Hydrogeology and Aquifer Storage and Recovery Performance in the Upper Floridan Aquifer, Southern Florida

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Appendix Tables (on CD in back pocket)

Conversion Factors, Abbreviations, and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
	Volume or Rate	
million gallons (Mgal)	3,785	cubic meter (m^3)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per year (Mgal/d)	3,785	cubic meter per year (m^3/yr)
	Specific Capacity	
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
foot squared per day (ft^2/d)	7.481	gallons per day per foot [(gal/d)/ft]
	Leakance	
inverse day (1/d)	7.481	gallons per day per cubic foot [(gal/d)/ft^3]

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C= (°F-32)/1.8

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 1927 (NAD 27), except as noted.

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

The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report; the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Acronyms

ASR	Aquifer Storage and Recovery
CERP	Comprehensive Everglades Restoration Plan
FDEP	Florida Department of Environmental Protection
GWSI	Ground-Water Site Inventory
SFWMD	South Florida Water Management District
TSV	Target Storage Volume
USGS	U.S. Geological Survey
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

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Abstract

Well construction, hydraulic well test, ambient water-quality, and cycle test data were inventoried and compiled for 30 aquifer storage and recovery facilities constructed in the Floridan aquifer system in southern Florida. Most of the facilities are operated by local municipalities or counties in coastal areas, but five sites are currently being evaluated as part of the Comprehensive Everglades Restoration Plan. The relative performance of all sites with adequate cycle test data was determined, and compared with four hydrogeologic and design factors that may affect recovery efficiency.

Testing or operational cycles include recharge, storage, and recovery periods that each last days or months. Cycle test data calculations were made including the potable water (chloride concentration of less than 250 milligrams per liter) recovery efficiency per cycle, total recovery efficiency per cycle, and cumulative potable water recovery efficiencies for all of the cycles at each site. The potable water recovery efficiency is the percentage of the total amount of potable water recharged for each cycle that is recovered; potable water recovery efficiency calculations (per cycle and cumulative) were the primary measures used to evaluate site performance in this study. Total recovery efficiency, which is the percent recovery at the end of each cycle, however, can be substantially higher and is the performance measure normally used in the operation of water-treatment plants.

The Upper Floridan aquifer of the Floridan aquifer system currently is being used, or planned for use, at 29 of the aquifer storage and recovery sites. The Upper Floridan aquifer is continuous throughout southern Florida, and its overlying confinement is generally good; however, the aquifer contains brackish to saline ground water that can greatly affect freshwater storage and recovery due to dispersive mixing within the aquifer. The hydrogeology of the Upper Floridan varies in southern Florida; confinement between flow zones is better in southwestern Florida than in southeastern Florida. Vertical hydraulic conductivity in the upper part of the aquifer also may be higher in southeastern Florida because of unconformities present at formation contacts within the aquifer that may be better developed in this area.

Recovery efficiencies per cycle varied widely. Eight sites had recovery efficiencies of less than about 10 percent for the first cycle, and three of these sites had not yet achieved recoveries exceeding 10 percent, even after three to five cycles. The highest recovery efficiency achieved per cycle was 94 percent. Three southeastern coastal sites and two southwestern coastal sites have achieved potable water recoveries per cycle exceeding 60 percent. One of the southeastern coastal sites and both of the southwestern coastal sites achieved good recoveries, even with long storage periods (from 174 to 191 days). The high recovery efficiencies for some cycles apparently resulted from water banking—an operational approach whereby an initial cycle with a large recharge volume of water is followed by cycles with much smaller recharge volume. This practice flushes out the aquifer around the well and builds up a buffer zone that can maintain high recovery efficiency in the subsequent cycles.

The relative performance of all sites with adequate cycle test data was determined. Performance was arbitrarily grouped into “high” (greater than 40 percent), “medium” (between 20 and 40 percent), and “low” (less than 20 percent) categories based primarily on their cumulative recovery efficiency for the first seven cycles, or projected to seven cycles if fewer cycles were conducted. The ratings of three sites, considered to be borderline, were modified using the overall recharge rate derived from the cumulative recharge volumes. A higher overall recharge rate (greater than 300 million gallons per year) can improve recovery efficiency because of the water-banking effect. Of the 30 sites in this study, a rating was determined for 17 sites, of which 7 sites were rated high, 5 sites were rated medium, and 5 sites were rated low.

Four hydrogeologic and design factors that may affect recovery were compared with the relative performance ratings. These factors are the thickness, transmissivity, and ambient chloride concentration (correlated with salinity) of the storage zone, and the thickness of the portion of the aquifer above the top of the storage zone. Threshold values for these factors of 150 feet, 30,000 square feet per day, 2,500 milligrams per liter, and 50 feet were chosen, respectively; each represents a value above which recovery efficiency could be adversely affected.

Some general correlation of the performance ratings with the number of factors above the threshold value was found. The best correlation was found with the transmissivity and ambient chloride concentration factors, but some correlation also was indicated with the thickness of the storage zone.

Long intercycle or storage periods can adversely affect recovery efficiency. This adverse effect appears to be more likely for Upper Floridan aquifer sites in southeastern Florida than in southwestern Florida; southeastern Florida has higher ambient salinity, higher apparent vertical hydraulic conductivity, and more storage zones located greater than 50 feet below the top of the aquifer. This effect could be caused by upward migration of the recharged freshwater “bubble” during these periods as a result of buoyancy. Some evidence for this was found in the performance ratings for sites and in the analyses of certain cycles with long inactive periods.

Introduction

Interest and activity in aquifer storage and recovery (ASR) in southern Florida have greatly increased during the past 10 to 15 years, and many utility-operated ASR facilities now have wells completed in deep confined aquifers for this purpose. In southern Florida, ASR has been used to store excess freshwater during the wet season and subsequently recover it during the dry season for use as an alternative drinking-water supply source. Water is injected down an ASR well, stored in an aquifer, and withdrawn using the same well.

The principal aquifer used for ASR in southern Florida is the carbonate Upper Floridan aquifer of the Floridan aquifer system. There are 30 sites with wells completed in the Floridan aquifer system in this area; the ASR storage zone is located (or is planned to be) within the Upper Floridan aquifer at 29 sites and within the middle Floridan aquifer at the remaining site. Another storage zone being utilized at several other sites in southwestern Florida is the mid-Hawthorn aquifer, which overlies the Upper Floridan aquifer.

Most ASR sites described herein are owned by local municipalities or county water authorities in coastal areas (fig. 1) and are presently (end of 2004) at different stages of completion and operation. Of the 30 sites, 3 have at least one operating well, 11 are undergoing “operational testing,” 11 require further infrastructure development or regulatory approval prior to “operational testing,” and 5 have been discontinued (abandoned) after experimental testing was completed. Operational (cycle) testing is conducted during the first phase of operation and involves a multi-year period of regulatory review. During this time, the ASR well system is tested prior to receiving a full operating permit by the Florida Department of Environmental Protection (FDEP).

The expanded use of ASR on an unprecedented scale in southern Florida has been proposed as a cost-effective water-supply alternative to help meet the needs of agricultural, municipal, and recreational users, and for Everglades ecosystem restoration (U.S. Army Corps of Engineers and South Florida Water Management District, 1999). Under the Comprehensive Everglades Restoration Plan (CERP), construction of about 330 ASR wells is proposed for southern Florida. To be economically viable, each well must have an operational capacity of 5 Mgal/d during recharge (injection) or recovery. Wells were drilled at five sites as part of the CERP pilot study program (fig. 1), and large-diameter test injection wells (exploratory wells) were constructed with storage zones in the Upper Floridan aquifer at four of the sites for the purpose of cycle testing. A test well was drilled at the fifth site (site 9), but has not been completed.

Several current or potential problems with ASR have been identified in southern Florida. These problems include: (1) reduced recovery due to mixing of recharged water with brackish to saline ground water in the Upper Floridan aquifer (Reese, 2002); (2) stringent water-quality requirements for recharge into the aquifer (Federal Regulations Code, 2002a; Florida Administrative Code, 2002); and (3) the release, or potential for release, of water-quality constituents of concern (such as arsenic and radionuclides) into the stored water as a result of the interaction between injected freshwater and the aquifer matrix (Mirecki, 2004). The present study focuses only on the issue of recovery.

The Upper Floridan is continuous and well confined throughout southern Florida. The depth to the top of the aquifer ranges from 500 to 1,200 ft below land surface. In southern Florida, however, the Upper Floridan aquifer contains brackish to saline water, which can affect the recovery of the freshwater because of mixing within the aquifer during injection, storage, and withdrawal.

ASR wells are evaluated and operated through a cyclical process. Each cycle includes periods of injection (recharge) of water into the ASR well, storage in the aquifer, and withdrawal (recovery) from the same well; each period can last days or months. During operational testing, the recovery period often begins immediately after recharge is completed, with no period of storage. The volume of water recharged for each cycle and the duration of cycles and storage periods usually increase as part of the testing process. The recovery efficiency for each cycle is the total volume of water recovered, expressed as a percentage of the volume of water recharged into the storage zone. The salinity of water during the recovery period of each cycle typically increases over time; recovery is terminated when salinity reaches a level predetermined by operational or regulatory considerations. This limiting salinity constraint is usually the potable water limit of 250 mg/L chloride (Federal Regulations Code, 2002b), or slightly higher if the recovered water is mixed with potable water at a water-treatment plant (WTP). Chloride concentration and salinity (dissolved-solids concentration) are well correlated as shown by linear regression in the Floridan aquifer system in southern Florida (Reese, 1994; 2000; 2004; and Reese and Memberg, 2000), and chloride concentration is used in this report to define salinity in this aquifer system.

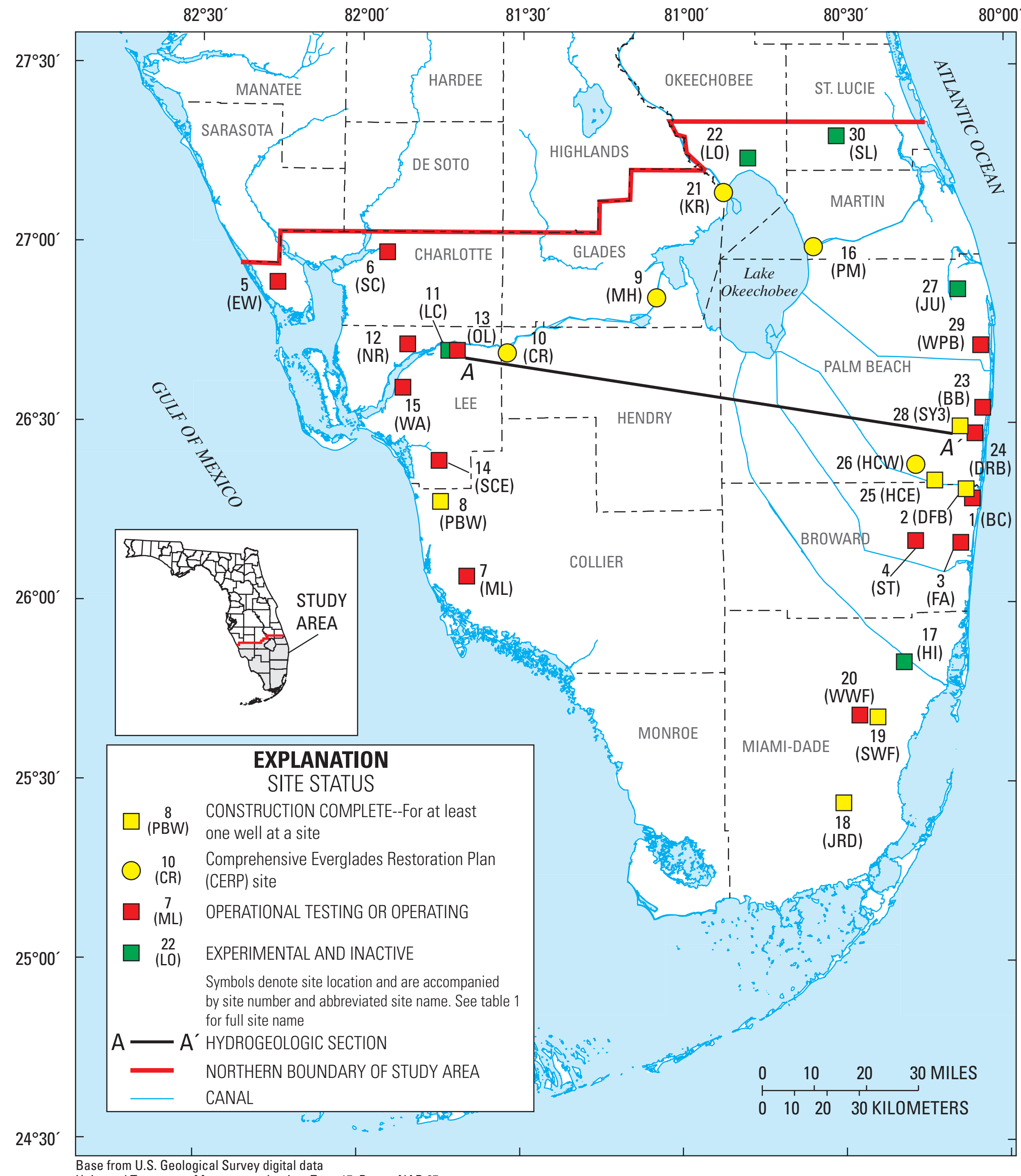


Figure 1. Study area and location and status of aquifer storage and recovery sites in the Floridan aquifer system.

Regional Floridan aquifer system hydrogeologic studies in southern Florida have not focused on ASR issues. Conversely, little effort has been made to link ASR site information into a regional hydrogeologic analysis. Additionally, ASR sites have been selected primarily on factors such as land availability, source-water proximity (preexisting surface-water canal systems or surficial aquifer system well fields), or proximity to a WTP. New tools, data, and synthesis are needed to make informed decisions that incorporate constraining hydrogeologic factors in the placement and construction of ASR sites.

The U.S. Geological Survey (USGS), as part of its Greater Everglades Priority Ecosystems Science Initiative, conducted a study to assimilate and compile data on existing ASR sites in southern Florida, and identify and evaluate various hydrogeologic, design, and management factors that control the recovery of freshwater recharged into ASR wells. Phases 1 and 2 of this study have been completed. Phase 1 involved preliminary data inventory, review, and analysis (Reese, 2002). Phase 2 (this report) involved a more comprehensive evaluation of ASR data, including additional data made available since the completion of phase 1.

Purpose and Scope

This report documents phase 2 of the study and presents additional ASR data made available since phase 1, which was covered in an earlier report (Reese, 2002). The purposes of the present (2006) report are to: (1) provide a site-specific hydrogeologic framework analysis at existing ASR sites; (2) provide a performance evaluation of each site and comparative analysis of the performance at all sites; and (3) further evaluate the effect of hydrogeologic, design, and management factors on performance. Recovery efficiency on a per-cycle basis, as previously defined, is used to evaluate site performance. The limiting salinity level during the recovery period for this evaluation is the potable water limit of 250 mg/L chloride concentration. Data for all wells at the 30 Floridan aquifer system sites are compiled into four main categories: (1) well identification, location, and construction; (2) hydraulic testing; (3) ambient formation water quality; and (4) cycle testing. Cycle test data include calculations of recovery efficiency for each cycle and the cumulative recovery efficiency for all cycles.

The study area includes Charlotte, Glades, Lee, Hendry, Collier, Monroe, Miami-Dade, Broward, Palm Beach, and Martin Counties, and parts of Okeechobee and St. Lucie Counties in southern Florida (fig. 1). The northern boundary of the study area approximately coincides with the southern limit of ground water with less than 500 mg/L chloride concentration in the Upper Floridan aquifer in peninsular Florida (Sprinkle, 1989, pl. 6). The hydrogeology of each site is illustrated using geophysical logs and lithologic descriptions. These illustrations also include the location of the constructed storage zone. Principal hydrogeologic and well construction attributes determined for each ASR site are spatially illustrated to provide a comparative analysis. Well construction histories and results of cycle testing at seven sites are presented and discussed; analysis of the cycle testing data for these sites is made through graphical illustrations. Plots of both per cycle and cumulative recovery efficiency and cumulative recharge volume are made showing all sites with adequate data together. The relative performance of all sites with cycle test data is determined, and performance ratings are compared to several hydrogeologic and design factors that could affect recovery efficiency.

Previous Studies

Prior to the present study, the most recent overview and status reports on ASR well testing in southern Florida were by Merritt and others (1983) and Meyer (1989a), who presented data from four experimental ASR sites that also are included in this report. Additionally, experimental ASR test data were obtained from reports or written communications for the Jupiter facility, site 27 (J.J. Plappert, Florida Department of Environmental Protection, written commun., 1977), St. Lucie County facility, site 30 (Wedderburn and Knapp, 1983), the Lee County facility, site 11 (Fitzpatrick, 1986), the Hialeah facility, site 17 (Merritt, 1997), and the Taylor Creek/Nubbin Slough—Lake Okeechobee facility, site 22 (Quiñones-Aponte and others, 1996). Khanal (1980) and Merritt (1985) conducted theoretical studies regarding the feasibility of cyclic freshwater injection in southern Florida. Merritt (1997) also simulated the salinity of recovered water in a study at the Hialeah facility. As part of the CERP regional ASR program, Mirecki (2004) studied water-quality changes that occurred during storage of ASR systems in southern Florida, including increases in concentrations of constituents of concern for drinking water.

Some regional or local hydrogeologic studies of the Upper Floridan aquifer that encompass or include part of southern Florida are Miller (1986), Bush and Johnston (1988), Meyer (1989b), Reese (1994; 2000; 2004), and Reese and Memberg (2000). All but the first two reports are specific to southern Florida.

Hydrogeology of the Upper Floridan Aquifer

The three principal hydrogeologic units in southern Florida are the surficial, intermediate, and Floridan aquifer systems of Holocene to Paleocene age. These aquifer systems, the aquifers contained within them, their relation to geologic units, and their lithology in southern Florida are described in figure 2. Water-bearing rocks in the intermediate aquifer system grade by facies change or pinch out to the east, and this system becomes the intermediate confining unit in southeastern Florida. The Floridan aquifer system consists of the Upper Floridan aquifer, middle confining unit, and Lower Floridan aquifer (Miller, 1986). The two aquifers most commonly used for ASR in southern Florida are the mid-Hawthorn aquifer of the intermediate aquifer system (southwestern Florida) and the Upper Floridan aquifer (fig. 2).

The geologic and hydrogeologic characteristics at each of the 30 Floridan aquifer system ASR sites in southern Florida are presented in appendix 1. An illustration for a well at each site includes geophysical log traces, a lithologic column, delineation of flow zones, geologic and hydrogeologic units, the completed open-hole interval(s), and vertical changes in salinity as indicated by the chloride concentration of water samples collected from known intervals. The geologic and hydrogeologic unit boundaries and flow zones (app. 1) were determined in this study or previous investigations, or were derived from other sources, such as consulting reports. These boundaries and the sources of determination also are listed in appendix 1; in this study, the determinations were made using geophysical logs and lithologic descriptions.

The Upper Floridan aquifer is 100 to 700 ft thick in southern Florida (fig. 2) and is well confined above by thick (tens to hundreds of feet) units in the Hawthorn Group composed of clay, marl, silt, clayey sand, or clayey or carbonate mud-rich limestone; the hydraulic head in the aquifer is above land surface. The middle confining unit of the Floridan aquifer

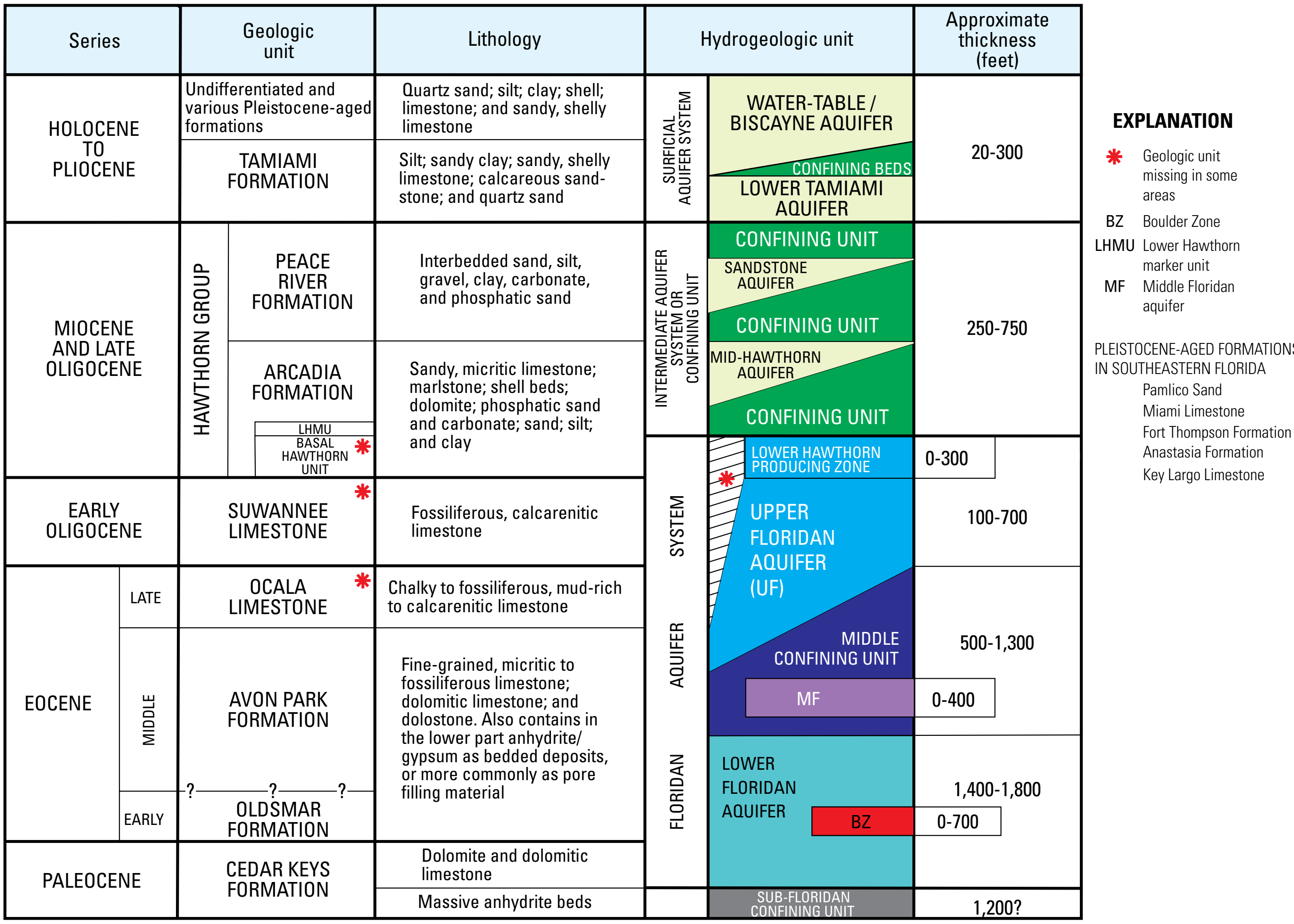


Figure 2. Generalized geology and hydrogeology of southern Florida. The middle Floridan aquifer is an informal unit.

system underlies the Upper Floridan aquifer and provides less effective to leaky confinement. This confining unit consists of fine-grained micritic limestone, dolomitic limestone, and dolomite or dolostone. Geologic units in the Upper Floridan aquifer in ascending order are the upper part of the Avon Park Formation, Ocala Limestone, Suwannee Limestone, and a basal unit of the Hawthorn Group (fig. 2)—some or all of these units above the Avon Park Formation are missing in some areas. The basal Hawthorn unit is defined by an overlying marker unit composed of micritic limestone or marl (Reese, 2000; 2004; Reese and Memberg, 2000). This marker unit, referred to as the lower Hawthorn marker unit (fig. 2), was correlated throughout most of southern Florida using gamma-ray logs; this unit provides part of the good confinement above the Upper Floridan aquifer.

