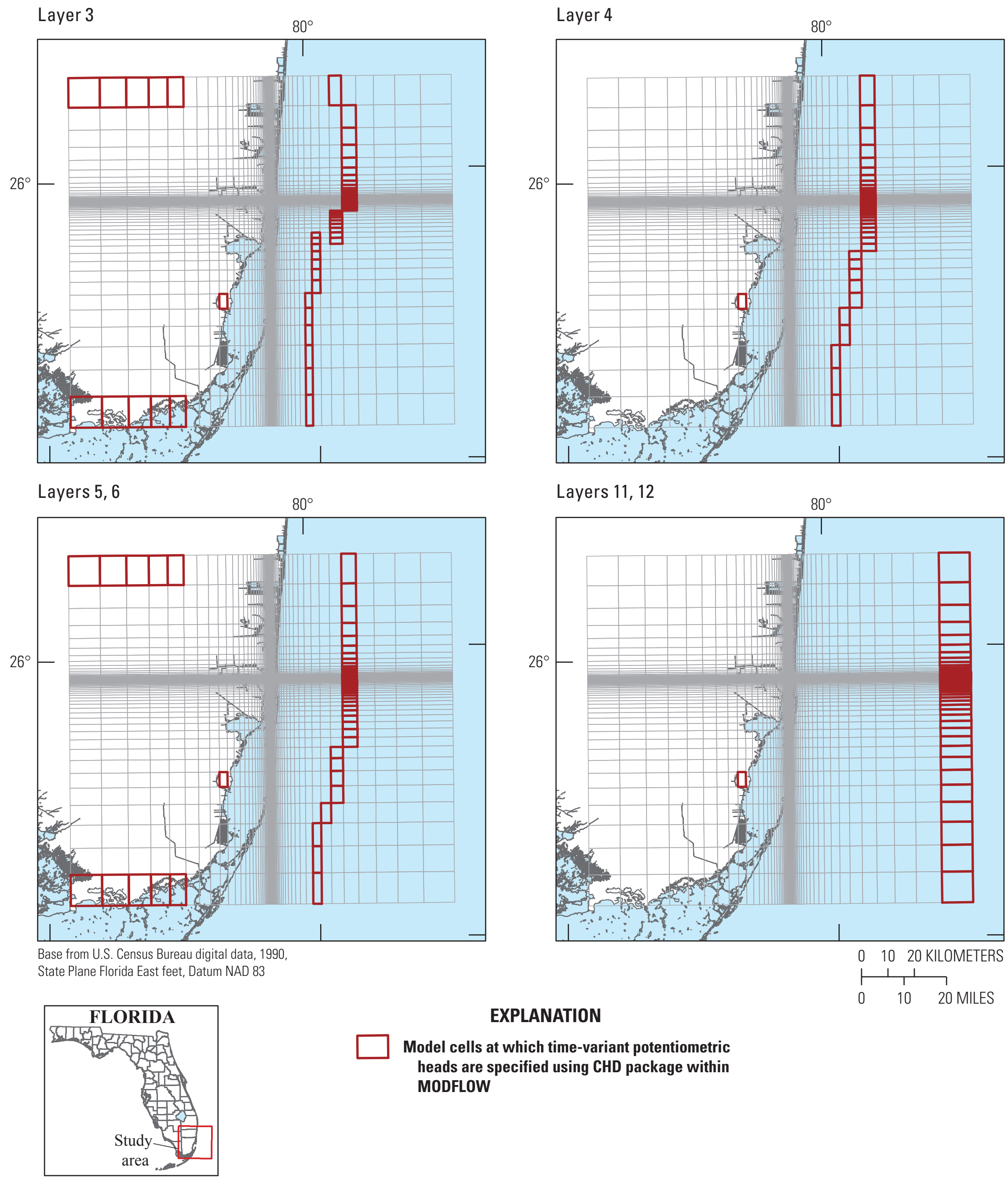

Figure 1–5. Model cells at which time-variant potentiometric heads are specified using the Time-Variant, Specified-Head (CHD) Package within MODFLOW.

was determined by assuming approximate potentiometric heads in each simulation cell as informed by the following: potentiometric-head time series at the treatment plant (figs. 21, 22); potentiometric-head time series at selected other locations in the Floridan aquifer system (figs. 18–20); and by Floridan aquifer system potentiometric surface elevations provided in Stringfield (1936), Parker and others (1955), Healy (1962), Kohout (1965), Healy (1975), Johnston and others (1980, 1981), Bush and Johnston (1988), the simulation described in Dausman and others (2010), and U.S. Army Corps of Engineers (2011).

Approximate potentiometric surface elevations for each layer were included in a preliminary simulation, with boundary conditions for potentiometric heads and TDS concentrations. The preliminary simulation was run until a quasi-steady state was established for potentiometric head, and it was used as the initial potentiometric-head condition for subsequent analyses. The quasi-steady state ensured that initial TDS concentrations were quasi-steady in response to initial potentiometric-head conditions, such that the initial TDS condition did not force potentiometric-head conditions to rapidly adjust during the first few time steps of a simulation

Table 1–1. Interpolated potentiometric surface elevations at selected locations in Miami-Dade and Broward Counties, Florida.

[Elevations are in meters, referenced to the National Geodetic Vertical Datum of 1929. NW, northwest; NE, northeast; SW, southwest; N, north; NDWWTP, North District Wastewater Treatment Plant]

Investigation	Potentiometric surface	Time period	Potentiometric surface elevation				
			Broward County		Miami-Dade County		
			NW corner	NE corner	SW corner	N end Elliot Key	NDWWTP
Johnston and others (1980)	Upper portion of Tertiary limestone aquifer system	Predevelopment	16	14	11	12	13
Bush and Johnston (1988)	Upper Floridan aquifer	Predevelopment	19	12	13	12	12
Stringfield (1936)	Artesian water	1934	14	12	6	9	11
Parker and others (1955)	Floridan aquifer	1944	14	12	6	6	11
Kohout (1965)	Principal artesian zone	1960	14	12	6	6	6
Healy (1962)	Floridan aquifer	July 1961	16	11	6	6	8
Healy (1975)	Floridan aquifer	May 1974	16	11	7	9	9
Johnston and others (1981)	Upper portion of Tertiary limestone aquifer system	May 1980	16	13	12	12	12
Bush and Johnston (1988)	Upper Floridan aquifer	May 1980	18	12	12	12	11

and the initial potentiometric-head condition did not force TDS conditions to rapidly adjust during the first few time steps of a simulation.

Drain-Return Flow Analog

Drain-return flow features were used to simulate radial flow away from injection wells IW-1 and IW-4 in the Boulder Zone, from the Boulder Zone to the uppermost major permeable zone of the Lower Floridan aquifer near IW–2, from the uppermost major permeable zone of the Lower Floridan aquifer to the Avon Park permeable zone northwest of the treatment plant, and from the Avon Park permeable zone to the Upper Floridan aquifer at monitoring sites FA–2 and FA–4 (fig. 1–9). In MODFLOW, the Drains with Return Flow (DRT) Package operates to allow flow between two nonadjacent model cells, a drain cell and a return cell, as governed by an assigned conductance (Banta, 2000). Conductance is defined by equation 31 of McDonald and Harbaugh (1988) as a function of hydraulic conductivity, cross-sectional area, and length. Flow in the drain-return element, flow returning to the simulation domain, and flow leaving the domain are calculated in the MODFLOW DRT Package using equations 3 and 5 of Banta (2000). For this simulation, the DRT Package was modified for SEAWAT to allow a head-dependent flux between the drain cell from which the flow originates and the return cell where the flow is received. Modifications to MODFLOW and MT3DMS codes detailed in the present report, which describe how MODFLOW DRT was incorporated into SEAWAT, are based on Guo and Langevin's (2002) MODFLOW Drain (DRN) Package documentation and review of the SEAWAT DRT code.

The SEAWAT DRT code was modified for the present investigation to allow a flow rate that is dependent on the freshwater equivalent heads in the return cell. In SEAWAT and MODFLOW, the drain elevation z_{DRT} is steady state and specified by the user. The SEAWAT DRT code was modified to read potentiometric head and constituent concentrations for the return cell from the most recent iteration of the simulation. The following changes were made to the SEAWAT code:

- The equivalent freshwater potentiometric head, $h_{f.DRT}$, in the drain-return feature, was equal to the most recently calculated equivalent freshwater potentiometric head at the return cell.
- The domain form of dimensionless density, $\frac{\rho_{(i,j,k)} - \rho_f}{\rho_{(i,j,k)}}$, was built from the average of most recently calculated densities in drain and return cells.
- The reference form of dimensionless density, $\frac{\rho_{(i,j,k)} - \rho_f}{\rho_f}$, was built from the average of most recently calculated densities in drain and return cells.
- The elevation of the return cell of the DRT element, z_{DRT}, was equivalent to the block center elevation in the return cell.

A drain-return flow feature using DRT was implemented between layers 11 and 12 (upper and lower layers, respectively, of the Boulder Zone) at six locations away from

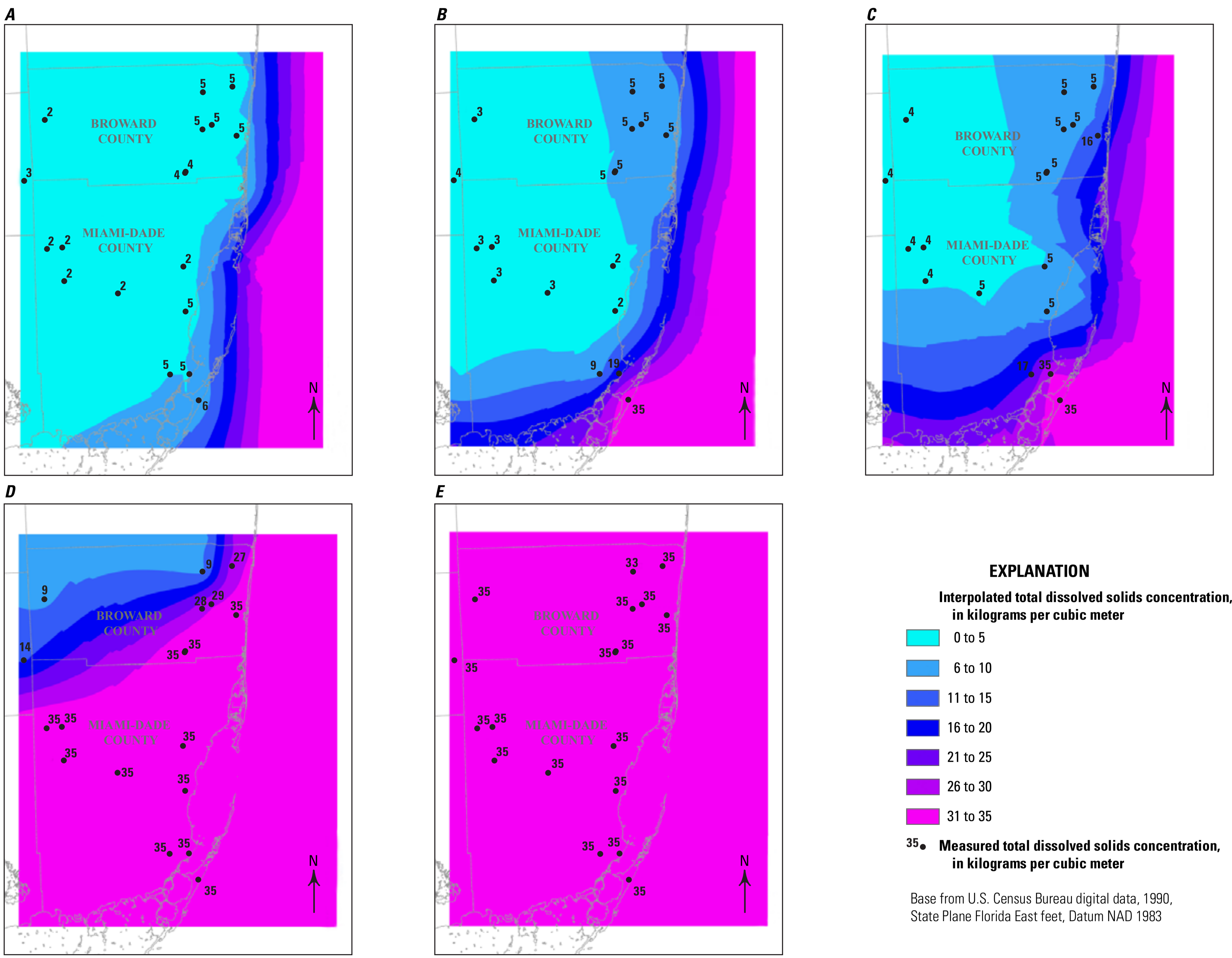

Figure 1–6. Generalized distributions of total dissolved solids (TDS) concentrations for the following hydrogeologic units in Miami-Dade and Broward Counties, Florida: *A*, Upper Floridan aquifer, *B*, upper part of the middle confining unit, *C*, Avon Park permeable zone, *D*, lower part of the middle confining unit, and *E*, uppermost major permeable zone of the Lower Floridan aquifer. Data are from Reese (1994), South Florida Water Management District (2011), and Dausman and others (2010).