The Upper Floridan aquifer generally consists of several thin water-bearing zones of high permeability (flow zones) interlayered with thicker zones of substantially lower permeability. Commonly, one or two major flow zones provide the bulk of the productive capacity. These flow zones are often less than 20 ft thick each and generally are present within the upper part of the Upper Floridan aquifer, within the lower Hawthorn producing zone and at or near the top of deeper formations (for example, see System 3 Palm Beach monitoring well shown in fig. 3). Unconformities are present at the top of the Suwannee Limestone, Ocala Limestone, or Avon Park Formation (Miller, 1986), and zones of dissolution occur in association with these unconformities in southern Florida (Meyer, 1989b). Flow zones are marked by abrupt and, in some cases, large changes in borehole flow and are determined primarily using borehole fluid logs, such as flowmeter and temperature logs; however, other geophysical logs, such as the caliper, formation resistivity, and porosity logs, can provide supporting data.

Because of good confinement above the Upper Floridan aquifer and artesian pressure within it, the top of the Upper Floridan aquifer is marked by artesian flow or a large increase in hydraulic head in the study area. Drilling characteristics, such as a lost-circulation zone or drilling break (a sudden increase in the rate of penetration), also may help to define the top of this hydrogeologic unit. Geophysical log characteristics include a decrease in gamma-ray log activity, increased electrical formation resistivity and porosity, anomalous caliper log readings indicating abrupt borehole enlargements (spikes), or

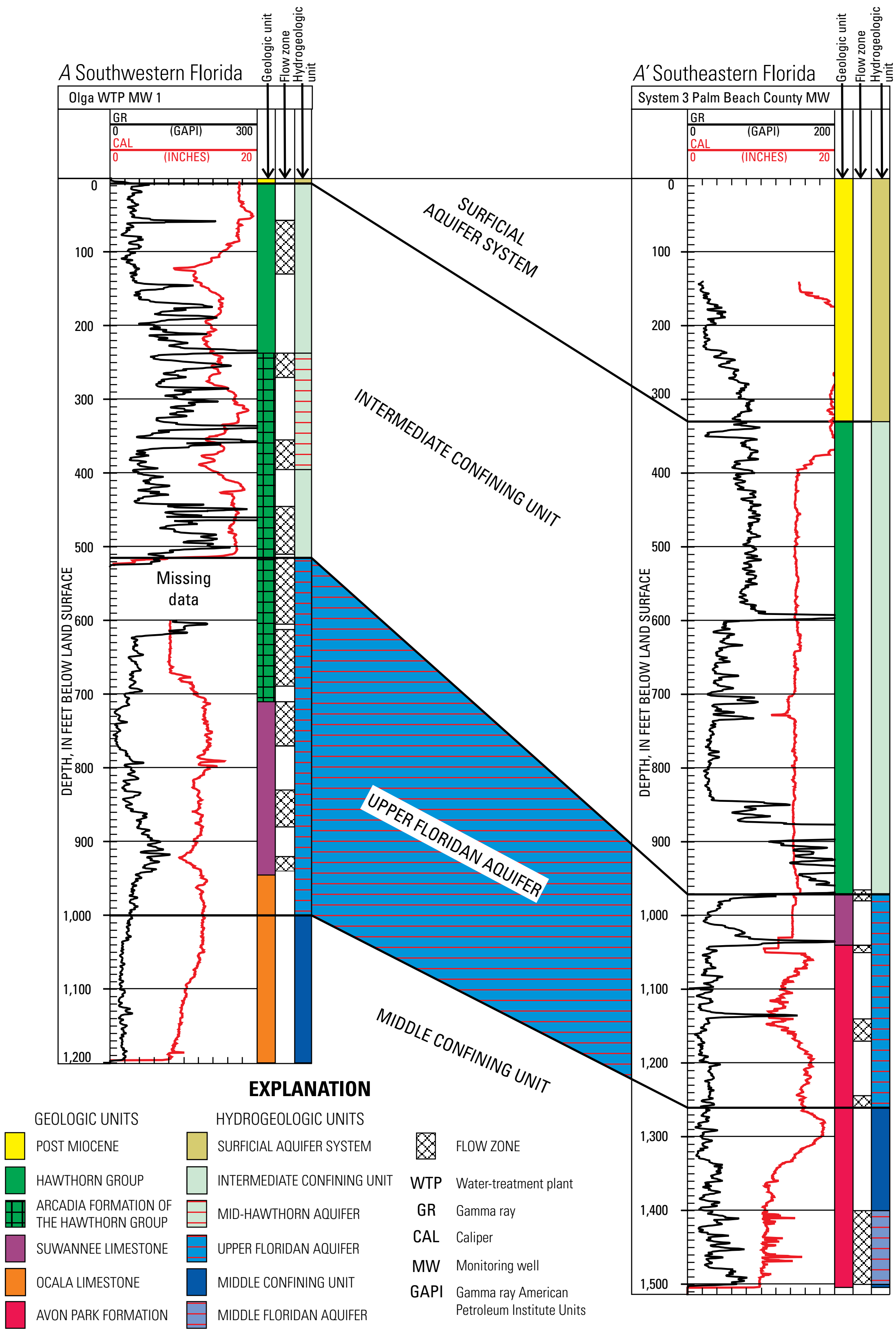


Figure 3. Section *A-A′* from monitoring wells at the Olga Water Treatment Plant (site 13) in southwestern Florida to System 3 Palm Beach County (site 28) in southeastern Florida showing gamma-ray and caliper logs, geologic units, flow zones, and hydrogeologic units. Line of section shown in figure 1. See appendix 1 for additional borehole geophysical log curves and lithologic data on these two wells.

thin zones of in-gage borehole where well cemented but permeable limestone or dolostone is present. Additionally, a large flow zone commonly marks the top of the Upper Floridan aquifer. Small flow zones can be present above the large flow zone near the top of the aquifer. These may or may not, however, be included in the Upper Floridan aquifer, depending on their head, permeability, and the degree of confinement provided by the unit(s) separating them from the main flow zone.

The hydrogeology of the Upper Floridan aquifer varies between southwestern and southeastern Florida. In southwestern Florida, the Upper Floridan aquifer commonly includes a basal unit of the Hawthorn Group (lower Hawthorn producing zone, fig. 2) and the Suwannee Limestone, which are thick and well developed (fig. 3). Additionally, the aquifer can extend down into the upper part of the Ocala Limestone, which also is thick; however, most of the Ocala Limestone usually has low permeability. As for southeastern Florida, the Upper Floridan aquifer is often interpreted to include only a relatively thin Suwannee Limestone and the upper part of the Avon Park Formation as shown at site 28 in Palm Beach County (fig. 3, Palm Beach County Water Utilities Department, 2003b) and site 4 (app. 1; Montgomery Watson, 1998a). An alternate interpretation is that the Suwannee Limestone is absent in parts of southeastern Florida (Miller, 1986; Reese and Memberg, 2000; Florida Geological Survey, 2004) or equivalent to the lower part of the basal Hawthorn unit (Reese, 2004), and that the Upper Floridan aquifer begins in the basal Hawthorn unit in these areas. The Suwannee Limestone is interpreted to be absent at site 2 in Broward County (app. 1; Florida Geological Survey, 2004). Additionally, in southeastern Florida, the Ocala Limestone is absent in some areas (Miller, 1986) or indistinguishable from the Avon Park Formation (Reese and Memberg, 2000).

In southwestern Florida, the principal flow zones tend to be associated with the lower Hawthorn producing zone and at the top of or within the Suwannee Limestone, whereas in southeastern Florida, an important flow zone is present at or near the top of the Avon Park Formation, or if present, at the top of the Ocala Limestone. Confinement is typically better between flow zones in southwestern Florida than in southeastern Florida, and some zones in southwestern Florida are referred to as separate aquifers or subaquifers; for example, Lower Hawthorn Zones I and II, Suwannee Zones I and II, and Ocala Zones I and II (Water Resources Solutions, Inc., 2000a).

The geologic structure near the top of the Upper Floridan aquifer in southern Florida has recently been described in detail through the mapping of geologic units, specifically, the altitude of the bottom of the basal Hawthorn unit in southwestern Florida (Reese, 2000) and the bottom of the Suwannee Limestone or an equivalent boundary in southeastern Florida (Reese, 1994, 2004; Reese and Memberg, 2000). The depth of these contacts was determined primarily by lithology and gamma-ray geophysical log patterns. The most important flow zone(s) in the upper part of the Upper Floridan aquifer is commonly present near these contacts. The altitude of these contacts varies considerably, ranging from less than 400 ft to greater than 1,200 ft below NGVD 29, and local relief can be as much as several hundred feet, particularly in southwestern Florida. Charlotte and Glades Counties, located within the study area (fig. 1), were not mapped in these earlier studies.

The top of the Upper Floridan aquifer has been interpreted in previous reports as being 200 to 300 ft above the top of the Suwannee Limestone (as defined in this study; app. 1 and table A2) at three sites (18, 19, and 20) in Miami-Dade County in southeastern Florida (CH2M HILL, 2003; 2001a; and 1998b, respectively). In the present (2006) study, however, the top of the aquifer at these sites is interpreted to be at the top of, or within, the Suwannee Limestone (app. 1 and table A3). In the consulting reports, the Upper Floridan aquifer at two of these sites (app. 1 and table A3, sites 18 and 20) was interpreted to include one or two flow zones in the lower part of the Hawthorn Group; however, evidence for a hydrologic connection between these flow zones and the Upper Floridan aquifer was not given. These flow zones are interpreted to lie above the basal Hawthorn unit as previously defined (fig. 2), which is based on gamma-ray log correlations. The uppermost flow zone even overlies the confining lower Hawthorn marker unit above the basal Hawthorn unit.

Some evidence exists for enhanced vertical hydraulic conductivity at the top of the Avon Park Formation and in the Suwannee Limestone in southeastern Florida. An aquifer performance test of the upper part of the Avon Park Formation was conducted in well BF-3 at the C-13 Canal site in northeastern Broward County (fig. 1, between sites 2 and 3) in which large quantities of phosphatic silt and fine quartz sand were produced, causing pump failure (Lukasiewicz, 2003a). This silt and sand production may have been caused by sinkhole development or karstification in the Avon Park Formation (Lukasiewicz, 2003a). Based on sample descriptions, abundant phosphatic sand is present only in an interval from 20 to 55 ft above the top of the production interval, in what is usually interpreted to be the upper part of the Suwannee Limestone or lower part of the Hawthorn Group, and this phosphatic zone (Reese, 1994, fig. 3) appears to have been the source of the sand that caused pump failure. Karstification in the Suwannee Limestone and Avon Park Formations, if present, could be related to regional unconformities present at the top of these formations.

An informally named water-bearing zone, the “middle Floridan aquifer,” is contained within the middle confining unit that underlies the Upper Floridan aquifer (figs. 2 and 3), and was first identified in a well located in northeastern Palm Beach County near site 27 (ViroGroup, Inc., 1994). This zone has since been observed at several South Florida Water Management District (SFWMD) test well sites farther south in southeastern Florida (Lukasiewicz and others, 2003a; 2003b). The middle Floridan aquifer typically consists of fractured dolostone and is well developed in part of southeastern Florida (St. Lucie, Martin, and Palm Beach Counties); the aquifer was mapped as being continuous and present in most of central and southern Florida (R.S. Reese, U.S.

Geological Survey, and E. Richardson, South Florida Water Management District, written commun., 2005). The zone had previously been identified as the upper part of the Lower Floridan aquifer in Okeechobee, St. Lucie, and Martin Counties (Lukasiewicz,1992; Miller, 1986) or as the lower part of the Upper Floridan aquifer in Palm Beach, Broward, and Miami-Dade Counties (Reese, 1994; Reese and Memberg, 2000).

Inventory and Compilation of Well and Test Data

Well data were inventoried and compiled for all wells at existing and historical ASR sites in the Floridan aquifer system in southern Florida, and all available cycle test data were also compiled. Consulting reports describing the construction and testing of wells and cycle testing provided much of these data. The consulting reports used to compile these data are listed in the references section and listed by site number in appendix 2. Historical and current ASR sites are listed in table 1 along with the utility or operator of the site, storage zone aquifer, site status, recharge source water type, and number of wells drilled at each site. The number of injection (storage) wells at each site ranges from zero to four, and 22 of the 30 sites have at least one monitoring well completed in the storage zone.

The type of recharge source water used in southern Florida has included treated drinking water, partially treated surface water, raw ground or surface water, and reclaimed water (table 1). Treated drinking water is the most common source-water type and has been used at 10 sites; however, raw ground water also has been used, or is proposed for use, at 9 sites in southeastern Florida. Partially treated surface water is planned for use in the CERP-ASR program. Special permits, obtained through the FDEP Underground Injection Control Program and the U.S. Environmental Protection Agency, are required to inject raw surface or ground water because these waters sometimes exceed maximum contaminant levels for primary or secondary drinking-water standards for some constituents.

Construction and Testing Data

Construction and testing data were compiled into three main categories: well-construction data, hydraulic well-test data, and ambient formation water-quality data. The well-construction data include well design, identification, and location. Data from two of the five CERP-ASR sites were obtained from Bennett and others (2001; 2004). Data for the other three CERP pilot sites were obtained from weekly drilling reports, permit applications, and responses to requests for information submitted to the FDEP Underground Injection Control Program and the Technical Advisory Committee for this program in southern Florida. The USGS serves as a member on this committee.

Well Identification and Construction Data

Well identification, location, and construction data for all ASR storage and associated monitoring wells are presented in table 2. All wells were assigned a USGS identification number, and data from these wells have been archived in the USGS Ground-Water Site Inventory (GWSI) database. The construction information compiled includes total hole depth, ending date of construction, casing depth and diameter, type of each casing string set in the well, and the completed (constructed) open interval and its diameter. All depths in this report are below land surface. In most instances, the completed interval is open hole, but a gravel-packed screen was installed in a few monitoring wells. At many sites, the first well drilled was plugged back to the selected storage zone after being drilled deeper to test other potential zones or to determine water-quality changes with depth.

The thickness and diameter of the open-hole storage intervals vary (fig. 4 and table 2). The thickness for most intervals typically ranges from about 100 to 200 ft; extremes range from 45 ft at the Marco Lakes facility (site 7, well C-1206) to 452 ft at the West Well Field (site 20). At sites 8 and 18, a test-monitoring well is shown in figure 4 because storage wells have yet to be constructed. The storage zone in future ASR wells at these sites may not be the same as the open interval in the test-monitoring well. Except for sites 8, 18, and 22, the average storage zone thickness for 26 of the sites (fig. 4) is 183 ft. The diameter of the open-hole storage intervals ranges from 5.125 in. at the St. Lucie County facility (site 30) to 29 in. at the Southwest and West Well Fields in Miami-Dade County (sites 19 and 20, respectively). Nine sites have ASR wells with a casing diameter of 20 in. or greater (fig. 4); these large-diameter open intervals were constructed to achieve a high pumping rate (5 Mgal/d or greater) during recharge and recovery. ASR wells with a storage zone diameter ranging from 10 to less than 20 in. have been constructed at 14 sites, and the permitted capacity for these wells typically ranges from 1 to 4 Mgal/d (R. Deuerling, Florida Department of Environmental Protection, written commun., 2003).

Hydraulic Well-Test Data

A wide variety of hydraulic tests have been used to determine the hydraulic properties of storage zones or potential storage zones, and hydraulic test data were compiled for all ASR well systems. The data include the reported results of packer tests conducted during drilling, step-drawdown tests, single-well constant-rate tests, and multiwell constant-rate tests (table 3). Tests of other permeable intervals at a site that are shallower or deeper than the interval selected to be the storage zone also are included in table 3.

Table 1. Historical and current aquifer storage and recovery sites in southern Florida.

[No., number; County: B, Broward; CH, Charlotte; CO, Collier; GL, Glades; HE, Hendry; L, Lee; M, Martin; MD, Miami-Dade; MO, Monroe; OK, Okeechobee; PB, Palm Beach; STL. St. Lucie. Utility or operator: BCOES, Broward County Office of Environmental Services; CERP, Central Everglades Restoration Project; USGS, U.S. Geological Survey; LCRWSA, Lee County Regional Water Supply Authority; MDWSD, Miami-Dade Water and Sewer Department; FKAA, Florida Keys Aqueduct Authority; SFWMD, South Florida Water Management District; FDEP, Florida Department of Environmental Protection; PBCWUD, Palm Beach County Water Utilities Department. Storage zone aquifer: MFA, middle Floridan aquifer; MHA, mid-Hawthorn aquifer; UFA, Upper Floridan aquifer. Other abbreviations: WTP, water treatment plant; WWTP, wastewater treatment plant]

Site no.[1]	Site name and abbreviation	County	Utility or operator	Storage zone aquifer	Status[2]	Source water (permitted or planned)	No. of injection wells	No. of monitoring wells in storage zone
1	Broward County WTP 2A (BC)	B	BCOES	UFA	Operational testing	Raw ground water	1	1
2	Deerfield Beach West WTP (DFB)	B	Deerfield Beach	UFA	Construction complete	Treated drinking water	1	1
3	Fiveash WTP (FA)	B	Fort Lauderdale	UFA	Operational testing	Raw ground water; previously treated drinking water	1	1
4	Springtree WTP (ST)	B	Sunrise	UFA	Operational testing	Treated drinking water	1	0
5	Englewood South Regional WWTP (EW)	CH	Englewood Water District	UFA	Operational testing	Reclaimed water	1	1
6	Shell Creek WTP (SC)	CH	Punta Gorda	UFA	Operational testing: 2 wells; Operating: 1 well	Treated drinking water	4	2
7	Marco Lakes (ML)	CO	Florida Water Services	UFA	Operational testing: 2 wells; Operating:1 well	Partially treated surface water	3	2
8	Pelican Bay Well Field (PBW)	CO	Collier County	UFA (planned)	Construction of exploratory well complete	Reclaimed water	0	1
9	Moore Haven S-77 (MH)	GL	CERP	--	Test well drilled	Partially treated surface water	0	[3]1
10	Caloosahatchee River/Berry Grove (CR)	HE	CERP	UFA	Construction of exploratory well complete[4]	Partially treated surface water	1	0
11	Lee County WTP (LC)	L	USGS	UFA	Experimental and inactive	Raw and partially treated surface water	1	2
12	North Reservoir (NR)	L	Lee County	UFA	Operational testing	Treated drinking water	1	1
13	Olga WTP (OL)	L	Lee County	UFA	Operational testing	Treated drinking water	1	2
14	San Carlos Estates (SCE)	L	Bonita Springs	UFA	Operational testing; UFA zone idle, MHA proposed	Treated drinking water	1	1
15	Winkler Avenue (WA)	L	Fort Myers	UFA	Operational testing	Treated drinking water	1	1
16	Port Mayaca S-153 (PM)	M	CERP	UFA	Construction of exploratory well complete[4]	Partially treated surface water	1	[3]1
17	Hialeah (HI)	MD	USGS	UFA	Experimental and inactive	Raw ground water	1	1

Table 1. Historical and current aquifer storage and recovery sites in southern Florida.—Continued

Site no.[1]	Site name and abbreviation	County	Utility or operator	Storage zone aquifer	Status[2]	Source water (permitted or planned)	No. of injection wells	No. of monitoring wells in storage zone
18	J.R. Dean WTP (JRD)	MD	FKAA	UFA (planned)	Construction of exploratory well complete	Raw ground water	0	1
19	Southwest Well Field (SWF)	MD	MDWSD	UFA	Construction complete	Raw ground water	2	0
20	West Well Field (WWF)	MD	MDWSD	UFA	Operational testing	Raw ground water	3	1
21	Kissimmee River (KR)	OK	CERP	UFA	Construction of exploratory well complete[4]	Partially treated surface water	1	[3]1
22	Taylor Creek/Nubbin Slough—Lake Okeechobee (LO)	OK	SFWMD	MFA	Experimental and inactive	Raw surface water	1	1
23	Boynton Beach East WTP (BB)	PB	Boynton Beach	UFA	Operating	Treated drinking water	1	0
24	Delray Beach North Storage Reservoir (DRB)	PB	Delray Beach	UFA	Operational testing	Treated drinking water	1	0
25	Hillsboro Canal, East (HCE)	PB	PBCWUD	UFA	Construction complete	Raw ground water	1	1
26	Hillsboro Canal, West, Site 1 (HCW)	PB	CERP	UFA	Construction complete	Partially treated surface water	1	1
27	Jupiter (JU)	PB	FDEP	UFA	Experimental and inactive	Raw surface water	1	1
28	System 3 Palm Beach County (SY3)	PB	PBCWUD	UFA	Construction complete	Raw ground water	1	1
29	West Palm Beach WTP (WPB)	PB	West Palm Beach	UFA	Operational testing	Partially treated surface water	1	1
30	St. Lucie County (SL)	STL	SFWMD	UFA	Experimental and inactive	Raw ground water	1	2

[1] Site numbers refer only to this report. Site locations are shown in figure 1.

[2] "Construction" refers only to wells, although some sites with "construction complete" also have surface infrastructure completed, but have not yet been approved for "operational testing."

[3] Well is an uncompleted test well.

[4] "Exploratory well" is first large-diameter injection well at site and is intended for aquifer storage and recovery testing.

Table 2. Well identification, location, and construction data for aquifer storage and recovery well systems in southern Florida.