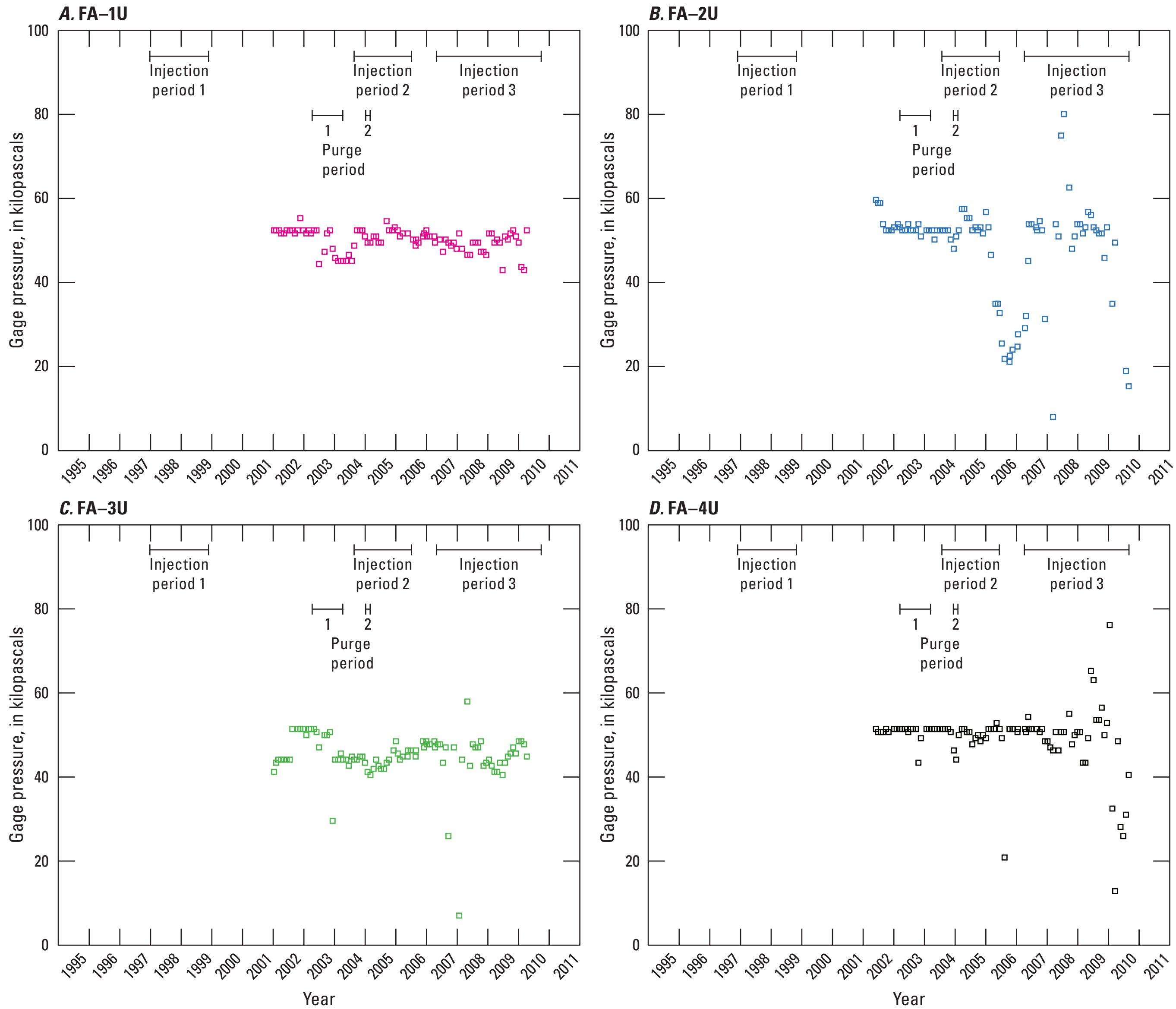

Figure 1–7. Measured, instantaneous gage pressure at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, from 2001 to 2010 in upper zones of Floridan aquifer system monitoring wells *A*, FA–1U, *B*, FA–2U, *C*, FA–3U, and *D*, FA–4U (Decker and King, 2018).

IW–1 and IW–4, to effect radial flow away from injection locations (fig. 1–8). DRT was implemented between layer 11 (upper Boulder Zone layer) and layer 9 (uppermost major permeable zone of the Lower Floridan aquifer) near IW–2 to represent bidirectional flow through a natural transport path, namely a karst-collapse feature. DRT was implemented between layer 9 (uppermost major permeable zone of the Lower Floridan aquifer) and layer 6 (lower layer of Avon Park permeable zone) northwest of the treatment plant to represent bidirectional flow through a hypothetical structure associated with a regional fault. DRT was implemented between layers 5 (upper layer of Avon Park permeable zone) and 3 (Upper Floridan aquifer) at monitoring sites FA–2 and FA–4 to represent interflow between monitoring zones through a breach in separation. Conductance was estimated using an inverse method (Doherty, 2010) to fit simulated to measured TDS (figs. 8, 10) and ammonium (figs. 9, 11) concentrations in Floridan aquifer system monitoring wells. Simulation sensitivities were quantified using PEST.

Parameter Estimation Measurements and Measurement Weights

Computed and measured potentiometric heads (see “Results,” figs. 18–22), measured TDS concentrations (see “Introduction,” figs. 8, 10), and measured ammonium concentrations (see “Introduction,” figs. 9, 11) were used to estimate parameters. About 10,000 computations and measurements were used. About 3,500 TDS concentrations and about 3,100 ammonium concentrations were measured

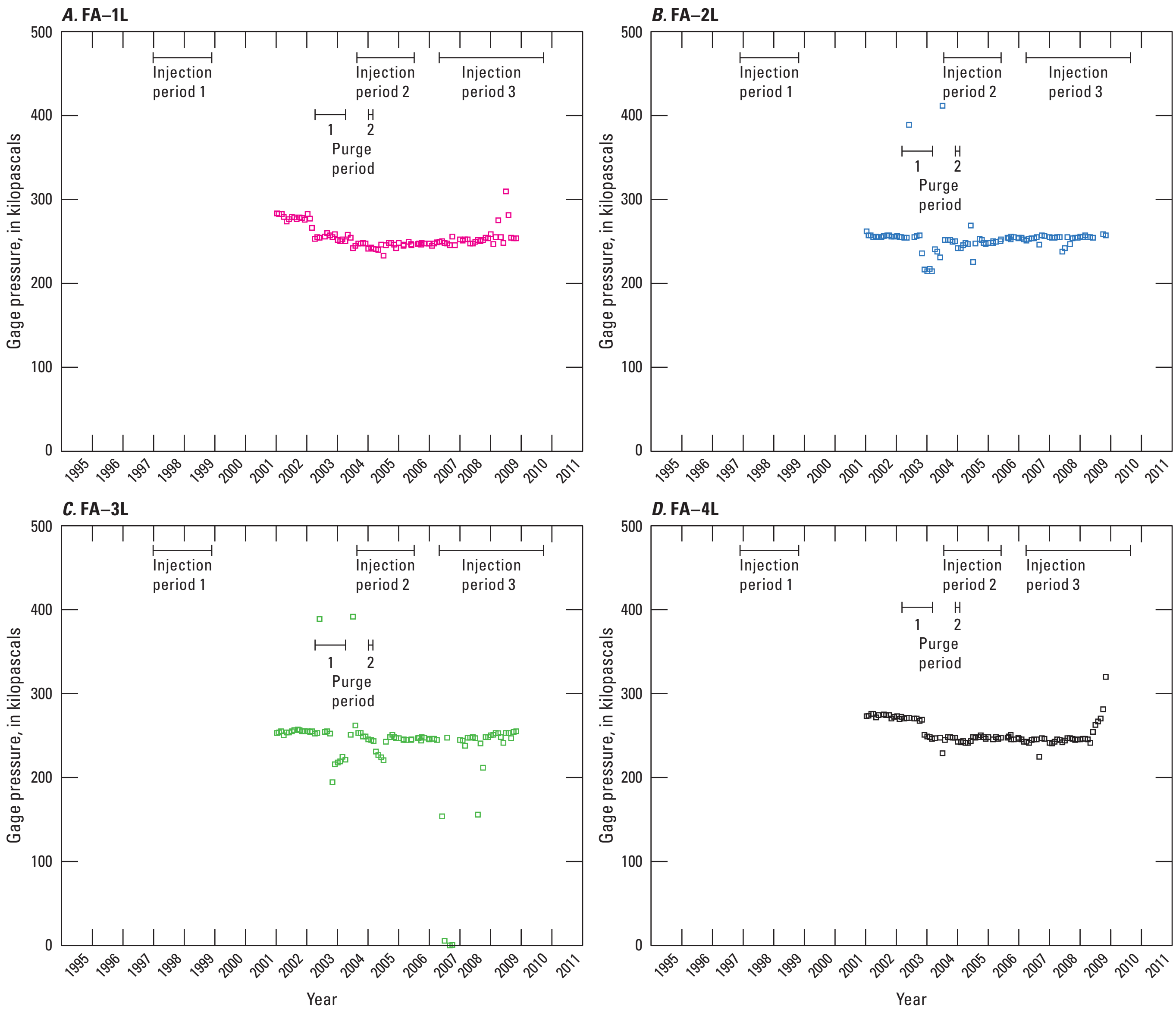

Figure 1–8. Measured, instantaneous gage pressure at the North District Wastewater Treatment Plant, Miami-Dade County, Florida, from 2001 to 2010 in lower zones of Floridan aquifer system monitoring wells *A*, FA–1L, *B*, FA–2L, *C*, FA–3L, and *D*, FA–4L (Decker and King, 2018).

in Floridan aquifer system monitoring wells at the treatment plant. Pressure was measured in monitoring wells completed in the Floridan aquifer system at the treatment plant (figs.1–6, 1–7). Density was computed from TDS concentration measurements (eq. 1–1). About 1,600 potentiometric heads (see “Results,” figs. 21, 22) were computed for Floridan aquifer system monitoring wells at the treatment plant using pressure measurements, elevation measurements, and density calculations (eq. 1–1). The South Florida Water Management District and the U.S. Geological Survey (USGS) made about 2,100 potentiometric-head measurements at six offsite locations in the Upper Floridan aquifer (see “Results,” figs. 18, 19) and three offsite locations in the Avon Park permeable zone (fig. 20).

Different strategies were used to weigh measurements and estimate parameters. Strategies were a function of the objective of the preliminary analysis; for example, in an early analysis, the objective was to estimate heterogeneous hydraulic conductivities for pilot points that described a regional hydraulic conductivity distribution. For the regional distribution, measurements of potentiometric head at the treatment plant were not necessarily more valuable than potentiometric heads at some distant location. For this analysis, potentiometric head at each of the nine offsite locations was weighted to contribute equally to the valuation of the objective function. Potentiometric head at the treatment plant was also included in this regional analysis, such that potentiometric heads at all eight Floridan aquifer system monitoring wells, considered together, and potentiometric