[Depths are in feet below land surface. Completed open intervals are open hole unless noted otherwise. Diameter of open interval for open-hole completions is size of bit used to drill or ream out hole. ddmmss, degrees, minutes, and seconds; LS, land surface; PVC, polyvinyl chlorinated; USGS, U.S. Geological Survey; WTP, water treatment plant; WWTP, wastewater treatment plant; ?, unknown; NR, not reported; ~, approximate]

Site name (and number)	USGS local well number	Other well identifier	Land-net or relative location	Latitude and Longitude (ddmmss)	Altitude of land surface (feet)	Total hole depth (feet)	Date at end of construction	Depth to top and bottom of casing (feet)	Casing diameter (inches)	Type of casing	Completed open interval (feet)	Diameter of open interval (inches)
Broward County												
Broward County WTP 2A (1)	G-2889	ASR-1	SE S12, 48S, 42E	261735 800625	16.6	1,200	12-03-96	0-40 0-397 0-995	36 26 16	Steel Steel Steel	995-1,200	16
	G-2916	MW-1	65 feet north, 275 feet west of ASR-1		17	1,200	09-25-96	0-40 0-400 0-990	24 14 6.63	Steel Steel Steel	990-1,200	6
Deerfield Beach West WTP (2)	G-2887	ASR-1	Same as for MW-1	261857 800726	13.17	1,128	10-1992	0-400 0-960	26 12	Steel PVC	960-1,128	10.63
	G-2888	MW-1	SENE S2, 48S,42E; 370 feet north of ASR-1	261901 800726	12	1,128	12-10-92	0-42 0-402 0-960	24 16 6	Steel Steel Steel	960-1,128	5.875
Fiveash WTP (3)	G-2917	ASR-1		261030 800915	NR	1,300	12-30-97	0-198 0-1,055	26 16	Steel Steel	1,055-1,200	16
	G-2918	FMW-1	350 feet south of ASR-1	261030 800914	NR	1,175	03-15-98	0-370 0-1,055	14 6.63	Steel Steel	1,055-1,175	13
	G-2919	SMW-1	56 feet south of ASR-1		NR	210	01-11-98	0-20 0-180 [1]180-200	12 2 2	Steel PVC PVC	[2]180-200	2
Springtree WTP (4)	G-2914	ASR-1	NW S21,49S,41E	[3,4]261033 801540	10	1,345	07-1997	0-170 0-1,110	26 16	Steel Steel	1,110-1,270	16
Charlotte County												
Englewood South Regional WWTP (5)	CH-318	TPW-1 (ASR-1)	S16, 41S, 20E	265415 821604	6	800	03-30-00	0-37 0-295 0-507	30 24 16	Steel Steel Steel	512-700	15
	CH-319	SZMW-1	400 feet west of TPW-1		NR	700	04-17-00	0-42 0-290 0-510	20 14 6	Steel Steel PVC	510-700	6
	CH-320	IMW-1	2,200 feet northwest of TPW-1		NR	320	04-06-00	0-40 0-280	14 4	Steel PVC	280-320	4
	CH-321	SMW-1	150 ft east of TPW-1		NR	205	03-23-00	0-40 0-170	14 6	Steel PVC	170-205	6

Table 2. Well identification, location, and construction data for aquifer storage and recovery well systems in southern Florida.—Continued

Site name (and number)	USGS local well number	Other well identifier	Land-net or relative location	Latitude and Longitude (ddmmss)	Altitude of land surface (feet)	Total hole depth (feet)	Date at end of construction	Depth to top and bottom of casing (feet)	Casing diameter (inches)	Type of casing	Completed open interval (feet)	Diameter of open interval (inches)
Charlotte County												
	CH-315	ASR-1	S29, 40S, 24E	265831 815607	19.4	1,043	04-1999	0-34 0-700 650-764	24 16 12	Steel Steel Steel	764-933	12.25
	CH-316	ASR-2	600 feet south, 270 feet east of ASR-1		NR	998	12-17-01	0-40 0-120 0-345 0-780	36 32 26 17.4	Steel Steel Steel PVC	780-998	15
	CH-317	ASR-3	970 feet south, 100 feet west of ASR-1		NR	1,000	01-2002	0-37 0-140 0-350 0-810	36 32 26 17.4	Steel Steel Steel PVC	810-912	15
Shell Creek WTP (6)	CH-325	ASR-4R	520 feet north, 170 feet east of ASR-1		NR	1,026	03-2002	0-36 0-124 0-350 0-800	36 32 26 17.4	Steel Steel Steel PVC	800-915	15
	CH-326	SZMW-1R	500 feet north of ASR-1		NR	815	03-2002	0-40 0-350 0-764	24 16 8.62	Steel Steel PVC	764-815	7
	CH-327	SZMW-2	1310 feet south, 260 feet east of ASR-1		NR	1,000	2-2002	0-40 0-140 0-350 0-785	36 32 26 17.4	Steel Steel Steel PVC	785-1,000	15
	CH-328	IAMW-1	90 feet south, 70 feet east of ASR-1		NR	400	03-2002	0-40 0-350	16 8.625	Steel PVC	350-400	7
Collier County												
	C-1206	ASR-1	NE S3, 51S, 26E	260356 [3,4]814136	NR	790	7-8-96	0-40 0-152 152-745	24 16 12	Steel PVC PVC	745-790	10
	C-1207	DZMW	140 feet south, 320 feet east of ASR-1	260353 [4]814133	NR	817	04-26-96	0-293 0-745	10 6	PVC Steel	293-352 745-817	9.625 9.625
Marco Lakes (7)	C-1208	ASR-2	SE S34, 50S, 26E 500 feet north, 320 feet east of ASR-1	260352 814123	7.5	780	08-26-99	0-27 0-736	26 16	Steel PVC	736-780	12.25
	C-1209	MHZ2MW	S34, 50S, 26E 730 ft south, 270 ft east of ASR-1		7.5	470	09-10-99	0-31 0-440	16 6	PVC	440-470	12.25
	C-1210	ASRZMW	2,000 feet north, 727 feet east of ASR-1		9.25	774	10-01-99	0-38 0-725	16 6	PVC	725-774	12.25

Table 2. Well identification, location, and construction data for aquifer storage and recovery well systems in southern Florida.—Continued

Site name (and number)	USGS local well number	Other well identifier	Land-net or relative location	Latitude and Longitude (ddmmss)	Altitude of land surface (feet)	Total hole depth (feet)	Date at end of construction	Depth to top and bottom of casing (feet)	Casing diameter (inches)	Type of casing	Completed open interval (feet)	Diameter of open interval (inches)
Collier County—Continued												
Marco Lakes (7)—Continued	C-1211	ASR-3	S34, 50S, 26E 820 feet north, 545 feet east ASR-1		7.5	780	11-08-99	0-30 0-736	26 16	Steel PVC	736-780	12.25
Pelican Bay Well Field (8)	C-1242	EW-1	SWNW S19, T48S, R26E	261659 814513.5	NR	1,100	05-16-02	0-35 0-322 0-772	30 16 6.63	Steel Steel Steel	322-432 772-833	11 11
Glades County												
Moore Haven S-77 (9)	GL-331	GLF-6 test well		265018.6 [4]810507.5	NR	2,030	11-23-01	0-82 0-205 0-855	24 18 12	Steel Steel Steel	855-1,700	8
Hendry County												
Caloosahatchee River/Berry Grove (10)	HE-1141	EXBRY-1	NWNE S6, 44S, 28E	264118 813327	NR	1,398	7-01-04	0-219 0-634	34 24	Steel Steel	640-900	23
Lee County												
Lee County WTP (11)	L-2530	MW-1	NESE S23, 43S, 26E	264308 814049	7.2	614	1977	0-475	4	NR	475-615	2
	L-2901	Deep test	SE S23, 43S, 26E	264309 814051	8	705	12-05-78	0-60	6	NR	60-705	4
	L-3224	MW-2	NESE S23, 43S, 26E	264309 814057	9.99	622	04-79	0-460	4	NR	460-620	4
	L-3225	ASR-1	NESE S23, 43S, 26E	264309 814052	10.72	602	1980	0-445	10	PVC	445-600	9
North Reservoir (12)	L-5810	ASR-1 LM-6210	SWSW S20, 43S, 25E	264238 815019	12	642	03-02-99	0-40 0-499 0-540	30 24 16	Steel Steel PVC	540-640	12
	L-5811	MW-1 LM-6208	260 ft south of ASR-1		12	980	01-27-99	0-42 0-495 0-537	18 12 6	Steel Steel PVC	537-615	8
Olga WTP (13)	L-5816	ASR-1 LM-6086	NESE S23, 43S, 26E	264312 [3,4]814056	6	920	10-22-99	0-35 0-737 0-859	34 24 16	Steel Steel PVC	859-920	13
	L-5817	MW-1 LM-6209	470 feet southwest of ASR-1	264309 [3,4]814100	6	1,200	09-08-99	0-30 0-525.5 0-674.5 0-850	18 12 8 4	Steel Steel PVC PVC	850-895	8

Table 2. Well identification, location, and construction data for aquifer storage and recovery well systems in southern Florida.—Continued

Site name (and number)	USGS local well number	Other well identifier	Land-net or relative location	Latitude and Longitude (ddmmss)	Altitude of land surface (feet)	Total hole depth (feet)	Date at end of construction	Depth to top and bottom of casing (feet)	Casing diameter (inches)	Type of casing	Completed open interval (feet)	Diameter of open interval (inches)
Lee County—Continued												
Olga WTP (13)—Continued	L-5818	MW-3 LM-6615	370 feet northwest of ASR-1	264313 [3,4]814100	6	945	05-13-99	0-35 0-742 0-864	18 12 6	Steel Steel PVC	864-945	8
San Carlos Estates (14)	L-5812	TPW-1 (ASR-1)	S14, 47S, 25E	262321 [3,4]814625	NR	718	08-03-99	0-93 0-650	20 12	Steel PVC	650-701	11
	L-5813	SZMW-1	~200 feet south of ASR-1, abandoned		NR	657	07-26-99	0-19 0-655	16 6	Steel PVC	Abandoned	12
	L-5814	SZMW-1R	~200 feet south of ASR-1, replacement well	262319 [4]814625	NR	721	07-29-99	0-19 0-659	16 6	Steel PVC	659-721	5.5
	L-5815	SMW-1	~100 feet east of ASR-1		NR	321	08-02-99	0-19 0-234	16 6	Steel PVC	234-321	5.5
Winkler Avenue (15)	L-5871	ASR-1	S35, 44S, 24E	263608 815253	NR	647	06-23-99	0-91 0-455	20 12	Steel PVC	455-553	9.625
	L-5872	SZMW-1	~220 feet southwest of ASR-1		NR	553	08-05-99	0-16 0-455	16 6	Steel PVC	455-553	5.5
	L-5873	MHMW-1	~80 feet south of ASR-1		NR	200	08-06-99	0-150	6	PVC	150-200	5.5
Martin County												
Port Mayaca (16)	M-1360	MF-37 test well	NR	265928.8 [4]803616.5	16	2,046	10-05-01	0-74 0-170 0-765	24 18 12	Steel NR NR	765-1,683	9-7/8
	M-1361	EXPM-1	NW S14 T40S R37E 1320 feet south, 380 feet west of MF-37	265917 [4]803620	22.2	1,380	11-20-03	0-36 0-155 0-800	42 34 24	Steel Steel Steel	800-1,040	22
Miami-Dade County												
Hialeah (17)	G-3061	ASR-1	NWSW S18, 53S, 41E	254941 801717	8.4	1,105	12-09-74	0-201 0-955	24 14	Steel Steel	955-1,105	12
	G-3062	MW-1	289 feet northwest of ASR-1	254944 801718	5.43	1,064	11-19-74 06-04-80	0-198 0-953 0-862	14 6.63 2.38	Steel Steel Steel	840-844 953-1,060	NR
J.R. Dean WTP (18)	G-3774	EW-1	NR	252636 [4]803031	See footnote 5	1,500	11-2003	0-37 0-180 0-880	30 18 8.5	Steel Steel Fiberglass	880-1,000 1,000-1,350	12 8
Southwest Well Field (19)	G-3768	ASR-1 (ASR-4)		254155 802817.3	NR	1,302	06-08-98	0-180 0-765	42 30	Steel Steel	765-1,169	29
	G-3769	ASR-2 (ASR-5)	610 feet south, 620 feet west of ASR-1	254204.2 802817.5	NR	1,200	05-28-99	0-180 0-760	42 30	Steel Steel	760-1,200	29

Table 2. Well identification, location, and construction data for aquifer storage and recovery well systems in southern Florida.—Continued

Site name (and number)	USGS local well number	Other well identifier	Land-net or relative location	Latitude and Longitude (ddmmss)	Altitude of land surface (feet)	Total hole depth (feet)	Date at end of construction	Depth to top and bottom of casing (feet)	Casing diameter (inches)	Type of casing	Completed open interval (feet)	Diameter of open interval (inches)
Miami-Dade County—Continued												
West Well Field (20)	G-3706	ASR-1		254200 802830	NR	1,302	12-23-96	0-170 0-850	40 30	Steel Steel	850-1,302	29
	G-3707	ASR-2	975 ft north of ASR-1		NR	1,350	02-14-97	0-170 0-845	40 30	Steel Steel	845-1,250	29
	G-3708	ASR-3	1,955 feet north of ASR-1	254213.5 802818.2	NR	1,300	03-11-97	0-170 0-835	40 30	Steel Steel	835-1,210	29
	G-3709	MW-1 Test 711	270 feet northwest of ASR-1		NR	1,643	01-03-97	0-170 0-855 0-1,370 [1]1,370-1,390	24 12 12 2	Steel Steel PVC PVC	855-1,010 [2]1,370-1,390	12 2
Okeechobee County												
Kissimmee River (21)	OK-100	OKF-100 test well	SW/4, Sec 8 T38S R35E	270917.4 [4]805216.5	13	2,048	09-22-01	0-80 0-207 0-565	24 18 12	Steel Steel Steel	565-2,048	NR
	OK-101	EXKR-1	Sec 19 T38S R35E 1,510 feet south, 1,200 feet east of OKF-100	270845 [4]805215	18	953	03-25-04	0-35 0-170 0-562	42 34 24	Steel Steel Steel	562-875	22
Taylor Creek/ Nubbin Slough—Lake Okeechobee (22)	OK-9000	ASR-1	S24, 37S, 35E	271420 804709	16	1,710	06-19-88	0-65 0-200 0-1,268	42 34 24	Steel Steel Steel	1,268-1,710	22
	OK-9001	MW-1	560 feet north of ASR-1	271420.7 [4]804707.5	16	1,800	07-22-88	0-82 0-200 0-990 0-1,270	24 12 6 1.50	Steel Steel Steel ?	990-1,075	8
	OK-9002	Deep monitoring tube in MW-1	560 feet north of ASR-1	271420.7 [4]804707.5	16						1,275-1,700	6
Palm Beach County												
Boynton Beach East WTP (23)	PB-1194	ASR-1	NE S33, 45S, 43E	263050 [3]800346	18.9	1,260	04-13-92	0-38 0-399 0-804	36 26 16	Steel Steel Steel	804-909	16
	PB-1195	MW-1	~50 feet south of ASR-1		18.9	435	05-21-92	0-300 [1]300-320	4 4	PVC PVC	[2]300-320	4
Delray Beach North Storage Reservoir (24)	PB-1702	ASR-1	S17, 46S, 43E	262800 800600	21.2	1,200	08-24-96	0-400 352-1,016	20 14	Steel Steel	1,016-1,120	18.5

Table 2. Well Identification, location, and construction data for aquifer storage and recovery well systems in southern Florida.—Continued

Site name (and number)	USGS local well number	Other well identifier	Land-net or relative location	Latitude and Longitude (ddmmss)	Altitude of land surface (feet)	Total hole depth (feet)	Date at end of construction	Depth to top and bottom of casing (feet)	Casing diameter (inches)	Type of casing	Completed open interval (feet)	Diameter of open interval (inches)
Palm Beach County—Continued												
Hillsboro Canal, East (25)	PB-1775	FAMW		262030 801323	16.33	1,650	02-06-02	0-35 0-220 0-1,005 0-1,007	34 24 14 6.63	Steel Steel Steel Fiber-glass	1,007-1,225	12.25
	PB-1776	ASR-1	758 W ft from FAMW	262003 801320	7.98	1,225	06-2003	0-35 0-235 0-1,010	48 34 24	Steel Steel Steel	1,010-1,225	22.5
Hillsboro Canal West, Site 1 (26)	PB-1765	EXW-1 (ASR-1)	NR	262119 [3,4]801743	NR	1,225	03-31-00	0-55 0-205 0-1,015	42 36 24	Steel Steel Steel	1,015-1,225	24
	PB-1766	PBF-12 test well	330 feet northwest of EXW-1	262120 [3,4]801746	12.5	2,370	?	0-375 0-1,000 0-1,505 0-2,130	24 18 12 2.38	Steel Steel Steel ?	1,505-1,670 2,130-2,260	12 12
	PB-1767	PBF-10R[6]	330 feet northwest of EXW-1	262120 [3,4]801746	NR	1,225	08-00	0-1,015	3	NR	1,015-1,225	8
Jupiter (27)	PB-747	PBF-14 (ASR-1)	S3, 41S, 42E	265606.5 [4]800824.5	13	1,280	06-74	0-400 0-990	20 12	Steel Steel	990-1,280	NR
	PB-1145	FAMW-1	500 feet from ASR-1	265608 800823	13	1,270	1975	0-400 0-990	12 5	NR NR	995-1,270	NR
System 3 Palm Beach County (28)	PB-1763	ASR-1	S?, 46S, 42E	262859 800811	NR	1,155	01-99	0-60 0-365 0-223 215-1,065	36 24 18 16	Steel PVC Steel PVC	1,065-1,155	14
	PB-1764	FAMW		262900 800810	NR	1,500	01-98	0-155 0-1,050 0-1,052	16 10.75 5	Steel Steel PVC	1,052-1,270	10
West Palm Beach WTP (29)	PB-1692	ASR-1	~100 feet east of MW-1	264259 [3,4]800349	19.13	1,200	01-29-97	0-56 0-389 0-985	42 36 24	Steel Steel Steel	985-1,200	22
	PB-1693	MW-1	NW S21, 43S, 43E	264257 [3,4]800350	18.97	1,410	11-13-96	0-65 0-379 0-975	30 24 12.75	Steel Steel Steel	975-1,191	12

Table 2. Well identification, location, and construction data for aquifer storage and recovery well systems in southern Florida.—Continued

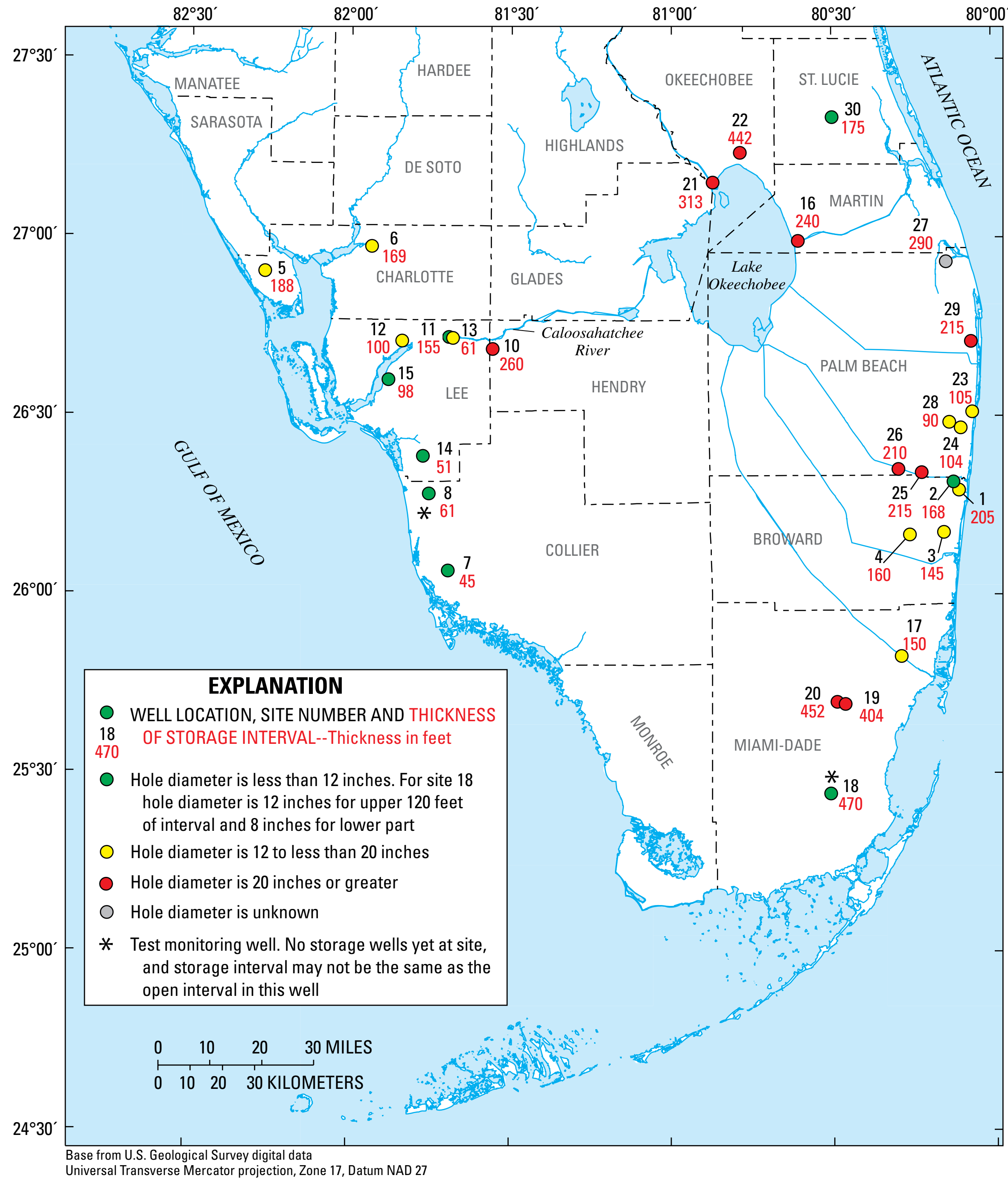
Site name (and number)	USGS local well number	Other well identifier	Land-net or relative location	Latitude and Longitude (ddmmss)	Altitude of land surface (feet)	Total hole depth (feet)	Date at end of construction	Depth to top and bottom of casing (feet)	Casing diameter (inches)	Type of casing	Completed open interval (feet)	Diameter of open interval (inches)
St. Lucie County												
	STL-356	ASR-1 SLF-50	SE S14, 36S, 39E	272017 802953	31.75	1,000	02-82	0-130 0-600	12 6	PVC PVC	600-775	5.125
St. Lucie County (30)	STL-357	MW-1 SLF-51	148 feet northeast of ASR-1	272019 802053	25.56	775	02-82	0-130 0-600	12 6	PVC PVC	600-775	5.125
	STL-355	MW-2 SLF-49	420 feet northwest of ASR-1	272020 802954	25.09	893	?	0-560	NR	NR	560-893	NR

[1]Top and bottom depth of screen.
[2]Screened interval.
[3]Latitude-longitude determined in the field using a hand-held global positioning system accurate to ± 0.2 seconds. The location for most of the other wells came from Florida Department of Environmental Protection construction permits.
[4]Datum is NAD 83; all other datums for location are NAD 27.
[5]Depths referenced to 4 feet above land surface.
[6]Replacement well to PBF-12, upper zone.

The hydraulic properties given in table 3 include transmissivity, storativity, leakance, and specific capacity; they are reported estimates and were not independently verified in this study. Transmissivity is a measure of the volume of water per unit of time that can be transmitted horizontally through a unit width and the full saturated thickness of the aquifer under a unit hydraulic gradient. Transmissivity also is equal to the thickness of the aquifer times its horizontal hydraulic conductivity. Hydraulic conductivity, which can be derived from transmissivity and aquifer thickness, is a measure of permeability and is defined as the volume of water per unit of time that will move through a unit area of an aquifer under a unit hydraulic gradient. Storativity, or the storage coefficient, is the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. Leakance is a measure of the degree of aquifer confinement and is defined as the vertical hydraulic conductivity of either a confining unit above or below an aquifer or both, divided by the thickness of the confining unit(s). Specific capacity is the yield (pumping or flowing rate) of a well divided by the drawdown in the well and can be used to estimate transmissivity (Brown, 1963; Heath, 1989). This property also can be used to make relative comparisons of the permeability of intervals tested, provided the thickness of the tested interval, length of the pumping period, pumping rate, storativity, and effective radius of the well are similar.

Packer tests are tests of open-hole intervals conducted during drilling using inflatable packers set on a string of drill pipe for the purpose of isolating the interval to be tested. Often, only specific capacity data are reported for packer tests (table 3). Transmissivity can be estimated either from packer test specific capacity results or from analysis of water-level recovery after a period of constant rate pumping during a packer test. This latter method, known as the Theis (1935) residual drawdown or recovery analysis, gives a more reliable estimate than the specific capacity method. Packer test results, however, can be unreliable because of partial penetration, a low pumping rate, a short pumping period, or incomplete isolation of the interval tested (leaky packers).