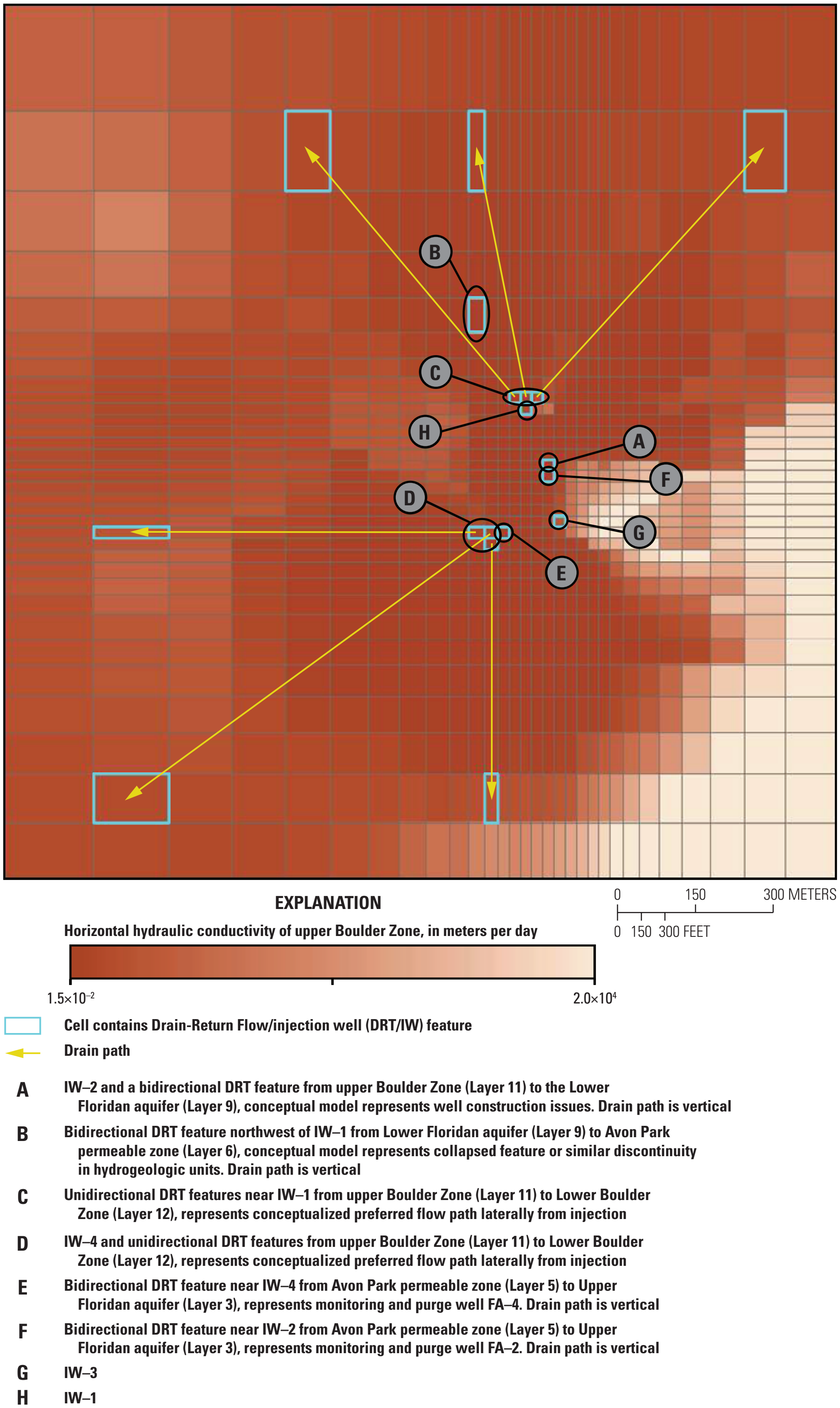

Figure 1–9. Location of drain and return cells, and estimated horizontal hydraulic conductivity values in layer 11, the upper Boulder Zone, at the North District Wastewater Treatment Plant, Miami-Dade County, Florida.

head at any of the nine offsite locations, each contributed equally to the valuation of an objective function. The preliminary analysis yielded hydraulic conductivity pilot points, which were subsequently used in preferred-value, or Tikhonov, regularization.

Parameter Estimation

Seventy-five parameters were estimated using PEST to describe the Upper Floridan aquifer, upper part of the middle confining unit, upper and lower parts of the Avon Park permeable zone, uppermost major permeable zone of the Lower Floridan aquifer, upper and lower parts of the Boulder Zone, and effluent transport paths that hypothetically connect permeable zones (table 1–2). Specifically, the following parameters were estimated: horizontal hydraulic conductivity, vertical hydraulic conductivity, mobile zone porosity, immobile zone porosity, mobile-immobile zone TDS mass transfer, mobile-immobile zone ammonium mass transfer, longitudinal dispersivity, horizontal transverse dispersivity ratio, vertical transverse dispersivity ratio, and transport path conductance. Boundary potentiometric heads in northwestern and southwestern simulation domain corners were also estimated for the Upper Floridan aquifer and upper and lower parts of the Avon Park permeable zone.

Parameter estimation involved thousands of simulation experiments. The final parameter set (table 1–2) was the result of successive refinement of individual parameters or groups of parameters; for example, in an early, simple test, the effects of heterogeneity and magnitude of Boulder Zone horizontal hydraulic conductivity on ammonium mass transport from the Boulder Zone to the Avon Park permeable zone were evaluated. A heterogeneous Boulder Zone hydraulic conductivity that ranged from 0.01 to 20,000 meters per day (m/d) forced a sufficient ammonium mass transport from the Boulder Zone to the Avon Park permeable zone to explain measured ammonium concentrations in the Avon Park permeable zone (fig. 1–10). Other parameters were fixed during the test; for example, parameters that govern transport in the Avon Park permeable zone were not varied during the test. Many heterogeneous Boulder Zone horizontal hydraulic conductivity distributions also generated a sufficient ammonium mass transport from the Boulder Zone to the Avon Park permeable zone to explain measured ammonium concentrations in the Avon Park permeable zone. The heterogeneous hydraulic conductivity distribution was bounded by literature values that ranged from 10^{-2} to 10^{4} m/d (Decker and King, 2018). Parameter correlation was not applicable because singular value decomposition regularization was used to estimate parameters (Doherty, 2010).

Parameter Sensitivity

The sensitivity metric (Doherty, 2010, equation 5.1) quantifies the impact of a unit change in a parameter on the simulation result. Units for the metric are mixed and of the form $[U_m]/[U_p]$, where $[U_m]$ was units for the simulation prediction and $[U_p]$ was units for the parameter. A unit change in a parameter having a relatively greater sensitivity metric caused a greater change in the simulation prediction than a unit change in a parameter having a relatively lesser sensitivity metric. For this reason, the sensitivity metric was not used to compare sensitivities of parameters having different dimensions, because the dimension of the metric was a function of the dimension of the parameter. Doherty (2010) provides further details about simulation sensitivity.

Multiplying the sensitivity metric by the parameter normalized the parameter-magnitude effect, producing an alternative measure of parameter sensitivity. This sensitivity product (table 1–2) is similar to scaled sensitivity (Hill, 1998). The units of this sensitivity product were $[U_p]\times[U_m]/[U_p] = [U_m]/\{[U_p]/[U_p]\}$, where the bracketed denominator in this unit construction represented a percentage change instead of a unit change. This sensitivity product was an alternative measure of parameter sensitivity and a measure of the potency of the parameter. Sensitivity products for two parameters with different units were comparable, because the units of the sensitivity product were equivalent to the units of the simulation prediction, regardless of the units of the parameter.

The most sensitive parameter with respect to the sensitivity product was the hydraulic conductivity of the upper layer of the Boulder Zone, followed by the horizontal and vertical hydraulic conductivity of the lower layer of the Boulder Zone, and the horizontal hydraulic conductivity of the upper layer of the Avon Park permeable zone (table 1–2). Total ammonium and TDS concentration measurements were weighted more heavily than other measurements, because these measurements are more descriptive of the plume than other measurements. Variation in the hydraulic conductivity of the Boulder Zone layers affect simulated TDS and ammonium concentrations more than other parameters. Lesser changes in hydraulic conductivity in the Boulder Zone layers affect simulated TDS and ammonium concentrations more than other parameters, such as mobile zone porosity in the Boulder Zone layers.

The simulation results were four times more sensitive to changes in hydraulic conductivity in the upper layer of the Boulder Zone ($K_{1/10BZ}$) than to changes in horizontal hydraulic conductivity in the lower layer of the Boulder Zone. The results of the simulation were 13 times more sensitive to changes in $K_{1/10BZ}$ than to changes in horizontal hydraulic conductivity in the lower layer of the Boulder Zone. The simulation results were 58 times more sensitive to changes in $K_{1/10BZ}$ than to changes in horizontal hydraulic conductivity in the upper layer of the Avon Park permeable zone. The results of the simulation were more than 100 times more sensitive to changes in $K_{1/10BZ}$ than to changes in other parameters, including, but not limited to, porosity in any permeable zone layer, conductance in the effluent transport path that connects the Boulder Zone to other permeable zone layers, boundary potentiometric heads, and dispersivity.

Table 1–2. Parameter, estimated parameter values, estimation method, hydrogeologic unit, and normalized sensitivity product.

[Min, minimum; Max, maximum; TDS, total dissolved solids; m/d; meter per day; n.d., not determined; 1/d, inverse day; m, meter; m NGVD, meters referenced to National Geodetic Vertical Datum of 1929; m^2/d, square meter per day; NA, not applicable]

Hydrogeologic unit	Model layer	Estimated parameter	Estimation method	Spatial distribution	Unit	Estimation			Sensitivity product		
						Value or mean value	Lower limit	Upper limit	Value or mean value	Min	Max
Upper Floridan aquifer	3	Horizontal hydraulic conductivity	Automated	Heterogeneous	m/d	5.76×10^{0}	9.00×10^{-2}	2.10×10^{1}	4×10^{-3}	7×10^{-5}	3×10^{-2}
		Vertical hydraulic conductivity	Trial-and-error	Homogeneous	m/d	2.94×10^{0}	1.00×10^{0}	5.00×10^{0}	3×10^{-3}	n.d.	n.d.
		Mobile zone porosity	Automated	Heterogeneous	Unitless	4.62×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	5×10^{-5}	5×10^{-6}	3×10^{-4}
		Immobile zone porosity	Trial-and-error	Homogeneous	Unitless	2.21×10^{-1}	6.50×10^{-2}	2.30×10^{-1}	2×10^{-4}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient TDS	Trial-and-error	Homogeneous	1/d	2.31×10^{-7}	1.00×10^{-8}	1.00×10^{-6}	1×10^{-3}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient NH_4^+	Trial-and-error	Homogeneous	1/d	1.00×10^{-7}	1.00×10^{-8}	1.00×10^{-6}	4×10^{-8}	n.d.	n.d.
		Longitudinal dispersivity	Trial-and-error	Homogeneous	m	3.49×10^{1}	9.00×10^{-1}	1.10×10^{2}	5×10^{-3}	n.d.	n.d.
		Horizontal transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	1.08×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	1×10^{-5}	n.d.	n.d.
		Vertical transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	9.00×10^{-4}	9.00×10^{-4}	2.10×10^{-2}	1×10^{-5}	n.d.	n.d.
		Boundary head -- northwest domain corner	Trial-and-error	Heterogeneous	m NGVD	1.69×10^{1}	1.68×10^{1}	1.71×10^{1}	5×10^{-4}	1×10^{-5}	1×10^{-3}
		Boundary head -- southwest domain corner	Trial-and-error	Heterogeneous	m NGVD	9.25×10^{0}	6.79×10^{0}	9.41×10^{0}	5×10^{-4}	7×10^{-6}	1×10^{-3}
Middle confining unit (upper part)	4	Horizontal hydraulic conductivity	Trial-and-error	Homogeneous	m/d	6.23×10^{-3}	1.00×10^{-4}	2.00×10^{-2}	8×10^{-6}	n.d.	n.d.
		Vertical hydraulic conductivity	Trial-and-error	Homogeneous	m/d	9.00×10^{-4}	9.00×10^{-4}	1.00×10^{-2}	1×10^{-6}	n.d.	n.d.
		Mobile zone porosity	Trial-and-error	Homogeneous	Unitless	9.00×10^{-3}	9.00×10^{-3}	2.10×10^{-1}	3×10^{-5}	n.d.	n.d.
		Immobile zone porosity	Trial-and-error	Homogeneous	Unitless	6.82×10^{-2}	6.50×10^{-2}	2.30×10^{-1}	5×10^{-5}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient TDS	Trial-and-error	Homogeneous	1/d	1.00×10^{-8}	1.00×10^{-8}	1.00×10^{-6}	8×10^{-5}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient NH_4^+	Trial-and-error	Homogeneous	1/d	9.53×10^{-8}	1.00×10^{-8}	1.00×10^{-6}	4×10^{-7}	n.d.	n.d.
		Longitudinal dispersivity	Trial-and-error	Homogeneous	m	9.99×10^{1}	9.00×10^{-1}	1.10×10^{2}	1×10^{-2}	n.d.	n.d.
		Horizontal transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	1.39×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	1×10^{-5}	n.d.	n.d.
		Vertical transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	1.87×10^{-3}	9.00×10^{-4}	2.10×10^{-2}	3×10^{-5}	n.d.	n.d.
Avon Park permeable zone	5	Horizontal hydraulic conductivity	Automated	Heterogeneous	m/d	7.38×10^{1}	5.00×10^{-2}	4.00×10^{2}	6×10^{-2}	3×10^{-5}	4×10^{-1}
		Vertical hydraulic conductivity	Trial-and-error	Homogeneous	m/d	9.59×10^{0}	1.00×10^{0}	2.00×10^{1}	1×10^{-2}	n.d.	n.d.
		Mobile zone porosity	Automated	Heterogeneous	Unitless	4.22×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	5×10^{-5}	5×10^{-6}	3×10^{-4}
		Immobile zone porosity	Trial-and-error	Homogeneous	Unitless	2.20×10^{-1}	6.50×10^{-2}	2.30×10^{-1}	1×10^{-4}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient TDS	Trial-and-error	Homogeneous	1/d	3.31×10^{-7}	1.00×10^{-8}	1.00×10^{-6}	6×10^{-4}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient NH_4^+	Trial-and-error	Homogeneous	1/d	2.97×10^{-8}	1.00×10^{-8}	1.00×10^{-6}	3×10^{-6}	n.d.	n.d.
		Longitudinal dispersivity	Trial-and-error	Homogeneous	m	9.00×10^{-1}	9.00×10^{-1}	1.10×10^{2}	1×10^{-4}	n.d.	n.d.
		Horizontal transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	1.25×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	1×10^{-5}	n.d.	n.d.
		Vertical transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	1.96×10^{-2}	9.00×10^{-4}	2.10×10^{-2}	2×10^{-4}	n.d.	n.d.
		Boundary head -- northwest domain corner	Trial-and-error	Heterogeneous	m NGVD	1.69×10^{1}	1.59×10^{1}	1.78×10^{1}	5×10^{-4}	1×10^{-5}	8×10^{-3}
		Boundary head -- southwest domain corner	Trial-and-error	Heterogeneous	m NGVD	7.48×10^{0}	7.22×10^{0}	7.78×10^{0}	5×10^{-4}	5×10^{-6}	1×10^{-3}

Table 1–2. Parameter, estimated parameter values, estimation method, hydrogeologic unit, and normalized sensitivity product.—Continued

[Min, minimum; Max, maximum; TDS, total dissolved solids; m/d; meter per day; n.d., not determined; 1/d, inverse day; m, meter; m NGVD, meters referenced to National Geodetic Vertical Datum of 1929; m^2/d, square meter per day; NA, not applicable]