Many of the tests reported in table 3 are single-well step-drawdown tests, which are run under variable discharge rate conditions; they are used to: (1) determine the specific capacity of a well; (2) provide insight into the productive capacity and permeability of the interval tested in a well; and (3) determine the size and depth of the pump to be used in the well for a multi-well test or for long-term operation. At some sites, the transmissivity of a storage zone was estimated from a step-drawdown test (table 3). Transmissivity of a confined aquifer can be estimated from a step-drawdown test using the Eden-Hazel's method (Kruseman and de Ridder, 1990). Only the initial and final pumping rates (first and last steps of the test) are given in table 3 together with the corresponding specific capacity values. Specific capacity determined from step-drawdown tests of storage zones in the Upper Floridan aquifer range from 7.0 (gal/min)/ft of drawdown at the North Reservoir (site 12) to 390 (gal/min)/ft at the West Palm Beach WTP (site 29), as noted in



Base from U.S. Geological Survey digital data
Universal Transverse Mercator projection, Zone 17, Datum NAD 27

Figure 4. Thickness and diameter of open-hole interval in storage wells at aquifer storage and recovery sites in southern Florida. All wells shown are the first storage well at each site, except for site 8 and 18 (see table 2).

table 3. Specific capacity is reported to be 1,600 (gal/min)/ft on the basis of a multiwell test at Taylor Creek/Nubbin Slough—Lake Okeechobee (site 22) site in the middle Floridan aquifer. Generally, specific capacity increases as the diameter of the open-hole interval increases and after well acidization because of dissolution of the rock matrix.

Hydraulic properties (transmissivity, storativity, and leakance) determined from a multiwell, constant rate (aquifer) test are considered the most reliable and representative data presented in table 3. Analytical solutions commonly used to analyze water-level data from this type of test include Theis (1935) and Cooper and Jacob (1946) for confined aquifers and Hantush and Jacob (1955) and Walton (1962) for semiconfined, leaky aquifers. Single-well constant rate tests provide only an estimate of transmissivity; usually only recovery water-level data from these tests are analyzed using the Theis (1935) solution for residual drawdown and the Cooper and Jacob (1946) solution.

Table 3. Hydraulic test data from aquifer storage and recovery well systems in southern Florida.

[Depths are in feet below land surface. Test type: M, multiwell constant rate; P, Packer test; R, single-well constant rate; S, step drawdown. Method of analysis: SC, specific capacity or step-drawdown test analysis; Theis, Theis (1935) confined aquifer; Theis Rec, Theis (1935) residual drawdown recovery; C-J, Cooper and Jacob (1946) confined aquifer; J-L, Jacob and Lohman (1952); H-J, Hantush and Jacob (1955) leaky aquifer; Hantush, Hantush (1960) leaky aquifer; Moench, Moench (1985) leaky aquifer; Walton, Walton (1962) leaky aquifer; avg., average; WTP, water treatment plant; WWTP, wastewater treatment plant; DD, drawdown; --, not applicable; NR, not reported; 1/day, per day]

Test date	Production well identifier	Open interval tested (feet)	Test type	Monitoring well	Pumping rate (gallons per minute)	Length of pumping period (hours)	Transmissivity (square feet per day)	Storativity (unitless)	Leakance (1/day)	Method of analysis	Specific capacity (gallons per minute per foot)	Background measurements	Problems and comments
Broward County - Site 1, Broward County WTP 2A													
11-21-96	ASR-1	[1]995-1,200	S	--	1,050-2,950	8	--	--	--	--	[2]90.6-51.1	Data collected for multiwell test, but no information on whether corrections were made.	Walton method should give same transmissivity if no leakance as C-J method(?).
11-26-96	ASR-1	[1]995-1,200	M	MW-1	1,000	24	28,900	$1.1x10^{-4}$	None	Walton	--		
11-26-96	ASR-1	[1]995-1,200	M	MW-1	1,000	24	37,200	$5.3x10^{-5}$	--	C-J	--		
11-26-96	ASR-1	[1]995-1,200	M	ASR-1	1,000	24	44,000	--	--	Theis Rec	NR		
09-19-96	MW-1	[1]990-1,200	S	--	480	6	--	--	--	--	20		
Broward County - Site 2, Deerfield Beach West WTP													
NR	ASR-1	[1]956-1,130	S	--	950-2,100	NR	--	--	--	--	[2]42.6-32.0		Step-drawdown test was performed prior to multi-well, but date of test was not given in report.
12-10-92	ASR-1	[1]956-1,130	M	MW-1	1,200	5.7	24,200	$1.33x10^{-6}$	$6.3x10^{-2}$	H-J	--	NR	
Broward County - Site 3, Fiveash WTP													
01-12-98	FMW-1	998-1,028	P,R	--	160	4	4,700	--	--	Theis Rec	4.7	NR	Third packer test showed apparent failure after about 10 minutes, which may have affected data. FMW-1 apparently not used in 24-hour test of ASR-1.
01-13-98	FMW-1	998-1,042	P,R	--	160	4	8,000	--	--	Theis Rec	5	NR	
01-15-98	FMW-1	[1]1,058-1,175	P	--	600	10 min	23,500	--	--	C-J	46		
03-16-98	FMW-1	[1]1,055-1,175	S	--	100-160	4	--	--	--	--	[2]3.8-3.6		
03-17-98	FMW-1	[1]1,055-1,175	S	--	164	24	NR	--	--	--	~3.5		
03-25-98	ASR-1	[1]1,055-1,200	S	--	968-2,104	4	--	--	--	--	[2]25.5-17.7		
03-30-98	ASR-1	[1]1,055-1,200	R	--	2,100	24	19,500	--	--	Theis Rec	~17.5	NR	
Broward County - Site 4, Springtree WTP													
06-06-97	ASR-1	[1]1,110-1,270	S	--	700-1,900	8	--	--	--	--	[2]18.4-16.5		Acidization of well done after step test and before constant rate test. Interpretation of recovery data favored late time data.
07-28-97	ASR-1	[1]1,110-1,270	R	--	2,115	48	5,700	--	--	Theis Rec	22.75	NR	
Charlotte County - Site 5, Englewood South Regional WWTP													
NR	TPW-1	563-583	P,R	--	10	1.33	450	--	--	Theis Rec	1	NR	Multiwell aquifer test planned in the future.
03-07-00	TPW-1	630-807	P	--	131	4	1,300	--	--	SC	5		
03-31-00	TPW-1	[1]507-700	S	--	490-1,050	NR	4,700	--	--	SC	17.34 (avg)		
04-20-00	SZMW-1	[1]510-700	S	--	31-101	NR	3,700	--	--	SC	13.87 (avg)		
04-18-00	IMW-1	280-320	S	--	28.3-59.5	NR	2,300	--	--	SC	[2]5.5-4.0		
04-18-00	SMW-1	170-205	S	--	9.3-17.7	NR	300	--	--	SC	1 (avg)		

Table 3. Hydraulic test data from aquifer storage and recovery well systems in southern Florida.—Continued

Test date	Production well identifier	Open interval tested (feet)	Test type	Monitoring well	Pumping rate (gallons per minute)	Length of pumping period (hours)	Transmissivity (square feet per day)	Storativity (unitless)	Leakance (1/day)	Method of analysis	Specific capacity (gallons per minute per foot)	Background measurements	Problems and comments
							Charlotte County - Site 6, Shell Creek WTP						
11-05-97	ASR-1	700-755	P,S	--	300-550	NR	--	--	--	--	[2]10-5.6		Transmissivity and leakance values measured during drawdown.
11-17-97	ASR-1	700-764	S	--	231-597	12	--	--	--	--	[2]5.3-4.6		
11-18-97	ASR-1	700-765	R	--	546	54	1,300	--	--	SC	4.4	NR	
06-28-99	ASR-1	[1]764-933	S	--	610-600	8	--	--	--	--	10.6		
02-02-02	ASR-2	[1]780-998	S	--	400-700	10	--	--	--	--	[2]10.0-9.0		
01-31-02	ASR-3	810-1,000	S	--	500-800	11.25	--	--	--	--	[2]13.0-11.3		
02-13-02	ASR-4R	800-1,026	S	--	400-700	9.8	--	--	--	--	[2]8.5-8.0		
02-28-02	ASR-3	810-1,000	M	ASR-2, SZMW-2	760	120	5,977	2.8×10^{-4}	5×10^{-3}	H-J	NR	NR	
02-28-02	ASR-3	810-1,000	M		760	120	6,627	1.6×10^{-4}	2.1×10^{-3}	H-J	NR	NR	
							Collier County - Site 7, Marco Lakes						
NR	DZMW	296-399	S	--	220-600	NR	67,000	--	--	Walton	[2]220-170		Estimated transmissivity in lower Hawthorn zone I (550-622 feet) too low for consideration as an ASR storage interval. No dates were reported for any tests. Good agreement between tests.
NR	DZMW	296-399	R	--	600	3	42,400	--	--	Theis Rec	NR	NR	
NR	DZMW	550-622	P,R	--	5	4	47	--	--	Theis Rec	NR	NR	
NR	DZMW	[1]745-811	R	--	187	4.5	8,200	--	--	Theis Rec	NR	NR	
NR	ASR-1	[1]745-790	M	ASR-1	463	8.3	16,300	--	--	Theis Rec	NR	NR	
NR	ASR-1	[1]745-790	M	DZMW	463	8.3	9,100	6.5×10^{5}	7×10^{-4}	H-J	--	NR	
NR	ASR-1	[1]745-790	M	DZMW	463	8.3	12,000	--	--	Theis Rec	--	NR	
NR	ASR-2	[1]736-780	S	ASR-1	400-650	NR	--	--	--	--	[2]25-24		
NR	ASR-3	[1]736-780	S,M	ASR-2, ASRZMW	400-820	NR	8,000-8,100	--	--	C-J	[2]17.4-15	NR	
							Collier County - Site 8, Pelican Bay Well Field						
NR	EW-1	322-500	R	--	335	4	8,400	--	--	Theis Rec	NR	NR	
NR	EW-1	322-566	R	--	325	4	9,600	--	--	Theis Rec	NR	NR	
NR	EW-1	320-833	R	--	490	4	24,700	--	--	Theis Rec	NR	NR	Pump test after well was plugged back to 833 feet.
							Glades County - Site 9, Moore Haven S-77						
11-15-01	GLF-6	1,440-1,490	P	--	25	NR	--	--	--	--	0.3		
11-19-01	GLF-6	1,135-1,185	P	--	3	2	--	--	--	--	0.009		
11-20-01	GLF-6	930-980	P	--	100	NR	--	--	--	--	1.3		

Table 3. Hydraulic test data from aquifer storage and recovery well systems in southern Florida.—Continued

Test date	Production well identifier	Open interval tested (feet)	Test type	Monitoring well	Pumping rate (gallons per minute)	Length of pumping period (hours)	Transmissivity (square feet per day)	Storativity (unitless)	Leakance (1/day)	Method of analysis	Specific capacity (gallons per minute per foot)	Background measurements	Problems and comments
Hendry County - Site 10, Caloosahatchee River/Berry Grove													
12-04-03	EXBRY-1	620-752	SC	--	103.2	NR	--	--	--	--	4.4		Measurements conducted during reverse-air circulation drilling through 6-inch casing.
02-16-04	EXBRY-1	640-661	SC	--	1,153	NR	--	--	--	--	16.1		
02-17-04	EXBRY-1	640-661	SC	--	617	NR	--	--	--	--	15.1		
02-18-04	EXBRY-1	640-704	SC	--	615	NR	--	--	--	--	17.0		
02-19-04	EXBRY-1	640-725	SC	--	615	NR	--	--	--	--	19.1		
02-19-04	EXBRY-1	640-740	SC	--	635	NR	--	--	--	--	17.7		
03-09-04	EXBRY-1	640-757	SC	--	645	NR	--	--	--	--	19.9		
03-09-04	EXBRY-1	640-788	SC	--	609	NR	--	--	--	--	19.4		
03-09-04	EXBRY-1	640-819	SC	--	632	NR	--	--	--	--	20.1		
03-10-04	EXBRY-1	640-851	SC	--	588	NR	--	--	--	--	18.4		
03-10-04	EXBRY-1	640-883	SC	--	612	NR	--	--	--	--	18.8		
03-10-04	EXBRY-1	[1]640-900	SC	--	698	NR	--	--	--	--	23.3		
03-25-04	EXBRY-1	[1]640-900	S	--	880-2,450	4.2	--	--	--	--	[2]30.1-23.8		Submersible test pump set in well.
05-18-04	EXBRY-1	[1]640-900	X	--	1,200-4,000	52	--	--	--	--	[2]31-38		Submersible test pump set in well.
Lee County - Site 11, Lee County WTP													
NR	ASR-1	[1]445-600	M	NR	350	48	800	$1.00x10^{-4}$	$1.0x10^{-2}$	H-J	NR	NR	Storage zone in ASR-1 is located in the lower Hawthorn producing zone of the Upper Floridan aquifer as defined by Reese (2000).
Lee County – Site 12, North Reservoir													
12-18-98	MW-1	480-518	S	--	92-430	NR	14,400	--	--	SC	[2]44.4-41.3		
03-03-99	MW-1	[1]529-619	P,S	--	73-295	NR	5,200	--	--	SC	[2]9.7-3.5		
03-08-99	MW-1	640-703	P,S	--	79-281	NR	2,040	--	--	SC	[2]6.6-2.8		
03-08-99	MW-1	808-890	P,S	--	55-190	NR	680	--	--	SC	[2]2.8-1.8		
03-08-99	MW-1	904-977	P,S	--	85-322	NR	9,590	--	--	SC	[2]10.5-3.1		
03-03-99	ASR-1	[1]540-642	S	--	162-590	4	2,220	--	--	SC	[2]8.65-7.00		
03-08-99	ASR-1	[1]540-642	M	MW-1	379	72	8,290	$3.27x10^{-4}$	$7.33x10^{-4}$	H-J	--	Data collected for 3 days prior to the multiwell test.	Fit of line to ASR-1 recovery data for multi-well test is poor.
03-08-99	ASR-1	[1]540-642	M	MW-1	379	72	8,740	$4.64x10^{-4}$	--	C-J (recov)	--		
03-08-99	ASR-1	[1]540-642	M	ASR-1	379	72	8,570	--	--	C-J (recov)	NR		

Table 3. Hydraulic test data from aquifer storage and recovery well systems in southern Florida.—Continued

Test date	Production well identifier	Open interval tested (feet)	Test type	Monitoring well	Pumping rate (gallons per minute)	Length of pumping period (hours)	Transmissivity (square feet per day)	Storativity (unitless)	Leakance (1/day)	Method of analysis	Specific capacity (gallons per minute per foot)	Background measurements	Problems and comments
Lee County – Site 13, Olga WTP													
01-05-99	MW-1	515-605	S	--	110-400	NR	2,500	--	--	SC	NR	Measured for multiwell test, but unknown if used to correct drawdown.	H-J results for multiwell test agree better with single well and packer test than C-J results. A second multiwell constant rate test was run, but is not reported here. Storage zone is about 1500 feet below top of Suwannee Limestone.
01-07-99	MW-1	612-689	P	--	70-200	NR	1,300	--	--	SC	NR		
02-03-99	MW-1	[1]835-935	P	--	70-355	NR	7,600	--	--	SC	NR		
02-04-99	MW-1	710-935	P	--	70-350	NR	7,600	--	--	SC	NR		
02-04-99	MW-1	[1]835-935	P	--	70-350	NR	7,600	--	--	SC	NR		
02-08-99	MW-1	945-1,101	P	--	6-15	NR	33	--	--	SC	NR		
03-17-99	MW-3	740-820	S	--	78-480	NR	1,900	--	--	SC	NR		
03-25-99	MW-3	[1]830-945	P	--	80-340	NR	9,000	--	--	SC	NR		
03-25-99	MW-3	[1]854-945	P	--	75-350	NR	6,400	--	--	SC	NR		
03-26-99	MW-3	[1]857-945	R	--	300	NR	8,700	--	--	Theis Rec	NR		
11-01-99	ASR-1	[1]859-920	S	--	112-545	5	5,000	--	--	SC	[2]14.9-8.5		
11-03-99	ASR-1	[1]859-920	M	MW-1	500	60	7,200	5.10×10^{-5}	5.2×10^{-3}	H-J	--		
11-03-99	ASR-1	[1]859-920	M	MW-1	500	60	12,000	4.10×10^{-5}	--	C-J	--		
11-03-99	ASR-1	[1]859-920	M	MW-3	500	60	9,400	5.50×10^{-5}	6.0×10^{-2}	H-J	--		
11-03-99	ASR-1	[1]859-920	M	MW-3	500	60	11,000	4.20×10^{-4}	--	C-J	--		
Lee County – Site 14, San Carlos Estates													
06-07-99	TPW-1	[1]650-701	S	--	710-1,480	8	--	--	--	--	[2]250-130	Unknown for multiwell test. Test followed 10 days of recharge at 1,955 gallons per minute and then 6-day static period.	High specific capacity in TPW-1 due two pilot holes in open interval. Pumping rate for test on 11/10/99 or 985 gallons per minute was natural flow. C-J solution for drawdown in SZMW-1R is suspect. Solution is for very late time only, and back-ground changes due to prior recharge may have affected response.
07-29-99	SZMW-1R	[1]659-721	S	--	170-350	8	--	--	--	--	[2]15-9.0		
08-02-99	SMW-1	234-321	S	--	150-220	8	--	--	--	--	[2]8.9-6.5		
11-10-99	TPW-1	[1]650-701	M	SZMW-1R	985	8	39,000	1.00×10^{-4}	--	C-J	--		
11-10-99	TPW-1	[1]650-701	M	SZMW-1R	985	8	70,000	--	--	Theis Rec	--		
Lee County – Site 15, Winkler Avenue													
NR	ASR-1	[1]455-554	S	--	135	15 min	--	--	--	--	59.7	Ninety hours collected prior to multiwell test, but apparently not used to correct drawdown data.	Pumping rate for multiwell test was 1,540 gallons per minute for first 6.5 hours, then changed to 1,400 gallons per minute. No attempt was made to analyze multiwell test data for storage coefficient or leakance.
NR	ASR-1	455-647	S	--	160	15 min	--	--	--	--	86.3		
06-16-99	ASR-1	[1]455-574	P	--	479	70 min	29,100	--	--	C-J (recov)	NR		
06-17-99	ASR-1	[1]455-575	P	--	483	18 min	26,600	--	--	C-J (recov)	NR		
10-23-99	ASR-1	[1]455-553	M	ASR-1	1,540-1,400	27	24,700	--	--	C-J	NR		
10-23-99	ASR-1	[1]455-553	M	ASR-1	1,540-1,400	27	25,400	--	--	C-J (recov)	--		
10-23-99	ASR-1	[1]455-553	M	SZMW-1	1,540-1,400	27	27,400	NR	NR	C-J	--		
10-23-99	ASR-1	[1]455-553	M	SZMW-1	1,540-1,400	27	29,000	--	--	C-J (recov)	--		

Table 3. Hydraulic test data from aquifer storage and recovery well systems in southern Florida.—Continued

Test date	Production well identifier	Open interval tested (feet)	Test type	Monitoring well	Pumping rate (gallons per minute)	Length of pumping period (hours)	Transmissivity (square feet per day)	Storativity (unitless)	Leakance (1/day)	Method of analysis	Specific capacity (gallons per minute per foot)	Background measurements	Problems and comments
Martin County – Site 16, Port Mayaca S-153													
10-16-01	MF-37	1,992-2,046	P	--	155	2	--	--	--	--	27.2		
10-23-01	MF-37	1,782-1,850	P	--	129	3	--	--	--	--	61.7		
10-26-01	MF-37	1,496-1,543	P	--	170	NR	--	--	--	--	106.3		
10-30-01	MF-37	1,610-1,660	P	--	123	2	--	--	--	--	9.1		
11-01-01	MF-37	1,241-1,288	P	--	107	2	--	--	--	--	2.2		
10-26-01	MF-37	765-900	P	--	210	2.3	--	--	--	--	11.5		
10-07-03	EXPM-1	800-900	S	--	980-2,150	NR	--	--	--	--	[2]25.5-17.7		
10-15-03	EXPM-1	[1]800-1,040	S	--	1,600-2,900	NR	--	--	--	--	[2]30.05-24.15		
11-03-03	EXPM-1	[1]800-1,040	S	--	1,700-4,400	NR	--	--	--	--	[2]66.14-47.75		Post-acidization with 4,200 gallons of 18-Baume hydrochloric acid.
11-05-03	EXPM-1	[1]800-1,040	R	--	3,250	24	12,700	--	--	Theis Rec	--	Collected for 3 days following test (11/7/03 to 11/11/03).	
Miami-Dade County – Site 17, Hialeah													
02-10-75	MW-1	[1]953-1,060	M	ASR-1	250	1.66	11,000	$8.4x10^{-5}$	--	J-L	--	NR	Transmissivity estimate from Meyer (1989b). Storage coefficient estimated by model simulation of pumping test.
Miami-Dade County – Site 18, J.R. Dean WTP													
05-14-03	EW-1	880-1,090	R	--	45	2	866	--	--	NR	4	NR	
05-23-03	EW-1	880-1,190	R	--	450	2	1,276	--	--	NR	6	NR	
05-30-03	EW-1	880-1,290	R	--	650	1	36,629	--	--	NR	23	NR	
06-04-03	EW-1	880-1,405	R	--	900	0.5	82,803	--	--	NR	34	NR	
06-09-03	EW-1	880-1,504	R	--	950	0.5	37,000	--	--	NR	40	NR	
07-02-03	EW-1	1,050-1,150	P	--	25	4	29	--	--	NR	<1		
07-09-03	EW-1	1,220-1,283	P	--	85	2	Not calc.	--	--	--	12		
07-10-03	EW-1	1,150-1,213	P	--	82	2	2,200	--	--	NR	3		
07-22-03	EW-1	880-1,040	P	--	60	2	492	--	--	NR	2		
10-08-03	EW-1	880-1,350	R	--	280-750	72	10,790	--	--	Theis Rec	[2]16-15	NR	Pumping rate was reduced because of increasing salinity during test.