Hydrogeologic unit	Model layer	Estimated parameter	Estimation method	Spatial distribution	Unit	Estimation: Value or mean value	Estimation: Lower limit	Estimation: Upper limit	Sensitivity product: Value or mean value	Sensitivity product: Min	Sensitivity product: Max
Avon Park permeable zone		Horizontal hydraulic conductivity	Automated	Heterogeneous	m/d	5.26×10^{0}	4.16×10^{-1}	2.10×10^{1}	4×10^{-3}	3×10^{-4}	3×10^{-2}
		Vertical hydraulic conductivity	Trial-and-error	Homogeneous	m/d	1.97×10^{0}	1.00×10^{0}	5.00×10^{0}	2×10^{-3}	n.d.	n.d.
		Mobile zone porosity	Automated	Heterogeneous	Unitless	3.63×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	4×10^{-5}	6×10^{-6}	4×10^{-4}
		Immobile zone porosity	Trial-and-error	Homogeneous	Unitless	2.22×10^{-1}	6.50×10^{-2}	2.30×10^{-1}	2×10^{-4}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient TDS	Trial-and-error	Homogeneous	1/d	1.00×10^{-9}	1.00×10^{-9}	1.00×10^{-7}	6×10^{-5}	n.d.	n.d.
	6	Mobile -- immobile zone mass transfer coefficient NH_4^+	Trial-and-error	Homogeneous	1/d	8.08×10^{-8}	1.00×10^{-8}	1.00×10^{-6}	1×10^{-6}	n.d.	n.d.
		Longitudinal dispersivity	Trial-and-error	Homogeneous	m	9.21×10^{-1}	9.00×10^{-1}	1.10×10^{2}	1×10^{-4}	n.d.	n.d.
		Horizontal transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	1.99×10^{-1}	9.00×10^{-3}	2.10×10^{-1}	2×10^{-4}	n.d.	n.d.
		Vertical transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	9.00×10^{-4}	9.00×10^{-4}	2.10×10^{-2}	1×10^{-5}	n.d.	n.d.
		Boundary head -- northwest domain corner	Trial-and-error	Heterogeneous	m NGVD	1.69×10^{1}	1.67×10^{1}	1.70×10^{1}	5×10^{-4}	1×10^{-5}	1×10^{-3}
		Boundary head -- southwest domain corner	Trial-and-error	Heterogeneous	m NGVD	7.48×10^{0}	7.33×10^{0}	7.78×10^{0}	5×10^{-4}	5×10^{-6}	2×10^{-3}
Uppermost major permeable zone of the Lower Floridan aquifer, lower part		Horizontal hydraulic conductivity	Trial-and-error	Homogeneous	m/d	1.01×10^{1}	9.00×10^{0}	1.10×10^{1}	2×10^{-2}	n.d.	n.d.
		Vertical hydraulic conductivity	Trial-and-error	Homogeneous	m/d	1.00×10^{1}	9.00×10^{0}	1.10×10^{1}	9×10^{-3}	n.d.	n.d.
		Mobile zone porosity	Trial-and-error	Homogeneous	Unitless	8.72×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	4×10^{-3}	n.d.	n.d.
		Immobile zone porosity	Trial-and-error	Homogeneous	Unitless	2.00×10^{-1}	6.50×10^{-2}	2.30×10^{-1}	2×10^{-4}	n.d.	n.d.
	9	Mobile -- immobile zone mass transfer coefficient TDS	Trial-and-error	Homogeneous	1/d	1.58×10^{-7}	1.00×10^{-8}	1.00×10^{-6}	4×10^{-4}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient NH_4^+	Trial-and-error	Homogeneous	1/d	5.67×10^{-8}	1.00×10^{-8}	1.00×10^{-6}	2×10^{-6}	n.d.	n.d.
		Longitudinal dispersivity	Trial-and-error	Homogeneous	m	1.04×10^{0}	9.00×10^{-1}	1.10×10^{2}	1×10^{-4}	n.d.	n.d.
		Horizontal transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	2.02×10^{-1}	9.00×10^{-3}	2.10×10^{-1}	3×10^{-4}	n.d.	n.d.
		Vertical transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	1.00×10^{-2}	9.00×10^{-4}	2.10×10^{-2}	1×10^{-6}	n.d.	n.d.
Boulder Zone		Horizontal hydraulic conductivity	Trial-and-error	Heterogeneous	m/d	5.95×10^{3}	1.00×10^{-2}	2.00×10^{4}	4×10^{0}	7×10^{-6}	2×10^{1}
		Vertical hydraulic conductivity	Trial-and-error	Heterogeneous	m/d	5.95×10^{3}	1.00×10^{-2}	2.00×10^{4}	4×10^{0}	7×10^{-6}	2×10^{1}
		Mobile zone porosity	Trial-and-error	Homogeneous	Unitless	9.54×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	1×10^{-4}	n.d.	n.d.
		Immobile zone porosity	Trial-and-error	Homogeneous	Unitless	2.20×10^{-1}	6.50×10^{-2}	2.30×10^{-1}	1×10^{-4}	n.d.	n.d.
	11	Mobile -- immobile zone mass transfer coefficient TDS	Trial-and-error	Homogeneous	1/d	2.84×10^{-4}	1.00×10^{-6}	1.00×10^{-3}	3×10^{-3}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient NH_4^+	Trial-and-error	Homogeneous	1/d	9.98×10^{-8}	1.00×10^{-8}	1.00×10^{-6}	2×10^{-8}	n.d.	n.d.
		Longitudinal dispersivity	Trial-and-error	Homogeneous	m	1.02×10^{0}	9.00×10^{-1}	1.10×10^{2}	1×10^{-4}	n.d.	n.d.
		Horizontal transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	1.03×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	8×10^{-6}	n.d.	n.d.
		Vertical transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	9.77×10^{-4}	9.00×10^{-4}	2.10×10^{-2}	7×10^{-6}	n.d.	n.d.

Table 1–2. Parameter, estimated parameter values, estimation method, hydrogeologic unit, and normalized sensitivity product.—Continued

[Min, minimum; Max, maximum; TDS, total dissolved solids; m/d; meter per day; n.d., not determined; 1/d, inverse day; m, meter; m NGVD, meters referenced to National Geodetic Vertical Datum of 1929; m^2/d, square meter per day; NA, not applicable]