Table 3. Hydraulic test data from aquifer storage and recovery well systems in southern Florida.—Continued

Test date	Production well identifier	Open interval tested (feet)	Test type	Monitoring well	Pumping rate (gallons per minute)	Length of pumping period (hours)	Transmissivity (square feet per day)	Storativity (unitless)	Leakance (1/day)	Method of analysis	Specific capacity (gallons per minute per foot)	Background measurements	Problems and comments
Miami-Dade County – Site 19, Southwest Well Field													
05-28-98	ASR-1	[1]765-1,169	S	--	1,500-3,350	6	--	--	--	--	[2]66.1-70.53		Post acidization
05-20-99	ASR-2	[1]760-1,200	S	--	1,500-3,500	6	--	--	--	--	[2]65.2-57.75		Post acidization
05-28-99	ASR-2	[1]760-1,200	M	ASR-1	3,500	12	11,900	6.05×10^{-4}	See comment	Walton	--	For 1 day prior to test.	Post acidization,. Leakance reported as 1.3×10^{-3} centimeters per second.
Miami-Dade County – Site 20, West Well Field													
02-26-97	ASR-1	[1]850-1,302	S	--	1,400-4,000	8	--	--	--	--	[2]269-52.1	Measured for multi-well test. Correction not done due to negligibility.	All three aquifer storage and recovery wells were heavily acidized prior to all tests. Late time drawdown data problematic because of pump going down several times.
02-25-97	ASR-2	[1]845-1,250	S	--	1,500-3,800	8	--	--	--	--	[2]126.6-51.1		
04-08-97	ASR-3	[1]835-1,210	S	--	1,500-3,800	8	--	--	--	--	[2]46.1-38.2		
12-09-97	ASR-1	[1]850-1,302	M	ASR-1	3,500	72	10,300	N/A	N/A	C-J	NR		
12-09-97	ASR-1	[1]850-1,302	M	ASR-2	3,500	72	15,400	3.90×10^{-4}	1.6×10^{-3}	Walton	--		
12-09-97	ASR-1	[1]850-1,302	M	ASR-2	3,500	72	18,200	2.90×10^{-4}	N/A	C-J	--		
12-09-97	ASR-1	[1]850-1,302	M	ASR-3	3,500	72	15,400	4.40×10^{-4}	3.9×10^{-5}	Walton	--		
12-09-97	ASR-1	[1]850-1,302	M	ASR-3	3,500	72	19,700	3.30×10^{-4}	N/A	C-J	--		
Okeechobee County – Site 21, Kissimmee River													
12-06-01	OKF-100	1,955-2,030	P	--	25	NR	--	--	--	--	0.4		
12-14-01	OKF-100	1,790-1,850	P	--	5	NR	--	--	--	--	0.08		
12-17-01	OKF-100	1,640-1,700	P	--	205	NR	--	--	--	--	125		
03-25-04	EXDR-1	[1]562-875	S	--	1,356	NR	--	--	--	--	39		Post acidization
05-04-04	EXDR-1	[1]562-875	R	--	3,500	24	40,000	--	--	C-J and Theis Rec.	--		Post acidization
Okeechobee County – Site 22, Taylor Creek/Nubbin Slough—Lake Okeechobee													
04-20-98	MW-1	1,175-1,227	P	--	10	6.4	706	NR	--	C-J	NR	Water-level data taken for 5 days prior to multiwell test; correc-tions made using a long-term increasing trend.	Leakance derived by extrapolation; longer pumping period required for more accurate value.
04-20-98	MW-1	1,175-1,227	P,R	--	10	6.4	2,940	--	--	Recovery analysis	NR		
08-02-98	ASR-1	[1]1,268-1,710	M	ASR-1	6,500	24	620,000	N/A	N/A	C-J (recov)	1,600		
08-02-98	ASR-1	[1]1,268-1,710	M	MW-1	6,500	24	586,000	$1,25 \times 10^{-3}$	.01-.001	H-J	1,600		
08-02-98	ASR-1	[1]1,268-1,710	M	MW-1	6,500	24	765,000	1.90×10^{-4}	N/A	C-J (recov)	1,600		
Palm Beach County – Site 23, Boynton Beach East WTP													
04-09-92	ASR-1	[1]804-900	S	--	320-2,100	NR	6,800-	NR	--	C-J	[2]18-28		Second step test is with permanent equipment installed in well. Average of estimates for transmissivity was 9,400 square feet per day.
10-15-92	ASR-1	[1]804-909	S	--	798-1,723	NR	13,000 Not calc.	--	--	C-J	[2]29-27		

Table 3. Hydraulic test data from aquifer storage and recovery well systems in southern Florida.—Continued

Test date	Production well identifier	Open interval tested (feet)	Test type	Monitoring well	Pumping rate (gallons per minute)	Length of pumping period (hours)	Transmissivity (square feet per day)	Storativity (unitless)	Leakance (1/day)	Method of analysis	Specific capacity (gallons per minute per foot)	Background measurements	Problems and comments
Palm Beach County – Site 24, Delray Beach North Storage Reservoir													
06-05-96	ASR-1	849-899	P	--	49	NR	--	--	--	--	0.37		Second step test performed after well acidization. For the second step test, pump malfunctioned after about 10 minutes of pumping during the last step at 2,550 gallons per minute.
06-11-96	ASR-1	900-952	P	--	83	NR	--	--	--	--	0.90		
06-14-96	ASR-1	974-1,020	P	--	90	NR	--	--	--	--	2.40		
06-18-96	ASR-1	1,020-1,100	P	--	98	NR	--	--	--	--	2.00		
09-20-96	ASR-1	[1]1,020-1,200	S	--	575-1,100	24	--	--	--	--	[2]10.8-7.8		
02-24-98	ASR-1	[1]1,020-1,200	S	--	76-2,550	13.2	--	--	--	--	[2]17.2-15.7		
Palm Beach County – Site 25, Hillsboro Canal, East (PBCWUD)													
09-06-01	FAMW	1,597-1,627	P	--	99.5	4	--	--	--	--	2.73		
09-12-01	FAMW	1,310-1,340	P	--	92.0	4	--	--	--	--	1.71		
09-25-01	FAMW	[1]1,005-1,198	P	--	71.0	4	--	--	--	--	6.76		
09-28-01	FAMW	1,005-1,041	P	--	92.6	4	--	--	--	--	18.9		
12-14-01	FAMW	[1]1,007-1,232	S	--	308-956	4	--	--	--	--	[2]17.1-11.9		
12-18-01	FAMW	[1]1,007-1,232	R	FAMW	958	12	9,965	1.568	--	Theis Rec	11.85	NR	
04-24-02	ASR-1	[1]1,010-1,225	S	--	1,400-3,130	4	--	--	--	--	[2]35-24.1		Preacidization
04-29-02	ASR-1	[1]1,010-1,225	R,S	ASR-1	1,800-3,400	24	19,000	1.8×10^{-4}	--	Theis	[2]78.3-63	NR	Post acidization. Pumping rate at 3,400 gallons per minute was for 22 hours.
04-29-04	ASR-1	[1]1,010-1,225	M	FAMW	1,800-3,400	24	19,200	2.3×10^{-4}	2.3×10^{-4}	Moench (case 1)	--	NR	
Palm Beach County – Site 26, Hillsboro Canal, West (CERP)													
04-05-00	EXW-1	1,160-1,225	P	--	95	NR	--	--	--	--	22.6		Acidized EXW-1 with 4,30 gallons of 36 percent HCI on June 2, 2000.
04-10-00	EXW-1	1,015-1,150	P	--	105	NR	--	--	--	--	10.9		
05-25-00	EXW-1	[1]1,015-1,225	S	--	1,000-3,000	NR	--	--	--	--	[2]31.1-26.6		
06-16-00	EXW-1	[1]1,015-1,255	S	--	2,000-5,200	NR	--	--	--	--	[2]65.4-41.68		Conducted after well acidization.
11-15-00	EXW-1	[1]1,015-1,255	M	PBF-10R	3,050	60	8,100	9.7×10^{-5}	--	Hantush	NR	Collected for 7 days after recovery period.	
Palm Beach County – Site 28, System 3 Palm Beach County													
02-25-99	ASR-1	[1]1,065-1,155	S	--	530-2,100	>6	8,800	--	--	--	[2]47.8-25.2		Transmissivity of ASR zone was estimated using recovery data. Post-acidization.

Table 3. Hydraulic test data from aquifer storage and recovery well systems in southern Florida.—Continued

Test date	Production well identifier	Open interval tested (feet)	Test type	Monitoring well	Pumping rate (gallons per minute)	Length of pumping period (hours)	Transmissivity (square feet per day)	Storativity (unitless)	Leakance (1/day)	Method of analysis	Specific capacity (gallons per minute per foot)	Background measurements	Problems and comments
Palm Beach County – Site 29, West Palm Beach WTP													
08-22-96	FAMW	975-1,091	P,S	--	64-142	NR	--	--	--	--	[2]194-86		Recovery was allowed following step test of ASR-1 before multiwell test begun.
09-14-96	FAMW	1,304-1,384	P,S	--	55-110	NR	--	--	--	--	[2]220-110		
08-29-96	FAMW	975-1,090	S	--	300-584	NR	--	--	--	--	[2]75-58		
09-01-96	FAMW	[1]975-1,190	S	--	300-584	NR	--	--	--	--	[2]110-101		
09-04-96	FAMW	975-1,290	S	--	550-740	NR	--	--	--	--	[2]116-105		
09-06-96	FAMW	975-1,384	S	--	550-740	NR	--	--	--	--	[2]116-99		
11-19-96	FAMW	[1]975-1,191	S	--	550-732	NR	--	--	--	--	[2]62-42		
01-30-97	ASR-1	[1]985-1,200	S	--	508-704	24	--	--	--	--	[2]390-306		
02-01-97	ASR-1	[1]985-1,200	M	FAMW	700	24	138,000	1.00×10^{-4}	--	C-J	--	NR	Large deviation from Theis curve during late time on multiwell test, but leaky aquifer solution not used.
02-01-97	ASR-1	[1]985-1,200	M	FAMW	700	24	108,000	8.00×10^{-4}	--	Theis	--	NR	
St. Lucie County – Site 30, St. Lucie County													
08-24-82	MW-1	[1]600-775	M	ASR-1	388	72	5,910	1.64×10^{-4}	4.3×10^{-2}	H-J (DD)	--	NR	Also conducted four pump tests of ASR-1 during drilling with total depth ranging from 617 to 1,000 feet and casing at 600 feet. Transmissivity was calculated from these tests based on recovery data from ASR-1.
08-24-82	MW-1	[1]600-775	M	ASR-1	388	72	6,430	2.67×10^{-4}	4.7×10^{-2}	H-J (DD)	--	NR	

[1]Open interval tested is the same (or about the same) as the storage zone.

[2]Specific capacity values are listed in same order as corresponding pumping rate under pumping rate column. Only initial and final pumping rate values are given.

Drawdown data for aquifer tests should be corrected for background factors including tides, barometric pressure, and regional pumping. Corrections are made by collecting pre-pumping background water-level data and determining if there are any trends, such as tidal fluctuations. If present, these trends are removed from the drawdown data of the test so that the change in water level analyzed for the aquifer test is caused only by the withdrawal from the on-site production well. Background measurements were made for tests at nine sites in table 3; however, corrections made using these data were reported to have been done for only the test at site 22.

Because of increased permeability in the rock formation around the borehole, constant-rate test transmissivity results are probably affected by pretest borehole acidization methods designed to increase specific capacity. Acidization of ASR wells prior to multiwell, constant rate tests, were performed at the: Springtree WTP (site 4) by Montgomery Watson (1998a), Southwest Well Field (site 19) by CH2M HILL (2001a), West Well Field (site 20) by CH2M HILL (1998b), Hillsboro Canal, east (site 25) by the Palm Beach County Water Utilities Department (2003a); and Hillsboro Canal west (site 26) by Bennett and others (2001).

The transmissivity and hydraulic conductivity of an aquifer are commonly incorrectly estimated because of partially penetrating wells or inclusion of nonproductive zones of the aquifer in the estimate of transmissivity. Hydraulic properties determined from tests of storage zones may apply only to the storage zone or to a thicker interval, if the aquifer containing the storage zone is thicker than the storage zone. Of 28 sites with the storage zone in the Upper Floridan aquifer, the base of the aquifer was as least 50 ft below the base of the storage zone at 14 sites, at least 100 ft at 11 sites, and at least 340 ft at one site (site 23) as noted in appendix 1. If the aquifer is thicker than the storage zone, the hydraulic conductivity of a storage zone will be less than that obtained by dividing the transmissivity determined from a test by the thickness of the storage zone. In the Upper Floridan aquifer, however, most of the response for partial penetration tests may come from the interval tested because of thick zones of relatively low permeability that separate flow zones. Thus, the value of transmissivity obtained is less than the total transmissivity of the entire aquifer (Wedderburn and Knapp, 1983). Corrections can be made for partial penetration, assuming that horizontal and vertical hydraulic conductivity in the aquifer are uniform (Kruseman and de Ridder, 1990). Corrections for partial penetration were not made for any of the tests in table 3.

Storage zone transmissivity estimates were selected and plotted on a map of southern Florida (fig. 5), with most values being derived from drawdown analysis of multiwell aquifer tests. If performed, the leaky aquifer solution for these multiwell tests was used. The values for some sites were obtained from single-well constant rate and step-drawdown tests, as shown in figure 5. The storage zone is in the Upper Floridan aquifer in all instances, except at the J.R. Dean WTP (site 18), West Well Field (site 20), and Taylor Creek/Nubbin Slough—Lake Okeechobee (site 22). At site 22, the storage zone is in the middle Floridan aquifer. At sites 18 and 20 in Miami-Dade County, the storage zone (or in the case of site 18, the open-hole interval in the test-monitoring well) is interpreted, as discussed previously, to include the upper part of the Upper Floridan aquifer and some flow zones well above the aquifer in the lower part of the Hawthorn Group.

The highest storage zone transmissivity in the Upper Floridan aquifer is 110,000 ft^2/d at the West Palm Beach WTP (fig. 5, site 29), and the lowest transmissivity is 800 ft^2/d at the Lee County WTP (fig. 5, site 11). Transmissivity at most sites ranges from about 5,000 to 30,000 ft^2/d. The low transmissivity at site 11 is due to the placement of its open interval, which includes only the lower Hawthorn producing zone of the basal Hawthorn unit (app. 1, site 13; Reese, 2000). The Olga WTP (site 13) was later constructed at the same location as the Lee County WTP; its storage zone is deeper in the Upper Floridan aquifer and is contained within the lower part of the Suwannee Limestone (app. 1, site 13). The estimated transmissivity for the Olga storage zone is 9,400 ft^2/d (fig. 5, site 13). The transmissivity value shown in figure 5 for the Shell Creek WTP (site 6, 6,000 ft^2/d) was determined from a multiwell test using ASR-3 as the production well. The open interval for ASR-3 extended from a depth of 810 to 1,000 ft; however, this well was back plugged to a depth of 912 ft after the test was completed (table 2).

Storativity values determined from storage zones test in the Upper Floridan aquifer at 14 sites ranged from 1.33×10^{-6} at site 2 to 8.00×10^{-4} at site 29 (table 3). The value for site 14 was higher than this range but was not included in this analysis because, as noted in table 3, the solution giving this value is suspect. Storativity ranged from 5×10^{-5} to 5×10^{-4} at 11 of the 14 sites.

Leakance was estimated at nine sites with Upper Floridan aquifer storage zones by multiwell aquifer tests, and values are somewhat higher than expected (table 3). Two of these sites (sites 11 and 13) are at approximately the same location, but the storage zones are in different parts of the aquifer. Leakance determined from an aquifer test applies to both the upper and lower confining units of the aquifer, unless one of the confining units is known to be nonleaky. Reported leakance estimates ranged from as low as 3.9×10^{-5} 1/d at the West Well Field (site 20) to as much as 6.3×10^{-2} 1/d at the Deerfield Beach West WTP (site 2). Leakance estimates less than 1×10^{-3} 1/d were used to indicate confining conditions within the surficial aquifer system in southern Florida (Reese and Cunningham, 2000). Of the nine sites where leakance values were reported (table 3), five had values that exceeded this confining threshold of 1×10^{-3} 1/d. These higher leakance estimates at Upper Floridan aquifer storage zones are probably best attributed to leakage from below the tested interval rather than from above, because of the good confinement that exists above the aquifer in southern Florida (Bush and Johnston, 1988). This upward leakage probably either originated from intervals deeper in the Upper Floridan aquifer or from the middle confining unit of the Floridan aquifer system.

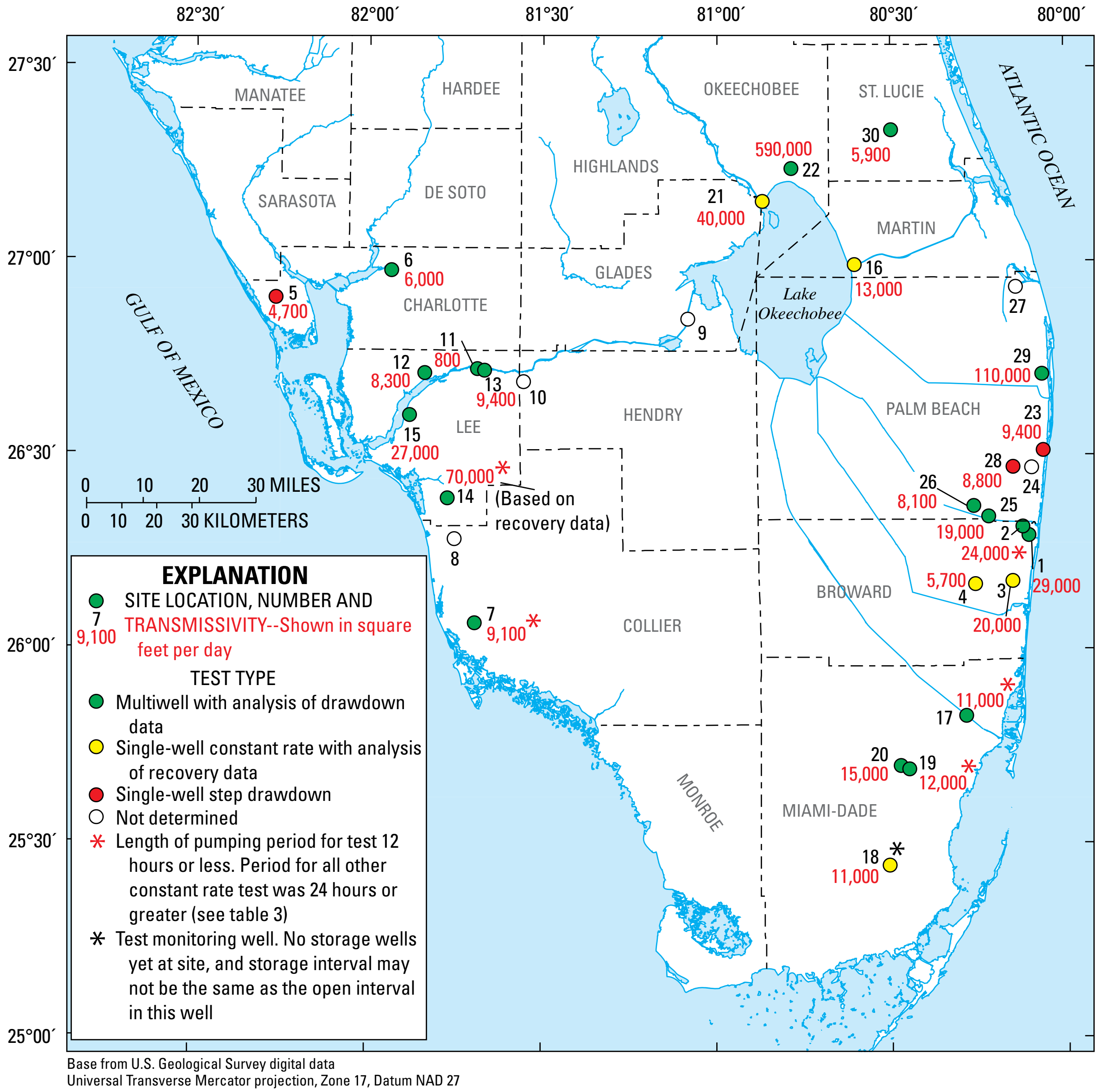


Figure 5. Transmissivity determined for storage zones in the Floridan aquifer system at aquifer storage and recovery sites in southern Florida. Values are rounded to two siginificant figures. The storage zone is in the Upper Floridan aquifer at all sites, except site 22, which is in the middle Floridan aquifer.

Quality of Ambient Ground Water

Ambient ground-water samples were collected from storage and monitoring wells at the ASR sites in the study area to design and implement ASR operations and satisfy FDEP regulatory requirements. Selected analyses of these samples were inventoried and are presented in table 4. Data in this table include the sampled interval, sample date, specific conductance, dissolved chloride concentration, dissolved-solids concentration, temperature, and dissolved sulfate concentration. The type of interval sampled and method of data collection used are listed in order of increasing reliability as follows: (1) sample collected during reverse-air rotary drilling with top of interval being the base of casing; (2) packer test interval; (3) pump-out test of open interval below casing during drilling; and (4) constructed (completed) open interval (table 4). The intervals sampled include the storage zone, intervals deeper or shallower than the storage zone, or both. In addition to samples from the Upper Floridan aquifer, at ASR sites in southwestern Florida samples usually were collected from shallow permeable zones of the intermediate aquifer system.

The chloride concentration of the ambient water in ASR storage zones in the Floridan aquifer system generally indicates salinity is greatest in wells in southeastern Florida (fig. 6). The samples selected were based on the most reliable sampling method available. Storage zone chloride concentrations ranged from as low as 500 mg/L at the Lee County WTP (site 11) to as high as 11,000 mg/L at the Englewood South Regional Wastewater Treatment Plant (WWTP) (site 5).

Table 4. Ambient water-quality data collected from aquifer storage and recovery well systems in southern Florida.

[Type of interval sampled: C, constructed (completed) open interval; O, pump out test of open interval below casing during drilling; P, packer test interval; R, sample collected during reverse-air rotary drilling with top of interval being the base of casing. USGS, U.S. Geological Survey; WTP, water treatment plant; WWTP, wastewater treatment plant; PD, post development; --, not determined or not reported]

Site number and name	Other identifier	USGS local number	Interval sampled (feet below land surface)	Type of interval sampled	Date sampled	Specific conductance (microsiemens per centimeter)	Dissolved chloride (milligrams per liter)	Dissolved solids (milligrams per liter)	Temper-ature (degrees Celsius)	Dissolved sulfate (milligrams per liter)
Broward County										
(1) Broward County WTP 2A	ASR-1	G-2889	[1]995-1,200	C	12-03-96	--	1,900	3,200	--	380
	MW-1	G-2916	[1]990-1,200	C	03-12-97	--	1,900	2,600	--	250
(2) Deerfield Beach West WTP	ASR-1	G-2887	[1]960-1,120	C	09-03-92	5,430	1,850	3,800	22.7	--
			[1]960-1,128	C	09-09-92	6,000	1,600	3,400	--	400
			[1]960-1,128	C	09-30-92	5,400	2,000	3,800	25.0	400
			[1]960-1,128	C	12-11-92	--	1,800	3,700	--	--
(3) Fiveash WTP	ASR-1	G-2917	1,055-1,300	R	--	7,800	4,000	--	--	--
	FMW-1	G-2918	[1]1,055-1,175	C	03-17-98	9,345	3,524	7,880	--	725
	SMW-1	G-2919	180-200	C	01-15-98	--	24	279	--	21
(4) Springtree WTP	ASR-1	G-2914	1,110-1,340	R	--	4,300	2,200	--	--	--
			[1]1,110-1,270	C	07-31-97	7,310	2,449	4,520	31.0	644
			[1]1,110-1,270	C	01-13-98	9,300	3,600	6,030	28.0	774
Charlotte County										
(5) Englewood South Regional WWTP	TPW	CH-318	295-808	O	03-02-00	16,800	5,200	10,267	--	664
			563-583	P	02-26-00	31,600	12,000	21,100	--	881
			630-808	P	03-06-00	50,100	17,500	31,133	--	--
			[1]507-700	C	03-31-00	27,000	11,600	19,350	24.2	1,279
	SZMW-1	CH-319	[1]510-700	C	04-20-00	21,600	10,997	22,100	21.0	1,106
	IMW-1	CH-320	280-320	C	04-18-00	11,780	4,458	8,040	21.0	535
	SMW-1	CH-321	170-205	C	04-18-00	8,410	2,875	6,000	21.0	204
(6) Shell Creek WTP	ASR-1	CH-315	700-1,040	R	--	3,540	--	2,020	--	--
			700-755	P	11-05-97	--	837	2,090	--	--
			700-764	C	11-18-97	--	850	1,918	--	--
			[1]764-933	C	08-07-99	--	900	1,900	--	380
	ASR-2	CH-316	[1]780-998	C	03-19-02	4050	746	2,020	--	344
	ASR-3	CH-317	[1]810-1,000	C	03-19-02	3,400	745	1,860	--	339
	ASR-4R	CH-325	[1]800-1,026	C	03-19-02	2,800	585	1,640	--	293
	SZMW-1R	CH-326	764-815	C	03-21-02	1,830	--	760	--	--
	SZMW-2	CH-327	[1]785-1,000	C	03-19-02	3,180	694	1,860	--	303
	IAMW-1	CH-328	350-400	C	03-19-02	3,880	687	1,730	--	298

Table 4. Ambient water-quality data collected from aquifer storage and recovery well systems in southern Florida.—Continued