Hydrogeologic unit	Model layer	Estimated parameter	Estimation method	Spatial distribution	Unit	Estimation			Sensitivity product		
						Value or mean value	Lower limit	Upper limit	Value or mean value	Min	Max
Boulder Zone		Horizontal hydraulic conductivity	Trial-and-error	Homogeneous	m/d	4.50×10^{3}	1.35×10^{3}	2.00×10^{4}	5×10^{0}	n.d.	n.d.
		Vertical hydraulic conductivity	Trial-and-error	Homogeneous	m/d	1.50×10^{3}	1.35×10^{3}	1.65×10^{3}	2×10^{0}	n.d.	n.d.
		Mobile zone porosity	Trial-and-error	Homogeneous	Unitless	9.79×10^{-2}	9.00×10^{-3}	2.10×10^{-1}	2×10^{-4}	n.d.	n.d.
		Immobile zone porosity	Trial-and-error	Homogeneous	Unitless	6.60×10^{-2}	6.50×10^{-2}	2.30×10^{-1}	6×10^{-5}	n.d.	n.d.
	12	Mobile -- immobile zone mass transfer coefficient TDS	Trial-and-error	Homogeneous	1/d	2.98×10^{-4}	1.00×10^{-6}	1.00×10^{-3}	3×10^{-4}	n.d.	n.d.
		Mobile -- immobile zone mass transfer coefficient NH_4^+	Trial-and-error	Homogeneous	1/d	9.94×10^{-8}	1.00×10^{-8}	1.00×10^{-6}	4×10^{-8}	n.d.	n.d.
		Longitudinal dispersivity	Trial-and-error	Homogeneous	m	3.78×10^{1}	9.00×10^{-1}	1.10×10^{2}	5×10^{-3}	n.d.	n.d.
		Horizontal transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	9.00×10^{-3}	9.00×10^{-3}	2.10×10^{-1}	1×10^{-5}	n.d.	n.d.
		Vertical transverse dispersivity ratio	Trial-and-error	Homogeneous	Unitless	2.01×10^{-2}	9.00×10^{-4}	2.10×10^{-2}	2×10^{-4}	n.d.	n.d.
N/A	5 to 3	Transport path conductance at well FA–2	Trial-and-error	Homogeneous	m^2/d	1.00×10^{1}	5.00×10^{0}	2.00×10^{1}	1×10^{-3}	n.d.	n.d.
	5 to 3	Transport path conductance at well FA–4	Trial-and-error	Homogeneous	m^2/d	1.00×10^{1}	5.00×10^{0}	2.00×10^{1}	1×10^{-3}	n.d.	n.d.
	9 to 6	Transport path conductance	Trial-and-error	Homogeneous	m^2/d	8.00×10^{1}	4.00×10^{1}	1.60×10^{2}	1×10^{-2}	n.d.	n.d.
	11 to 9	Transport path conductance	Trial-and-error	Homogeneous	m^2/d	8.01×10^{1}	4.00×10^{1}	1.60×10^{2}	1×10^{-2}	n.d.	n.d.
	11 to 12	Transport path conductance near well IW–1	Trial-and-error	Homogeneous	m^2/d	3.00×10^{2}	1.50×10^{2}	6.00×10^{2}	4×10^{-2}	n.d.	n.d.
	11 to 12	Transport path conductance near well IW–4	Trial-and-error	Homogeneous	m^2/d	3.00×10^{2}	1.50×10^{2}	6.00×10^{2}	4×10^{-2}	n.d.	n.d.

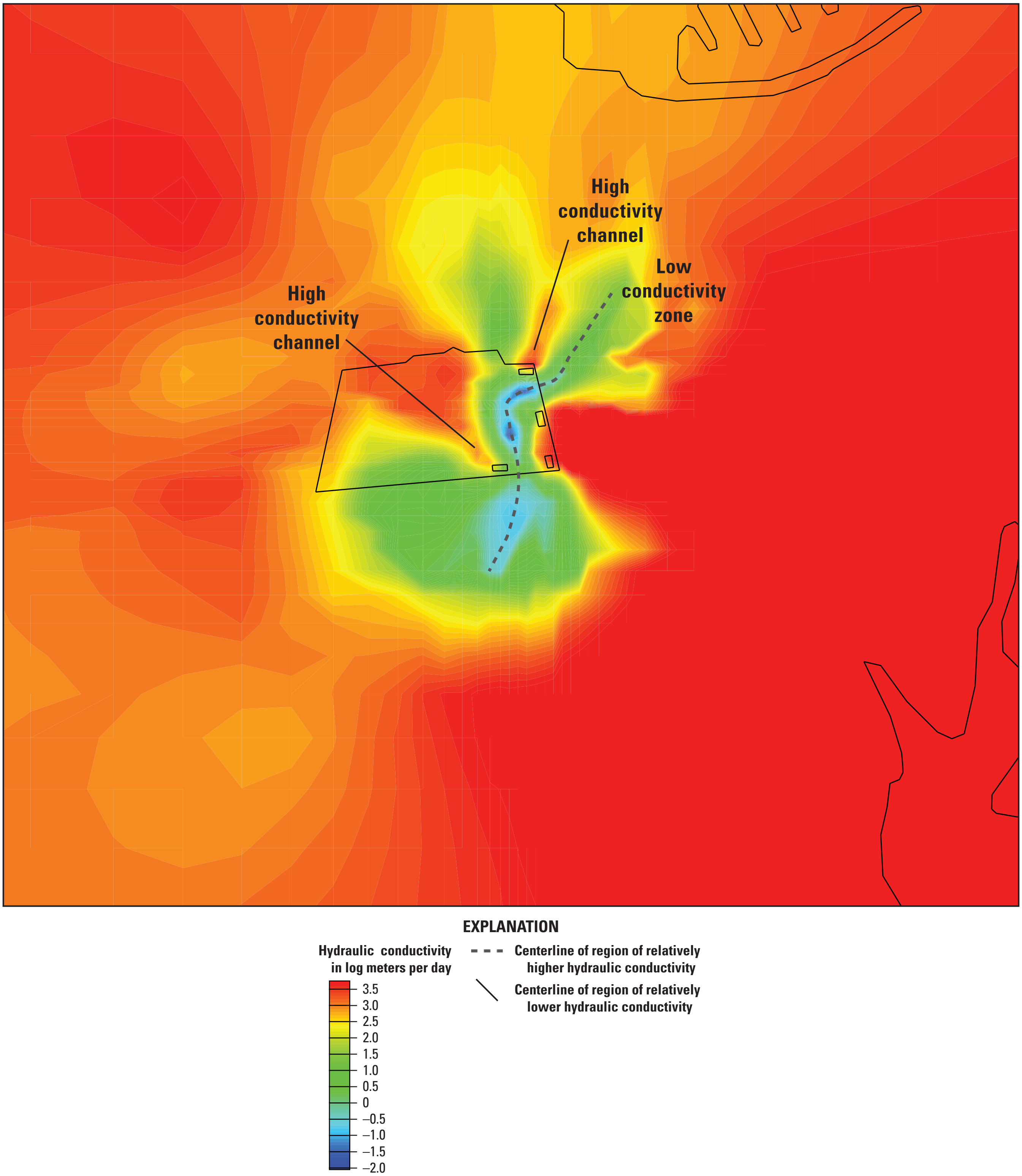

Figure 1–10. Estimated horizontal hydraulic conductivity in Layer 11, the upper Boulder Zone, at the North District Wastewater Treatment Plant, Miami-Dade County, Florida.

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