Site number and name	Other identifier	USGS local number	Interval sampled (feet below land surface)	Type of interval sampled	Date sampled	Specific conductance (microsiemens per centimeter)	Dissolved chloride (milligrams per liter)	Dissolved solids (milligrams per liter)	Temper-ature (degrees Celsius)	Dissolved sulfate (milligrams per liter)
Collier County										
	ASR-1	C-1206	[1]745-790	C	--	6,000	2,520	6,620	--	--
	ASR-1	C-1206	[1]745-790	C	06-24-97	--	3,740	5,500	--	744
	DZMW	C-1207	293-352	C	07-01-97	--	3,260	6,180	--	800
	DZMW	C-1207	[1]745-817	C	07-01-97	--	2,590	5,620	--	718
(7) Marco Lakes	ASR-2	C-1208	[1]735-780	C	PD	8,500	2,480	--	--	--
	ASR-2	C-1208	[1]735-780	C	09-20-99	6,860	2,449	4,280	--	663
	MHZ2MW	C-1209	440-470	C	09-20-99	8,700	2,999	5,665	25.8	758
	ASRZMW	C-1210	[1]725-774	C	10-01-99	9,120	2,958	5,816	29.8	699
	ASR-3	C-1211	[1]735-780	C	11-24-99	8,860	2,774	3,920	26.3	686
			322-435	O	--	8,630	2,430	--	--	--
			322-566	O	--	8,460	2,520	--	--	--
			322-844	O	--	8,630	2,520	--	--	--
(8) Pelican Bay Wellfield	EW-1	C-1242	624-770	P	--	7,550	2,100	--	--	--
			[1]777-860	P	--	8,790	2,600	--	--	--
			322-432	C	--	8,410	2,480	--	--	--
			[1]772-833	C	05-28-02	6,840	2,068	4,900	30.1	866
Glades County										
			1,587-2,030	P	10-22-01	10,207	[2]3,000	[2]6,328	30.9	--
			1,587-1,884	P	11-2-01	11,842	[2]3,500	[2]7,342	31.04	--
			1,587-1,745	P	11-9-01	14,692	[2]4,400	[2]9,109	30.22	--
(9) Moore Haven S-77	GLF-6	GL-331	1,440-1,490	P	11-15-01	4,289	[2]1,200	[2]2,660	29.62	--
			855-1,135	P	11-19-01	6,758	[2]1,900	--	28.14	--
			930-980	P	11-20-01	6,607	[2]1,900	[2]4,096	27.98	--
			855-930	P	11-20-01	7,352	[2]2,100	--	27.65	--
Hendry County										
(10) Caloosahatchee River/Berry Grove Site	EXBRY-1	HE-1141	640-752	R	12-04-03	2,763	820	--	28.3	--
			[1]640-900	C	03-26-04	3,680	900-940	2,040-2,150	28.9	--
Lee County										
(11) Lee County WTP	MW-1	L-2530	[1]475-615	C	09-25-79	2,500	500	1,520	26.5	270

Table 4. Ambient water-quality data collected from aquifer storage and recovery well systems in southern Florida.—Continued

Site number and name	Other identifier	USGS local number	Interval sampled (feet below land surface)	Type of interval sampled	Date sampled	Specific conductance (microsiemens per centimeter)	Dissolved chloride (milligrams per liter)	Dissolved solids (milligrams per liter)	Temper-ature (degrees Celsius)	Dissolved sulfate (milligrams per liter)
Lee County—Continued										
(12) North Reservoir	ASR-1 LM-6210	L-5810	[1]540-642	C	03-02-99	2,400	700	--	--	--
			[1]540-642	C	03-04-99	2,450	740	--	--	--
			[1]540-642	C	03-10-99	2,450	750	--	--	--
	MW-1 LM-6208	L-5811	480-518	P	12-07-98	3,230	890	--	--	--
			[1]529-619	P	12-09-98	2,640	700	--	--	--
			640-703	P	12-11-98	2,710	740	--	--	--
			808-890	P	12-16-98	2,450	720	--	--	--
			904-977	P	12-18-98	3,244	1,000	--	--	--
(13) Olga WTP	ASR-1 LM-6086	L-5816	[1]859-920	C	10-21-99	2,677	1,000	--	--	--
			[1]859-920	C	11-09-99	2,690	1,000	--	--	--
	MW-1 LM-6209	L-5817	520-610	P	01-05-99	1,988	540	--	--	--
			617-694	P	01-06-99	1,427	260	--	--	--
			[1]840-940	P	02-30-99	3,420	1,000	--	--	--
			[1]840-940	P	02-04-99	3,461	1,140	--	--	--
			715-940	P	02-04-99	2,928	900	--	--	--
			950-1,106	P	02-08-99	2,793	850	--	--	--
	MW-3 LM-6615	L-5818	826-945	P	03-25-99	2,350	790	--	--	--
			[1]857-945	P	03-25-99	2,948	970	--	--	--
(14) San Carlos Estates	ASR-1	L-5812	[1]650-687	R	--	4,660	1,100	2,800	31.5	560
			[1]650-718	R	--	4,680	1,110	2,900	32.2	560
			[1]650-701	C	06-07-99	4,700	1,100	3,000	--	520
	SZMW-1R	L-5814	[1]659-721	R	--	4,590	1,100	3,000	31.2	520
			[1]659-721	C	07-29-99	4,570	1,100	2,800	--	580
	SMW-1	L-5815	234-321	R	--	1,681	370	920	28.5	83
			234-321	C	08-02-99	1,694	340	950	--	77
(15) Winkler Avenue	ASR-1		[1]455-574	P	06-16-99	3,860	972	--	28.5	--
			[1]455-575	P	06-17-99	3,240	770	--	28.5	--
			[1]455-553	C	11-01-99	--	1,240	1,770	--	354
	SZMW-1		[1]455-553	C	09-16-99	--	1,282	2,998	--	414
	MHMW-1		150-200	C	11-01-99	--	1,540	2,410	--	323

Table 4. Ambient water-quality data collected from aquifer storage and recovery well systems in southern Florida.—Continued

Site number and name	Other identifier	USGS local number	Interval sampled (feet below land surface)	Type of interval sampled	Date sampled	Specific conductance (microsiemens per centimeter)	Dissolved chloride (milligrams per liter)	Dissolved solids (milligrams per liter)	Temper-ature (degrees Celsius)	Dissolved sulfate (milligrams per liter)
Martin County										
(16) Port Mayaca	MF-37	M-1360	1,992-2,046	P	10-16-01	49,941	[2]15,300	[2]31,000	30.0	--
			1,782-1,850	P	10-23-01	33,067	[2]10,100	[2]20,500	29.7	--
			1,496-1,543	P	10-26-01	6,434	[2]1,820	[2]3,990	28.0	--
			1,610-1,657	P	10-30-01	10,161	[2]2,970	[2]6,300	28.7	--
			1,241-1,288	P	11-01-01	1,140	[2]180	[2]707	27.7	--
			765-900	P	11-13-01	2,973	[2]750	[2]1,840	27.0	--
	EXPM-1	M-1361	800-840	P	10-07-03	2,700	700	1,755	26.75	260
			800-900	P	10-07-03	2,858	702	1,680	26.8	271
			[1]800-1040	P	10-15-03	3,180	640	1,640	27.25	246
			[1]800-1040	C	11-05-03	3,138	726	1,820	26.9	242
Miami-Dade County										
(17) Hialeah	ASR-1	G-3061	[1]955-1,105	C	12-04-74	4,750	1,200	2,920	--	500
	MW-1	G-3062	840-844	C	07-24-75	6,600	1,900	--	--	--
		G-3062	[1]953-1,060	C	11-20-74	4,200	1,200	2,830	--	480
(18) J.R. Dean WTP	ASR-1	G-3774	880-1,090	O	05-14-03	3,420	670	2,560	--	--
			880-1,190	O	05-23-03	4,470	1,550	3,116	--	--
			880-1,290	O	05-30-03	7,620	2,233	4,700	--	--
			880-1,405	O	06-04-03	8,210	2,254	5,110	--	--
			880-1,504	O	06-09-03	9,220	3,927	7,310	--	--
			880-1,040	P	07-22-03	12,970	4,789	10,800	--	--
			1,050-1,150	P	07-02-03	5,900	1,990	4,700	--	--
			1,150-1,213	P	07-10-03	6,000	2,700	8,000	--	--
			1,220-1,283	P	07-09-03	8,020	3,400	6,800	--	--
			880-1,350	C	10-10-03	--	2,185	4,550	--	485
(19) Southwest Well Field	ASR-1	G-3768	[1]765-1,169	C	06-10-98	6,400	1550	3640	27.1	480
	ASR-2	G-3769	[1]760-1,200	C	07-16-01	--	1690	3750	27.0	565
(20) West Well Field	ASR-1	G-3706	[1]850-1,302	C	01-26-97	8,980	2,000	5,980	25.0	238
	ASR-2	G-3707	[1]845-1,250	C	02-25-97	6,650	2,449	4,390	23.0	615
	ASR-3	G-3708	[1]835-1,210	C	04-09-97	6,750	2,349	4,040	--	595
	MW-1	G-3709	855-1,010	C	02-06-97	6,520	2,499	4,300	25.0	662
			1,370-1,390	C	02-06-97	10,590	4,649	7,220	25.0	466

Table 4. Ambient water-quality data collected from aquifer storage and recovery well systems in southern Florida.—Continued

Site number and name	Other identifier	USGS local number	Interval sampled (feet below land surface)	Type of interval sampled	Date sampled	Specific conductance (microsiemens per centimeter)	Dissolved chloride (milligrams per liter)	Dissolved solids (milligrams per liter)	Temper-ature (degrees Celsius)	Dissolved sulfate (milligrams per liter)
Okeechobee County										
(21) Kissimmee River	OKF-100	OK-100	1,955-2,030	P	12-06-01	23,100	[2]6,970	[2]14,300	29.3	--
			1,790-1,850	P	12-14-01	16,696	[2]4,990	[2]10,400	33.1	--
			1,640-1,700	P	12-17-01	20,590	[2]6,200	[2]12,800	29.2	--
	EXKR-1	OK-101	[1]562-875	C	03-25-04	--	600	--	--	--
(22) Taylor Creek/ Nubbin Slough—Lake Okeechobee	ASR-1	OK-9000	[1]1,268-1,710	C	11-04-89	9,270	2,910	5,730	--	--
			[1]1,268-1,710	C	04-17-91	--	3,100	7,180	35.0	--
	MW-1	OK-9001	1,175-1,227	P	04-20-88	800	131	656	28.5	210
			1,288-1,354	P	04-25-88	4,800	1,680	4,000	28.0	570
			1,347-1,370	P	04-25-88	4,800	1,900	4,230	30.0	630
			1,358-1,508	P	04-24-88	7,500	2,510	5,740	29.0	760
			1,540-1,662	P	04-23-88	7,500	2,920	6,710	28.0	930
			990-1,075	C	04-17-91	--	210	820	27.5	--
	MW-1	OK-9002	[1]1,275-1,700	C	04-17-91	--	2,200	5,230	27.0	--
Palm Beach County										
(23) Boynton Beach East WTP	ASR-1	PB-1194	[1]804-909	C	05-21-92	6,670	1,920	3,910	25.0	436
	MW-1	PB-1195	300-320	C	05-21-92	33,100	12,100	21,900	--	617
(24) Delray Beach North Storage Reservoir	ASR-1	PB-1702	849-899	P	06-05-96	9,160	2,630	5,670	--	--
			900-952	P	06-11-96	8,480	2,669	5,529	--	--
			974-1,020	P	06-14-96	7,440	2,143	4,363	--	--
			1,020-1,100	P	06-18-96	6,800	2,057	4,255	--	--
			1,020-1,120	O	07-26-96	6,930	2,069	4,752	--	--
			[1]1,020-1,200	O	09-06-96	6,810	2,556	4,234	--	--
			[1]1,016-1,200	C	09-20-96	--	2,300	8,000	--	430
(25) Hillsboro Canal, East (PBCWUD)	FAMW	PB-1775	1,596-1,626	P	09-06-01	8,300	2,400	4,600	--	870
			1,310-1,340	P	09-12-01	7,300	2,100	4,100	--	660
			[3]1,310-1,340	P	09-18-01	6,800	2,300	4,200	--	660
			[1]1,005-1,198	P	09-25-01	6,800	2,200	4,300	--	830
			1,005-1,041	P	09-28-01	7,300	2,200	4,200	--	830
			[1]1,007-1,225	C	12-18-01	8,200	2,300	4,400	--	1,000
	ASR-1	PB-1776	[1]1,007-1,225	C	04-30-02	8,300	2,100	4,400	--	470
			[1]1,010-1,225	C	06-23-03	5,800	1,900	4,100	24.0	440

Table 4. Ambient water-quality data collected from aquifer storage and recovery well systems in southern Florida.—Continued

Site number and name	Other identifier	USGS local number	Interval sampled (feet below land surface)	Type of interval sampled	Date sampled	Specific conductance (microsiemens per centimeter)	Dissolved chloride (milligrams per liter)	Dissolved solids (milligrams per liter)	Temper-ature (degrees Celsius)	Dissolved sulfate (milligrams per liter)
Palm Beach County—Continued										
(26) Hillsboro Canal, West (CERP)	EXW-1	PB-1765	1,160-1,225	P	04-05-00	4,600	1,287	2,932	23.9	397.9
			1,015-1,150	P	04-10-00	8,223	2,336	5,110	23.8	734
			[1]1,015-1,225	C	11-16-00	6,587	1,812	4,064	23.78	560.6
	PBF-10R	PB-1767	[1]1,015-1,225	C	09-03-03	9,881	2,460	5,830	23.91	813.0
	PBF-11	PB-1766	1,500-1,670	C	09-03-03	3,962	1,230	2,830	23.08	314.0
	PBF-12	PB-1766	2,135-2,260	C	09-03-03	47,761	16,400	30,300	22.56	1,690.0
(27) Jupiter	ASR-1	PB-747	[1]990-1,280	C	06-19-74	6,400	1,800	4,060	--	400
(28) System 3 Palm Beach County	ASR-1	PB-1763	[1]1,065-1,155	C	01-28-99	7,820	2,100	4,080	23.7	467
	FAMW	PB-1764	1,052-1,270	C	01-08-01	--	2,007	3,560	--	467
(29) West Palm Beach WTP	ASR-1	PB-1692	[1]985-1,200	C	07-17-97	7,600	2,800	5,056	--	--
	MW-1	PB-1693	975-1,091	P	08-22-96	7,700	2,600	3,800	--	--
			975-1,090	O	08-29-96	7,700	2,600	3,800	--	--
			[1]975-1,190	O	09-01-96	8,290	2,750	4,150	--	--
			975-1,290	O	09-04-96	7,970	2,300	4,270	--	--
			975-1,384	O	09-06-96	7,120	2,520	3,830	--	--
			1,304-1,384	P	09-14-96	6,860	2,060	3,650	--	--
			[1]975-1,191	C	11-16-96	7,350	2,381	3,550	--	--
St. Lucie County										
(30) St. Lucie County	ASR-1	STL-356	[1]600-766	P	03-11-82	3,400	888	2,058	27.8	--
			770-1,000	P	03-12-82	3,200	1,015	1,888	27.8	--
			[1]600-775	C	03-12-82	3,325	955	2,379	27.8	--
	MW-1	STL-357	[1]600-775	C	03-12-82	3,500	1,022	2,143	27.8	--

[1] Interval sampled is the same (or about the same) as the storage zone.

[2] Calculated using specific conductance. For chloride concentration, relation from Reese (2004, fig. 20) is used. For dissolved-solids concentration, calculated value is from weekly drilling reports.

[3] Second packer test of same interval followed a 250 gallon acid stimulation.

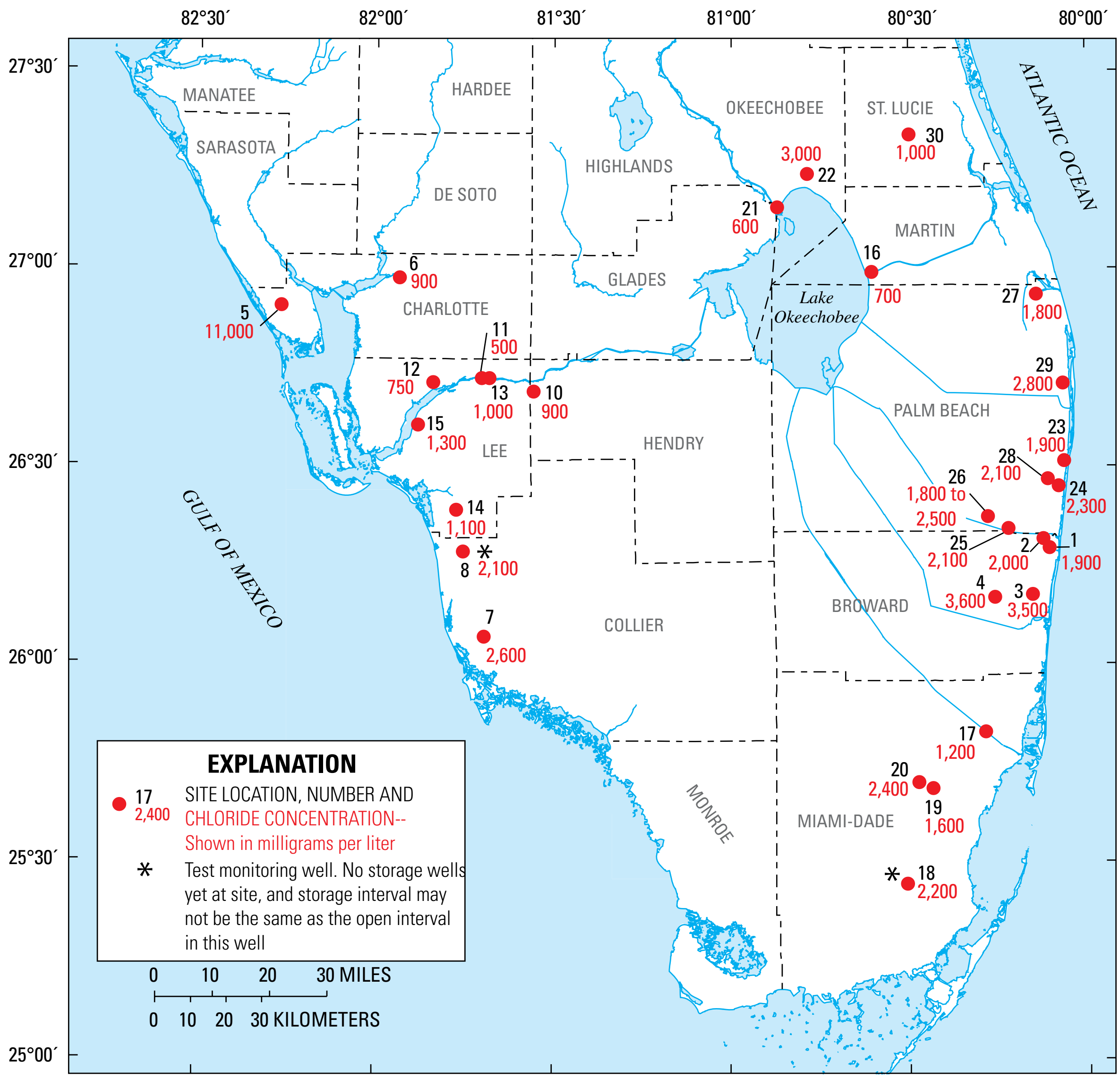


Figure 6. Ambient water salinity, expressed as chloride concentration, of storage zones in the Floridan aquifer system at aquifer storage and recovery sites in southern Florida. Values are rounded to two significant figures.

The highest value found in southeastern Florida was 3,600 mg/L at the Springtree WTP (site 4). At most sites, however, the chloride concentration ranged from about 1,000 to 3,000 mg/L.

The vertical distribution of ambient salinity at each site is indicated on the lithologic and geophysical log plots in appendix 1 by chloride concentration values of water samples from known intervals and resistivity geophysical logs that approximate formation resistivity. These data indicate that ambient salinity increases with depth below the storage zone at some of the sites (app. 1), which include site 3 (Fiveash WTP), site 5 (Englewood South Regional WWTP), site 8 (Pelican Bay Well Field), site 18 (J.R. Dean WTP), site 19 (Southwest Well Field), and site 20 (West Well Field, see sample from lower monitoring zone in MW-1). Salinity may increase below storage zones at other sites, such as site 7 (Marco Lakes); however, data from greater depths were not collected because of the limited penetration of the wells drilled.

Cycle Test Data

ASR cycle test information was obtained from consulting reports, published reports, monthly operating reports (required by the FDEP as part of the permitting process during operational testing), and in several instances, daily records provided by a WTP (table 5). Cycle testing has been conducted at only 20 of the 30 ASR sites listed in table 1. Eight of the remaining 10 sites (including sites 2, 8, 9, 10, 16, 18, 21, and 26) require additional wells or infrastructure, and the final two (sites 25 and 28) have had testing delayed by regulatory issues or mechanical problems such as well pump failure. Seven of the ten sites with wells constructed during the 1990s

Table 5. Cycle test data from aquifer storage and recovery wells in southern Florida.

[Test data at all sites, except for Shell Creek WTP, Marco Lakes, Southwest Well Field, and West Well Field, are only for one storage well at the site (ASR-1). Cycle test data, except where noted, are from consultant or other published reports given in selected references. SDIW, see dates for individual wells; SVIW, see values for individual wells; mg/L, milligrams per liter; Mgal, million gallons; NA, not applicable; NRC, not reached; NRP, not reported; recov, recovery; WTP, Water Treatment Plant; WWTP, Wastewater Treatment Plant; >, greater than; ≤, equal to or less than; ~, approximately]

Cycle			Recharge, storage, recovery periods (days)[1]	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water (chloride concentration limit of 250 mg/L)		Comments
Cycle number	Beginning date	End date				Recharge water (mg/L)	Recovered water at end of cycle (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
Broward County – Site 1, Broward County WTP 2A											
1	07-09-98	07-21-98	11, 0, 2	22.13	1.5	30	168	6.8	NRC	>6.8	Ambient chloride concentration is ~1,900 mg/L.
2	07-27-98	11-12-98	91, 0, 17	195.84	36.65	35	240	18.7	NRC	>18.7	
3	11-13-98	03-11-99	87, 9, 22	181.94	56.63	35	227	31.1	NRC	>31.1	
Broward County – Site 3, Fiveash WTP											
[2]1	10-12-99	10-23-99	10, 0, 1	11.0	1.2	60	225	10.9	NRC	>10.9	Ambient chloride concentration is ~2,000 mg/L.
[2]2	10-25-99	12-06-99	39, 1, 2	70.3	4.4	59	225	6.23	NRC	>6.3	
1	10-12-99	10-23-99	11, 0, 1	19.5	1.0	60	212	5.3	NRC	>5.3	
2	10-25-99	12-06-99	40, 0, 3	75.0	4.7	55	160	6.2	NRC	>6.2	
3a	12-07-99	06-05-01	114, 433, 0	224.4	0.0	55	NA	NA	NA	NA	
3b	06-06-01	03-21-02	216, 0, 48	413.5	54.2	55	244	13.1	NRC	>13.1	
3(a+b)	12-07-99	03-21-02	343, 433, 48	638.0	54.2	55	244	8.5	NRC	>8.5	
4	06-19-02	10-02-02	30, 0, 75	56.1	34.3	60	260	61.1	~34.3	~61.1	
5	10-04-02	01-02-03	30, 0, 58	61.8	37.2	54	268	60.2	35.6	57.6	
6	05-28-03	12-29-03	120, 0, 9	240.1	50.0	58	252	20.8	50.0	20.8	
[3]7	01-20-04	08-02-04	121, 3, 70	193.1	67.9	63	240	35.2	~67.9	~35.0	
Broward County – Site 4, Springtree WTP											
1	07-29-99	08-21-99	20, 0, 4	20	4	70	61	20	NRC	~30	Except for cycle 7, recovery efficiencies at chloride concentration of 250 mg/L are estimated by extrapolation of recovery curve. Ambient chloride concentration is ~3,600 mg/L.
2	08-22-99	10-12-99	40, 1, 11	40	11	65	213	28	NRC	~30	
3	10-13-99	12-09-99	42(39), 0, 15	41	15	60	220	37	NRC	~41	
4	12-10-99	03-27-00	62(39), 31, 15	40	15	60	222	37.5	NRC	~42	
5	03-28-00	11-23-00	178(119), 29, 31	121	32	65	218	26.4	NRC	~31	
6	11-24-00	10-31-01	188, 131, 23	187	23	65	171	12.3	NRC	~19	
[2]7	02-01-03	08-26-03	129, 0, 79	120.3	74.3	69	224	61.75	NRC	>61.75	
[2]8	09-03-03	In progress	151, NA, NA	140.54	NRP	65					Well in storage, no recovery reported.

Table 5. Cycle test data from aquifer storage and recovery wells in southern Florida.—Continued

Cycle: Cycle number	Cycle: Beginning date	Cycle: End date	Recharge, storage, recovery periods (days)[1]	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration: Recharge water (mg/L)	Chloride concentration: Recovered water at end of cycle (mg/L)	Recovery efficiency at end of cycle (percent)	Potable water (chloride concentration limit of 250 mg/L): Recovery volume (Mgal)	Potable water (chloride concentration limit of 250 mg/L): Recovery efficiency (percent)	Comments
Charlotte County – Site 5, Englewood South Regional WWTP											
1	Early 8/01	01-17-02	2 (recov)	37	2	~170	[4]660	5.4	NA	NA	The Englewood TPW-1 well has remained in recharge mode since cycle testing began in August 2001. Only four short recovery events with no storage periods have been conducted because of low demand for reuse water. Total recharge as of end of August 2004 was 534 Mgal. Ambient chloride concentration is 11,000 mg/L.
2	01-17-02	06-25-02	22 (recov)	51	12	~170	165	24	NA	NA	
3	06-25-02	02-28-03	25 (recov)	162	3.1	~170	160	1.9	NA	NA	
4	02-28-03	05-27-03	22 (recov)	33	9.5	~170	170	29	NA	NA	
Charlotte County – Site 6, Shell Creek WTP											
1	07-01-99	08-07-99	21, 0, 9	4.9	1.47	100	250	30	1.47	30	Ambient chloride concentration is ~900 mg/L.
2	08-16-99	09-08-99	17, 0, 8	1.6	.59	75	250	37	.59	37	
3	01-10-00	02-08-99	24, 1, 3	20.3	1.8	180-230	250	9	1.8	9	
OP-1 (ASR-1)	2000	NRP	NRP	23	NRP	NRP	NRP	NRP	2.3	10	
OP-2 (ASR-1)	2001	NRP	NRP	36.18	NRP	NRP	NRP	NRP	.43	1.2	
OP-3 (ASR-1)	May 2002	NRP	NRP	198.97	NRP	NRP	NRP	NRP	10.46	5.3	
OP-4 (ASR-1)	07-31-02	04-16-03	186(154), 26, 47(40)	158.06	23.73	107	>250	15	23.4	14.8	
OP-4 (ASR-3)	11-19-02	04-16-03	73(52), 29, 46(26)	30.3	15.66	94	>252	51.7	15.5	51.2	
OP-4 (ASR-4R)	11-20-02	04-02-03	74(56), 29, 32(28)	33	21.45	94	242	64.8	21.4	64.8	
OP-4 (ASR-1, 3, & 4R combined)	SDIW	SDIW	SVIW	221.36	60.83	SVIW	SVIW	27.5	60.3	27.2	
OP-5 (ASR-3)[2]	06-16-03	06-16-04	125(110), 166, (59)	100.73	43.05	94.9	~270	42.7	39.09	38.8	
OP-5 (ASR-4R)[2]	06-16-03	06-23-04	125(110), 166,	97.2	54.28	94.1	~250	55.9	54.28	55.9	
OP-5 (ASR-3 & 4R combined)[2]	SDIW	SDIW	82(72) SVIW	197.93	97.33	SVIW	SVIW	49.2	93.37	47.2	
Collier County – Site 7, Marco Lakes											
1	06-26-97	08-19-97	39, 3, 12	19.4	6	97.6	384	30.9	4.3	22.26	Ambient chloride concentration is ~2,600 mg/L.
2	08-21-97	02-25-98	86, 63, 39	86.7	31.7	115	398	36.6	3.5	4	
[2]3	03-05-98	04-29-98	26, 2, 27	21.05	17.24	130	370	81.9	7.0	33.2	
4	09-01-98	06-30-99	134(103), 85, 83(74)	112.5	65.2	130	420	58.0	38.8	34.5	
5	08-19-99	07-02-00	132(111), 108, 77	132.3	75	118	395	56.7	47.1	35.6	
6	07-19-00	06-14-01	106(92), 125, 98(96)	125	80.4	136	360	64.3	55.0	44	
1E (ASR-1)	10-04-01	06-24-02	68(65), 112, 83	100.4	55.5	105	250	55.3	55.5	55	
1E (ASR-2)	09-01-01	06-24-02	101(95), 112, 83	130.4	50.5	105	350	38.7	38.3	29	

Table 5. Cycle test data from aquifer storage and recovery wells in southern Florida.—Continued

Cycle			Recharge, storage, recovery periods (days)[1]	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water (chloride concentration limit of 250 mg/L)		Comments
Cycle number	Beginning date	End date				Recharge water (mg/L)	Recovered water at end of cycle (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
					Collier County – Site 7, Marco Lakes—Continued						
1E (ASR-3)	09-01-01	06-18-02	101(95), 112, 76	95.2	38.5	105	310	40.4	29.3	31	Ambient chloride concentration is ~2,600 mg/L.
1E (ASR-1, 2, & 3 combined)	SDIW	SDIW	SVIW	326	144.5	105	SVIW	44.3	123.1	37.8	
2E (ASR-1)	07-22-02	08-13-03	162, 121, 104	239	52.3	88.4	120	21.9	NRC	>21.9	
2E (ASR-2)	07-22-02	08-13-03	162, 121, 104	258.6	48.9	88.4	110	18.9	NRC	>18.9	
2E (ASR-3	07-22-02	08-13-03	162, 121, 104	172.7	45.4	88.4	150	26.3	NRC	>26.3	
2E (ASR-1, 2, & 3 combined)	07-22-02	08-13-03	162, 121, 104	670.3	146.6	88.4	SVIW	21.9	NRC	>21.9	
3E (ASR-1)	09-18-03	07-14-04	68, 181(179), 51	86.4	57.2	56	130	66.2	NRC	>66.2	
3E (ASR-2)	09-18-03	07-14-04	68, 181(179), 51	87.2	58.3	56	150	66.9	NRC	>66.9	
3E (ASR-3)	09-18-03	07-14-04	68, 181(179), 51	72.5	51.4	56	200	70.9	NRC	>70.9	
3E (ASR-1, 2, & 3 combined	09-18-03	07-14-04	68, 181(179), 51	246.1	166.9	56	SVIW	67.8	NRC	>67.8	
					Lee County – Site 11, Lee County WTP						
1	10-14-80	NRP	1.7, 0, 1.4	0.6	.22	60	250	28.7	.22	36.7	Ambient chloride concentration is ~500 mg/L.
2	03-26-81	NRP	16, 47, 2.8	6.83	.66	150-350	250	9.7	.66	9.7	
3	08-18-81	NRP	79, 98, 40.8	29.03	8.82	60-100	250	30.4	8.82	30.4	
					Lee County – Site 12, North Reservoir						
Test[2]	02-26-00	03-18-00	13, 7, 1	6.179	.61	155	250	9.8	.61	9.8	Plugging of ASR well during cycle 2 recovery reduced performance. Ambient chloride concentration is ~750 mg/L.
1	07-11-01	05-15-02	123, 168, 16	60.4	6.6	65	250	11	6.6	11	
2	06-24-02	07-31-03	246, 50, 93	126.8	23.7	80	240	19	NRC	~19	
[2]3	08-01-03	07-20-04	150, 128, 70(59)	104.21	17.84	73.1	254	17.12	17.84	17.12	
					Lee County – Site 13, Olga WTP						
1	07-17-01	06-12-02	163, 123, 44	79.7	18.9	85	260	23.7	~18.9	~23.7	For cycle 2, recovery efficiency at chloride concentration of 250 mg/L was estimated by extrapolation of recovery curve. Ambient chloride concentration is ~1,000 mg/L.
2	06-24-02	07-28-03	218, 99, 82	129	35	83	200	27.1	NRC	~39	
[2]3	08-19-03	09-16-04	83, 191, 123(104)	56.94	42.22	77	204	74.1	NRC	>74.1	
					Lee County – Site 14, San Carlos Estates						
Test	10-25-99	11-15-99	10, 6, 5	28	7	90	600	25	.6	2	For cycle 2, recharge rate was reduced to 100 to 200 gallons per minute in early Dec. 2000 until end of recharge period. Ambient chloride concentration is ~1,100 mg/L.
1	11-30-99	06-28-00	175, 0, 36	138	13	90	466	9.4	4.6	3.3	
2	09-14-00	05-09-01	221, 0, 17(12)	159.5	9.7	91.5	>340	6.1	4.5	2.8	

Table 5. Cycle test data from aquifer storage and recovery wells in southern Florida.—Continued

Cycle			Recharge, storage, recovery periods (days)[1]	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water (chloride concentration limit of 250 mg/L)		Comments
Cycle number	Beginning date	End date				Recharge water (mg/L)	Recovered water at end of cycle (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
					Lee County – Site 15, Winkler Avenue						
1	11-15-00	02-04-01	63, 12, 7	45.73	4.55	164	390	10.0	.2	.451	Ambient chloride concentration is ~1,300 mg/L.
					Miami-Dade County – Site 17, Hialeah						
1	07-17-75	12-17-75	53, 2, 98	41.9	13.8	65	NRP	NRP	13.8	32.9	Recovery continued past reported recovery volume for all cycles, at which chloride concentration was 250 mg/L. Ambient chloride concentration is ~1,200 mg/L.
2	01-05-76	07-21-76	65, 54, 79	85	40.7	65	NRP	NRP	40.7	47.8	
3	07-23-76	01-30-80	179, 181, 926	208	80.1	65	NRP	NRP	80.1	38.5	
					Miami-Dade County – Site 19, Southwest Well Field						
1 (ASR-1)	01-30-02	02-19-03	26, 359, 1	96.61	6.48	NRP	1,300	6.7	0	0	Recovery continued until background water quality was reached plus an additional 33 percent. Recovery began at a chloride concentration of 1,300 mg/L in ASR-1 and 910 mg/L in ASR-2. Ambient chloride concentration is ~1,600 mg/L.
1 (ASR-2)	01-30-02	03-19-03	26, 360, 28	131.54	140.69	NRP	1,260	107.0	0	0	
1 (ASR-1 & 2 combined)	01-30-02	SDIW	SVIW	228.15	147.17	NRP	SVIW	64.5	0	0	
					Miami-Dade County – Site 20, West Well Field						
[2,3]1 (ASR-1)	02-18-99	07-21-99	146, 0, 7	359.7	27.8	48	164	7.7	NRC	>7.7	Ambient chloride concentration is ~2,400 mg/L.
[2,3]2 (ASR-1)	07-31-99	02-15-00	187, 0, 12	212.2	53.3	43	80	25.1	NRC	>25.1	
[2,3]2 (ASR-2)	09-03-99	02-15-00	153, 0, 12	276.1	61.7	43	212	22.3	NRC	>22.3	
[2,3]2 (ASR-1 & 2 combined)	SDIW	02-15-00	SVIW	488.3	115.0	43	SVIW	23.6	NRC	>23.6	
[2,3]3 (ASR-1)	02-15-00	03-23-01	299, 18, 85	338.56	359.37	41	500	106.1	194.3	57.4	
[2,3]3 (ASR-2)	03-27-00	03-23-01	153, 123, 85	175.3	446.56	41	1,150	254.7	95.0	54.2	
[2,3]3 (ASR-3)	02-15-00	03-23-01	Recharge = 299	200.47	No recov	41	No recov	NA	NA	NA	
[2,3]3 (ASR-1, 2, & 3 combined)	SDIW	03-23-01	SVIW	714.33	805.93	41	SVIW	112.8	289.3	40.5	
					Okeechobee County – Site 22, Taylor Creek-Nubbin Slough—Lake Okeechobee						
4	09-05-89	11-04-89	20, 0, 40	90.94	NRP	NRP	1,385	24	NRP	NRP	Cycle 4 conducted by CH2M Hill, and cycles 1, 2, and 3 conducted by the U.S. Geological Survey. A specific conductance value of 5,000 microsiemens per centimeter was used to terminate recovery for all cycles, which equals 1,385 mg/L chloride concentration. Ambient chloride concentration is ~3,000 mg/L.
1	04-17-91	05-29-91	35, 0, 7	181.35	28.06	150	1,385	15	5.6	3.1	
2	06-24-91	09-20-91	63, 8, 17	342.10	342.10	≤100	1,385	22	9.2	2.7	
3	09-23-91	12-02-91	65, 5, 0	355	128	≤70	1,385	36	25.6	7.2	

Table 5. Cycle test data from aquifer storage and recovery wells in southern Florida.—Continued

Cycle			Recharge, storage, recovery periods (days)[1]	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water (chloride concentration limit of 250 mg/L)		Comments
Cycle number	Beginning date	End date				Recharge water (mg/L)	Recovered water at end of cycle (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
Palm Beach County – Site 23, Boynton Beach East WTP											
1	10-21-92	11-10-92	14, 0, 8	12.52	9.58	60	760	76.5	5.9	47	Ambient chloride concentration is ~1,900 mg/L. For cycle 17, recovery volume and recovery efficiency at chloride concentration of 250 mg/L were estimated by interpolation of recovery curve. During the storage period for cycle 21 ending on February 29, 2004, 4.83 Mgal were recharged during 9 days.
2	11-10-92	01-22-93	43, 0, 31	57.32	26.1	50	420	45.5	17.2	30	
3	01-25-93	04-06-93	43, 5, 25	58.34	32.24	50	NRP	55.3	27.4	47	
[3]3	01-25-93	04-06-93	41, 8, 22	54.31	32.04	47	300	59.0	26.6	49	
[3]4	04-20-93	05-28-93	16, 8, 14	17.87	17.24	51	274	96.5	16.1	90	
[3]5	06-02-93	12-06-93	55, 98, 34	60.16	39.30	46	300	65.3	32.3	53.7	
[3]6	02-24-94	07-02-94	55, 57, 39	61.24	47.71	47	306.5	77.9	39.2	64	
[3]7	07-25-94	02-13-95	44, 124, 35	60.06	20.05	48	302	33.4	16.0	26.7	
[3]8	04-20-95	07-03-95	46, 2, 26	42.91	20.60	52	320.5	48.0	17.2	40	
[3]9	09-27-95	12-20-95	33, 22, 29	40.09	31.70	52	301	79.1	25.3	63	
[3]10	01-18-96	05-22-96	46, 52, 27	41.76	34.84	48	307	83.4	31.3	75	
[3]11	06-04-96	12-31-96	34, 149, 27	41.22	37.35	41	314	90.6	33.8	82	
[3]12	01-03-97	06-16-97	42, 81, 41	40.59	32.06	49	302	79.0	26.8	66	
[3]13	06-19-97	02-23-98	35, 174, 40	42.50	37.06	48	317.5	87.2	29.7	70	
[3]14	02-24-98	08-20-98	45, 1, 131	33.36	95.84	62	1,004	287.0	27.0	81	
[3]15	11-13-98	06-03-99	83, 57, 62	110.83	37.56	46	146	33.9	NRC	>33.9	
[3]16	06-15-99	01-28-00	156(118), 4, 68	89.98	88.67	NRP	310	98.5	76.1	84.5	
[3]17	02-17-00	07-13-00	57, NRP, (55)	38.86	46.88	NRP	348	120.6	~37.3	~96	
[3]18	07-12-00	04-08-01	(120), 8, 138(89)	76.80	56.58	NRP	319	73.7	47.2	61.45	
[3]19	06-01-01	08-26-02	(186), 86, 158(107)	201.26	148.60	NRP	308	73.8	127.1	63.16	
[3]20	09-10-02	05-23-03	(98), 56, 81(76)	103.69	108.83	NA	337	105.0	83.95	81.0	
[3]21	05-23-03	07-28-04	(113), 113, 140(99)	119.25	155.64	NA	508	130.5	91.17	76.5	
Palm Beach County – Site 24, Delray Beach North Storage Reservoir											
1	05-23-00	01-29-01	114, 118, 17	313	50	40	225	16.0	NRC	>16.0	Recovery pump failed at the end of the recharge period for cycle 1. Cycle 7 incomplete due to pump failure. Ambient chloride concentration is ~2,300 mg/L.
2	01-30-01	03-11-01	18, 4, 18	50	47	40	250	94.0	47	94.0	
3	03-13-01	04-16-01	19, 1, 14	48	38	40	230	79.2	NRC	>79.2	
4	04-18-01	06-19-01	41, 0, 21	102	54	40	185	52.9	NRC	>52.9	
5	06-19-01	08-15-01	35, 0, 22	69	52	40	180	75.4	NRC	>75.4	
6	08-22-01	10-15-01	26, 2, 22	70.57	55.36	NRP	225	78.4	NRC	>78.4	
7	10-16-01	11-30-01	34, 0, 11	73.065	20.632	NRP	62	28.2	NRD	>28.4	
Palm Beach County – Site 27, Jupiter											
1	NRP	NRP	Storage = 15	20.5	0	65	250	0	0	0	Injection rate for all cycles was 2,000 gallons per minute, and recovery rate was 1,000 gallons per minute. Ambient chloride concentration is ~1,800 mg/L.
2	NRP	NRP	Storage = 30	100	4.7	65	250	4.7	4.7	4.7	
3	NRP	NRP	Storage = 30	306	55.5	65	250	18	55.5	18	
4	NRP	NRP	Storage = 120	102	36.1	65	250	35.2	36.1	35.2	

Table 5. Cycle test data from aquifer storage and recovery wells in southern Florida.—Continued

Cycle			Recharge, storage, recovery periods (days)[1]	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water (chloride concentration limit of 250 mg/L)		Comments
Cycle number	Beginning date	End date				Recharge water (mg/L)	Recovered water at end of cycle (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
Palm Beach County – Site 29, West Palm Beach WTP											
1	10-03-97	11-15-97	43, 0, 1	114.1	4	65	133	3.5	NRC	>3.5	Ambient chloride concentration is ~2,800 mg/L.
2	11-18-97	01-22-98	45, 3, 17	132.3	36	54	766	27.2	4.0	3.0	
3	01-23-98	03-27-98	40, 1, 22	110.7	46	50	850	41.6	7.2	6.5	
4	04-01-98	06-08-98	37 3, 28	102.6	58	42	820	56.5	6.2	6.0	
5	08-10-98	11-10-98	53, 3, 36	145.8	73.82	80	790	50.3	4.4	3.0	
St. Lucie County – Site 30, St. Lucie County											
1	10-19-82	02-04-83	3, 38, 67	1.5	3.41	200	NRP	NRP	NRP	3	Ambient chloride concentration is ~1,000 mg/L.
1	10-19-82	02-04-83	3, 38, 67	1.5	NA	[5]50	NRP	NRP	[5]0.5	[5]33	

[1]Values in parenthesis are actual (net) days for recharge, storage, and recovery periods. For storage period, extra days are recovery during storage period.

[2]Data extracted from monthly operating reports provided to the Florida Department of Environmental Protection.

[3]Data extracted from daily reports provided by the water-treatment plant.

[4]Recovery began at 430 mg/L chloride concentration (site 5, cycle 1).

[5]Recovery efficiency estimated using a hypothetical value for recharge chloride concentration (Wedderburn and Knapp, 1983).

have conducted only three or fewer cycles. Sites with wells constructed during the 1990s experiencing delays are listed in the following table.

Site number and name	Year of well construction	Number of cycles completed
(1) Broward County 2A	1996	3 (none since 1999)
(2) Deerfield Bch W WTP	1992	No cycle testing
(12) North Reservoir	early 1999	4 (cycle testing began in 2000)
(13) Olga WTP	early 1999	3 (cycle testing began in 2001)
(15) Winkler Ave	1999	1
(19) Southwest Well Field	1999	1
(20) West Well Field	1997	3 (none since 2000)
(24) Delray Bch No. Stor Res	1996	7 (none prior to 2000; none after 2001)
(28) System 3 Palm Bch Co.	1999	No cycle testing
(29) West Palm Bch WTP	1997	5 test cycles (none since 1998)

Besides regulatory issues and mechanical problems, delays in cycle testing have been caused by an insufficient supply of source water; for example, cycle testing was delayed by 1 to 2 years at sites 12 and 13 because of reduced WTP-drinking water production. In contrast, 21 cycles have been conducted at the Boynton Beach East WTP (site 23) since the well was constructed in 1992.

Cycle testing has been conducted using more than one ASR well at some sites in southern Florida. Multiwell sites include Shell Creek WTP (site 6) with three wells, Marco Lakes (site 7) with three wells, Southwest Well Field (site 19) with two wells, and West Well Field (site 20) with three wells. For multiwell cycles, which are conducted using the wells simultaneously or nearly so, data are reported in table 5 for each well used in the cycle and for all wells combined.

For this study, two types of recovery efficiency performance measures were determined on a per-cycle basis (table 5). The first measure is total recovery efficiency per cycle, which is the percent recovery at the end of a cycle. The chloride concentration of the recovered water at the end of the cycle also is given in table 5 and typically ranges from 250 to 400 mg/L, depending on operational considerations. The second measure is the potable water recovery efficiency per cycle, which is the percent recovery when the chloride concentration of the recovered water during a cycle reaches 250 mg/L. In several instances, however, the chloride concentration at the completion of a withdrawal period is less than 250 mg/L, and the potable recovery efficiency is reported in table 5 as being greater than the total recovery efficiency. In a few of these cases, the potable water recovery efficiency is estimated by extrapolating the cycle recovery curve on a plot of chloride concentration against percent recovery (for example, site 4, cycles 1-6, table 5). At some sites, such as Fiveash WTP and Springtree WTP (sites 3 and 4), a regulatory limit for chloride concentration in recovered water of 225 mg/L has been in place for some or all of the cycles. The reported or estimated volume of recovered water when recovered water chloride concentration reaches 250 mg/L also is given in table 5. Finally, cumulative recharge volume, cumulative potable water recovery volume, and cumulative recovery efficiencies for each cycle were calculated, and the results are presented in table 6. Both the per-cycle and cumulative potable recovery efficiency numbers were used to compare ASR sites.

Total recovery efficiency can be substantially higher than potable water recovery efficiency (table 5), and it is the performance measure commonly used in the operation of WTPs. The recovery period is extended past the potable water salinity limit. The additional recovered water is blended with low salinity water at the WTP without substantially increasing the salinity of the finished product.

Potable recovery efficiency numbers could not be determined at two sites because of operational procedures (table 5). At the Englewood South Regional WWTP (site 5) only four short recovery events were conducted during a long and ongoing recharge period. Recovery was discontinued prior to reaching a salinity limit because of low demand for reclaimed water (CH2M HILL, 2004a). At the Southwest Well Field (site 19), 228 Mgal were used to recharge two ASR wells starting in January and February 2002. Recovery was not initiated until about 1 year later (February 2003). At the beginning of the recovery period, chloride concentration was well above the potable water limit (1,300 mg/L in well ASR-1 and 910 mg/L in well ASR-2, Miami-Dade Water and Sewer Department, 2003). The source water for the recharge at site 19 was the Biscayne aquifer.

As will be discussed later, the number of cycles completed or in progress at a site is important in determining site performance (table 5). The number of cycles completed or in progress at the 20 sites that have conducted cycle testing (including test cycles) are listed in the following table.

Site number and name	Number of cycles completed or in progress
(1) Broward County 2A	3
(3) Fiveash WTP	7 (seventh cycle in progress)
(4) Springtree WTP	8
(5) Englewood South Regional WTP	4 (short recovery periods with ongoing recharge)
(6) Shell Creek WTP	8 (includes 2 multiwell cycles)
(7) Marco Lakes	9 (includes 3 multiwell cycles)
(11) Lee County WTP	3
(12) North Reservoir	4 (includes 1 test cycle)
(13) Olga WTP	3
(14) San Carlos Estates	3 (includes 1 test cycle)
(15) Winkler Ave.	1
(17) Hialeah	3
(19) Southwest Well Field	1
(20) West Well Field	3 (includes 2 multiwell cycles)
(22) Taylor Creek/Nubbin Slough	7
(23) Boynton Beach East WTP	21
(24) Delray Beach No. Storage Res	7
(27) Jupiter	4
(29) West Palm Beach WTP	5 (test cycles)
(30) St. Lucie County	1

Table 6. Calculated cumulative volumes and cumulative potable water recovery efficiencies at selected aquifer storage and recovery sites.

[Based on data from table 5. no., number; Mgal, million gallons; mg/L, milligrams per liter; NR, not reported; WTP, water treatment plant]

Cycle			Cumulative recharge volume (Mgal)	Potable water (chloride concentration of 250 mg/L or less)	
Cycle no.	Beginning date	End date		Cumulative recovery volume (Mgal)	Cumulative recovery efficiency (percent)
Broward County – Site 1, Broward County WTP 2A					
1	07-09-98	07-21-98	22.13	1.5	6.8
2	07-27-98	11-12-99	217.97	38.15	17.5
3	11-13-98	03-11-99	399.91	94.78	23.7
Broward County – Site 3, Fiveash WTP					
1	10-12-99	10-23-99	19.5	1	5.1
2	10-25-99	12-06-99	94.5	5.7	6.0
3 (a + b)	12-07-99	03-21-02	732.5	59.9	8.2
4	06-19-02	10-02-02	788.6	94.2	11.9
5	10-04-02	01-02-03	850.4	129.8	15.3
6	05-28-03	12-29-03	1,090.5	179.8	16.5
7	01-20-04	08-02-04	1,283.6	247.7	19.3
Broward County – Site 4, Springtree WTP					
1	07-29-99	08-21-99	20	4	20.0
2	08-22-99	10-12-99	60	15	25.0
3	10-13-99	12-09-99	101	30	29.7
4	12-10-99	03-27-00	141	45	31.9
5	03-28-00	11-23-00	262	77	29.4
6	11-24-00	10-31-01	449	100	22.3
7	02-01-03	08-26-03	569.3	174.3	30.6
8	09-03-03	In progress	709.84		
Broward County – Site 6, Shell Creek WTP					
1	07-01-99	08-07-99	4.9	1.47	30.0
2	08-16-99	09-08-99	6.5	2.06	31.7
3	01-10-00	02-08-00	26.8	3.86	14.4
OP-1 (ASR-1)	2000	NR	49.8.	6.16	12.4
OP-2 (ASR-1)	2001	NR	85.98	6.59	7.7
OP-3 (ASR-1)	05-01-02	NR	284.95	17.05	6.0
OP-4 (ASR-1, 3, & 4R combined)	07-31-02	04-16-03	506.31	77.35	15.3
OP-5 (ASR-3 & 4 combined)	06-16-03	06-23-04	704.24	167.75	23.8
Collier County – Site 7, Marco Lakes					
1	06-26-97	08-19-97	19.4	6	30.9
2	08-21-97	02-25-98	106.1	9.5	9.0
3	03-05-98	04-29-98	127.15	16.5	13.0
4	09-01-98	06-30-99	239.65	55.3	23.1
5	08-19-99	07-02-00	371.95	102.4	27.5
6	07-19-00	06-14-01	496.95	157.4	31.7
1E (ASR-1, 2, & 3 combined)	09-01-01	06-24-02	822.95	280.5	34.1
2E (ASR-1, 2, & 3 combined)	07-22-02	08-13-03	1,493.25	427.1	28.6
3E (ASR-1, 2, & 3 combined)	09-18-03	07-14-04	1,739.35	594	34.2

Table 6. Calculated cumulative volumes and cumulative potable water recovery efficiencies at selected aquifer storage and recovery sites.—Continued

Cycle			Cumulative recharge volume (Mgal)	Potable water (chloride concentration of 250 mg/L or less)	
Cycle no.	Beginning date	End date		Cumulative recovery volume (Mgal)	Cumulative recovery efficiency (percent)
Lee County, Site 11, Lee County WTP					
1	10-14-80	NR	0.6	0.22	36.7
2	03-26-81	NR	7.43	.88	11.8
3	08-18-81	NR	36.46	9.7	26.6
Lee County, Site 12, North Reservoir					
Test	02-26-00	03-18-00	6.179	0.61	9.9
1	07-11-01	05-15-02	66.579	7.21	10.8
2	06-24-02	07-31-03	193.379	30.91	16.0
3	08-01-03	07-20-04	297.589	48.75	16.4
Lee County, Site 13, Olga WTP					
1	07-17-01	06-12-02	79.7	18.9	23.7
2	06-24-02	07-28-03	208.7	53.9	25.8
3	08-19-03	09-16-04	265.64	96.12	36.2
Lee County, Site 14, San Carlos Estates					
Test	10-25-99	11-15-99	28	0.6	2.1
1	11-30-99	06-28-00	166	5.2	3.1
2	09-14-00	05-09-01	325.5	9.7	3.0
Miami-Dade County – Site 17, Hialeah					
1	07-17-75	12-17-75	41.9	13.8	32.9
2	01-05-76	07-21-76	126.9	54.5	42.9
3	07-23-76	01-30-80	334.9	134.6	40.2
Miami-Dade County – Site 20, West Well Field					
1 (ASR-1)	02-18-99	07-21-99	359.7	27.8	7.7
2 (ASR-1 & 2 combined)	07-31-99	02-15-00	848	142.8	16.8
3 (ASR-1, 2, & 3 combined)	02-15-00	03-23-01	1,562.33	432.1	27.7
Okeechobee County – Site 22, Taylor Creek/Nubbin Slough—Lake Okeechobee					
1	04-17-91	05-29-91	181.35	5.6	3.1
2	06-24-91	09-20-91	523.45	14.8	2.8
3	09-23-91	12-02-91	878.45	40.4	4.6
Palm Beach County – Site 23, Boynton Beach East WTP					
1	10-21-92	11-10-92	12.52	5.9	47.1
2	11-10-92	01-22-93	69.84	23.1	33.1
3	01-25-93	04-06-93	124.15	49.7	40.0
4	04-20-93	05-28-93	142.02	65.8	46.3
5	06-02-93	12-06-93	202.18	98.1	48.5
6	02-24-94	07-25-94	263.42	137.3	52.1
7	07-25-94	02-13-95	323.48	153.3	47.4
8	04-20-95	07-03-95	366.39	170.5	46.5
9	09-27-95	12-20-95	406.48	195.8	48.2
10	01-18-96	05-22-96	448.24	227.1	50.7
11	06-04-96	12-31-96	489.46	260.9	53.3
12	01-03-97	06-16-97	530.05	287.7	54.3
13	06-19-97	02-23-98	572.55	317.4	55.4
14	02-24-98	08-20-98	605.91	344.4	56.8
15	11-13-98	06-03-99	716.74	381.96	53.3
16	06-15-99	01-28-00	806.72	458.06	56.8

Table 6. Calculated cumulative volumes and cumulative potable water recovery efficiencies at selected aquifer storage and recovery sites.—Continued

Cycle			Cumulative recharge volume (Mgal)	Potable water (chloride concentration of 250 mg/L or less)	
Cycle no.	Beginning date	End date		Cumulative recovery volume (Mgal)	Cumulative recovery efficiency (percent)
Palm Beach County – Site 23, Boynton Beach East WTP—Continued					
17	02-17-00	07-13-00	845.58	495.36	58.6
18	07-12-00	04-08-01	922.38	542.56	58.8
19	06-01-01	08-26-02	1,123.64	669.66	59.6
20	09-10-02	05-23-03	1,227.33	753.61	61.4
21	05-22-03	07-28-04	1,346.58	844.78	62.7
Palm Beach County – Site 24, Delray Beach North Storage Reservoir					
1	05-23-00	01-29-01	313	50	16.0
2	01-30-01	03-11-01	363	97	26.7
3	03-13-01	04-16-01	411	135	32.8
4	04-18-01	06-19-01	513	189	36.8
5	06-19-01	08-15-01	582	241	41.4
6	08-22-01	10-15-01	652.57	296.36	45.4
7	10-16-01	11-30-01	725.635	316.992	43.7
Palm Beach County – Site 27, Jupiter					
1	NR	NR	20.5	0.0	0.0
2	NR	NR	120.5	4.7	3.9
3	NR	NR	426.5	60.2	14.1
4	NR	NR	528.5	96.3	18.2
Palm Beach County – Site 29, West Palm Beach WTP					
1	10-03-97	11-15-97	114.1	4	3.5
2	11-18-97	01-22-98	246.4	8	3.2
3	01-23-98	03-27-98	357.1	15.2	4.3
4	04-01-98	06-08-98	459.7	21.4	4.7
5	08-10-98	11-10-98	605.5	25.8	4.3

Aquifer Storage and Recovery Performance in the Upper Floridan Aquifer

Many factors affect the performance and freshwater recovery at ASR sites in southern Florida and can be grouped into three categories: hydrogeologic, design, and management factors. Following a discussion of these factors is a detailed analysis of cycle testing for the seven ASR sites in southern Florida having the greatest number of cycles completed or attempted. The relative performance of all sites with cycle test recovery efficiency data is then determined, and finally, recovery performance for each site is compared with four hydrogeologic and design factors to determine their importance.

Factors Affecting Freshwater Recovery

Recovery of stored freshwater in the brackish- to saline-water carbonate Floridan aquifer system of southern Florida is controlled by a wide variety of casual factors that pertain to hydrogeology, well or well-field design, and operational management. Hydrogeologic factors of a storage zone that can affect recoverability include: (1) ambient ground-water salinity, (2) magnitude of permeability and its distribution, (3) aquifer thickness, (4) confinement, (5) ambient hydraulic gradient, and (6) structural setting. Important design and management factors to consider are: (1) thickness and location of the storage zone within the aquifer, (2) volume of water injected for a cycle, (3) rate of recharge and recovery, (4) cycle frequency and time between cycles, (5) storage period length, (6) borehole performance problems such as plugging, and

(7) multiple-well configurations. A detailed discussion of most of these factors is provided in Reese (2002). The four factors that have been identified as being important, or potentially important, in southern Florida (Reese, 2002) are storage zone salinity, the distribution and magnitude of permeability, and the thickness and position of the storage zone within the aquifer.

During freshwater recharge in an ASR well, a radial or spherical mixing zone forms around the well in the aquifer. This zone, referred to as the transition zone (Merritt, 1985), separates ambient ground water from an inner flushed zone mostly containing injected water (fig. 7). The flushed zone is commonly described as a freshwater “bubble” or buffer zone, but its shape can be irregular. The degree of mixing between injected and native water and the width of the transition zone are primarily controlled by hydrodynamic dispersion (or dispersive mixing), which refers to the effects of molecular diffusion and mechanical dispersion. Mechanical dispersion results from uneven flow through porous media, and is predominant over diffusion at flow velocities that typically occur during ASR recharge and recovery.

Hydrogeologic Factors

The ambient salinity of ground water in the storage zone is a primary factor controlling the recovery of injected freshwater because of mixing between these waters during an ASR cycle and because of potential buoyancy stratification. Buoyancy stratification occurs during ASR in aquifers when the ambient salinity and the vertical hydraulic conductivity of the aquifer are both high (Merritt, 1985). Because of a substantial density contrast, the injected freshwater can move upward in the aquifer and flow out over the native saline ground water (fig. 7). During the recovery period, such stratification increases mixing. Buoyancy stratification is possible when the ambient dissolved-solids concentration of ground water is greater than 5,000 mg/L (Pyne, 1995), which equates to about 2,500 mg/L chloride concentration in the Floridan aquifer system of southern Florida (Reese, 1994).

The magnitude and distribution (heterogeneity) of permeability (or hydraulic conductivity) in the storage zone can greatly affect recovery efficiency because of its effect on mechanical dispersion. Increased permeability in a limestone aquifer typically translates to greater dispersive mixing, which

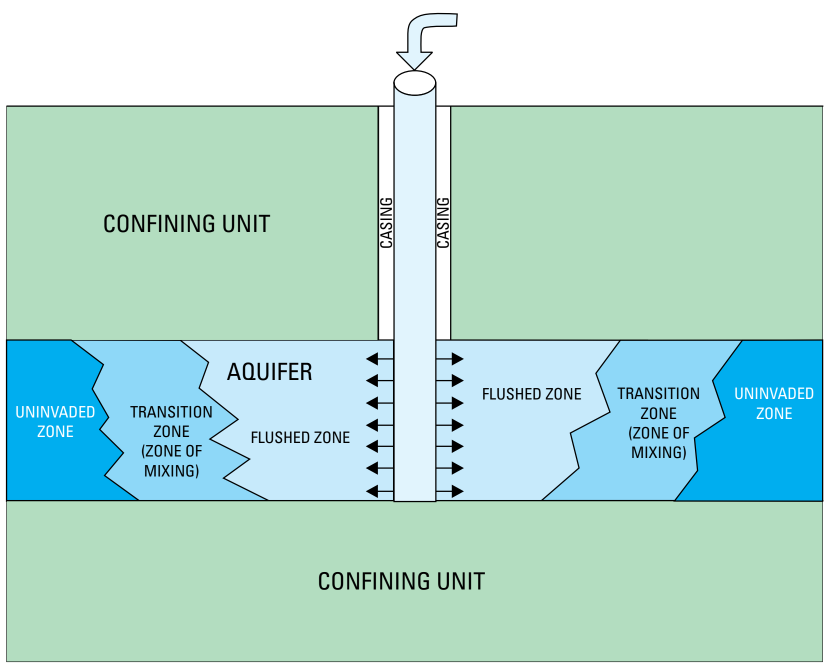


Figure 7. Aquifer storage and recovery well in a confined, brackish-to saline-water aquifer depicting idealized flushed and transition zones created by recharge.

tends to decrease recovery efficiency. Recovery efficiency in a sand aquifer of uniform permeability is good because dispersion results primarily from flow through intergranular pore spaces. In contrast, recovery efficiency in a limestone aquifer that has both conduit and diffuse flow components can be poor because dispersion results from preferential flow through a few thin horizontal zones of high permeability (flow zones) that are interlayered with thick zones having relatively low permeability. High transmissivity in a limestone aquifer commonly results from the high permeability associated with zones of secondary porosity development or karstification, including fracturing and dissolution along fractures or bedding planes. Because of localized development of high vertical hydraulic conductivity encountered by injected water as it flows outward along flow zones in carbonate aquifers of Florida, greater vertical mixing can occur, and bodies of injected freshwater can become isolated and “essentially nonrecoverable” (Missimer and others, 2002). For a storage zone in the Upper Floridan aquifer, a transmissivity of 30,000 ft^2/d has been identified as an approximate minimum level at which this factor could affect recovery efficiency (Reese, 2002). In another study, a maximum acceptable transmissivity in carbonate aquifers of Florida of about 47,000 ft^2/d was identified for a maximum well capacity of 5 Mgal/d (Missimer and others, 2002).

Design and Management Factors

Recovery efficiency is typically greater in a thin storage zone compared to a thick one because of the lower vertical extent of the transition zone along which mixing occurs. Minimizing the thickness of the storage zone within a thick aquifer when designing the construction of an ASR well can be beneficial, but this depends on the distribution of horizontal and vertical hydraulic conductivity within the aquifer and the desired rate of recharge and recovery.

The thickness and position of a storage zone within an aquifer can affect recovery efficiency. Merritt (1985) simulated hypothetical recovery efficiency where the open interval extended only over the lower part of the actual storage zone and an important flow zone near the top of the Upper Floridan aquifer at the Hialeah facility (site 17). Recovery efficiency is virtually unaffected when compared to a well open to the full thickness of the flow and storage zone. The low ambient salinity (1,200 to 1,300 mg/L chloride concentration) and the low to moderate vertical hydraulic conductivity values (0.01 to 40 ft/d) used in the simulation, however, may have prevented the occurrence of any appreciable buoyancy effects that could increase vertical flow and mixing. Placement of a storage zone below the top of an aquifer could have a negative effect, depending on the vertical hydraulic conductivity and ambient salinity. The buoyancy of the injected freshwater could cause part of the bubble to migrate above the level of the open-hole interval (base of casing), where it may be more difficult to recover.

The final casing depth, which is the top of the storage zone, is commonly set well below the interpreted top of the Upper Floridan aquifer. This practice is common in eastern Broward and Palm Beach Counties, with 10 of 11 sites in this area having the casing set below the top of the aquifer, and 8 of these 10 sites having a casing depth of 50 ft or more below the top of the aquifer (app. 1). The storage zones at Shell Creek WTP (site 6) and Olga WTP (site 13) on the west coast of Florida are located in the lower part of the Suwannee Limestone at 160 and 344 ft below the top of the aquifer, respectively (app. 1). A step-drawdown test of the upper part of the Suwannee in MW-3 at the Olga site indicated relatively low transmissivity; the upper part of the Suwannee Limestone was not used for storage at this site because this zone was considered to be too thick and hydraulically heterogeneous and to have a potential sand inflow problem (Water Resources Solutions, Inc., 2000a).

The practice of placing the final casing below the top of the Upper Floridan aquifer is often the result of two concerns. The first concern is having rock of adequate competency for a good cement seal (or “casing seat”) between the casing and borehole wall at the bottom of the casing. Limestone in the upper Suwannee Limestone and lower Hawthorn Group can have high silt and sand content and be soft, friable, and poorly cemented. The second concern is the release, or potential for release, of water-quality constituents of concern into the stored water, such as arsenic, gross alpha radioactivity, and radium isotope activity ($Ra^{226} + Ra^{228}$) caused by the interaction between injected freshwater and the aquifer matrix (Mirecki, 2004). Minerals that release these water-quality constituents can be more common in the lower Hawthorn Group and Suwannee Limestone (Mirecki, 2004) and tend to be associated with the phosphate sand present in these geologic units.

The bottom of the final casing was set at a depth of about 300 ft (from 270 to 310 ft) above the top of the Upper Floridan aquifer, as interpreted in this study (previously discussed), at three sites in Miami-Dade County (app. 1, sites 18, 19, and 20). The purpose of setting the casing much higher in the section at these sites was to include several flow zones in the lower part of the Hawthorn Group in the storage zone (CH2M HILL, 1998b, 2001a, 2003).

The volume of water recharged per cycle and the rate of injection or recovery also may affect recovery efficiency. Recharge volumes per cycle varied widely, ranging from as low as 0.6 Mgal in the first cycle at the Lee County WTP (site 11) to as much as 714 Mgal in multiwell cycle 3 at the West Well Field (site 20). On a per-cycle basis, simulated recovery efficiency generally increases as the total volume of injected water increases (Merritt, 1985). High volumes recharged because of a high injection rate, however, may not improve recovery efficiency because injected water in a flow zone can travel faster and farther away from the well and create a greater potential for vertical mixing in the aquifer (Missimer and others, 2002).

A high pumping rate during recovery may lower recovery efficiency because it results in high water velocities and mixing within the borehole and can cause the upconing of more saline native water (Hazen and Sawyer, P.C., 2003). The reduction in recovery efficiency caused by upconing depends on the vertical hydraulic conductivity in the storage zone and the ambient ground-water salinity and confinement below the storage zone.

Recovery efficiency increases with repeated cycles (Merritt, 1985) because part of the water that was recharged from a previous cycle remains in the aquifer, and during the next cycle, recharged water mixes with aquifer water of salinity lower than ambient water. To improve recovery efficiency during repeated cycles, Pyne (1995) has recommended initially recharging a large volume of water to flush out ambient ground water near a well and to create a buffer zone. With this approach, a target storage volume (TSV) is recharged prior to beginning cycle testing. The TSV is defined by CH2M HILL (2002a) as:

> "The sum of the stored water volume required to meet a predetermined recovery volume goal, plus the volume of water in a freshwater buffer zone surrounding the stored water volume. At such time as this TSV may be achieved in each well, it should be possible to achieve 100 percent recovery efficiency for all subsequent water stored and recovered in that well to meet the targeted recovery volume."

Accordingly, recovery efficiency should be greater for a cycle with a low recharge volume immediately preceded by a cycle with a large recharge volume, than for the second cycle when the two cycles have equal recharge volumes. In the present (2006) study, a large initial volume designated as a TSV is included with the recharge volume for the following cycle to calculate recovery efficiency, and the TSV approach or a similar practice is referred to as "water banking."

The length of time between cycles is a factor because water left in the aquifer from previous cycles tends to disperse and migrate downgradient with the ambient ground-water flow, or migrate upward or updip depending on buoyancy, confinement, and local geologic structure. The storage period duration within a cycle also can affect recovery efficiency. A bubble tends to disperse or may migrate upward or laterally during storage. A 4- to 6-month storage period (about 120 to 180 days) may be optimal under the ideal wet-season/dry season strategy for an ASR cycle in southern Florida. The longest planned storage period was 191 days for cycle 3 at the Olga WTP (site 13, table 5). During long storage periods (4 months or greater), loss of recharge water as a result of buoyancy and vertical mixing can occur if vertical zones of high hydraulic conductivity are encountered as recharge water travels outward through flow zones (Missimer and others, 2002).

Well plugging can occur during recharge in the Upper Floridan aquifer and reduce the recharge rate and freshwater recovery. This plugging occurs at the wellbore face or in the aquifer and is usually caused by: (1) deposition of particulate matter present in the injected water, or (2) by the formation of precipitates or sludge through geochemical reactions between the injected water, aquifer water, and aquifer matrix. Well plugging may preferentially affect one flow zone in an open-hole interval more than another, reducing overall recovery. During recovery, the less-affected zone contributes more of the flow, and the salinity of water from this zone can exceed the limiting salinity level before all the recoverable water from the plugged zone is obtained.

To optimize recovery efficiency, it is necessary to use recharge water with low salinity. The chloride concentration of recharged water used for most sites ranged from 40 to 100 mg/L (table 5). Recharge water with higher chloride concentration (greater than 100 mg/L) can adversely affect recovery efficiency; cycles with higher recharge chloride concentration are mostly on the west coast of Florida and are listed in the following table:

Site number and name	Cycle number	Chloride concentration of recharged water (milligrams per liter)
(5) Engelwood So RegWTP	1-4	about 170
(6) Shell Crk WTP	3	180-230
	OP-4	107
(7) Marco Lakes	2-6	115-136
	1E	105
(11) Lee County WTP	2	150-350
(12) North Reservoir	initial test cycle	155
(15) Winkler Avenue	1	164
(22) Taylor Crk/Nubbin Slough	1	150
(30) St. Lucie County	1	200

Analysis of Cycle Test Data at Selected Sites

Well-construction histories and results of cycle tests at the seven ASR sites with the greatest number of cycles are discussed in the subsequent sections. For each site, recharge and recovery volumes and recovery efficiencies for each cycle are plotted and compared. Storage period length and the chloride concentration at the end of each recovery period also are considered.

Fiveash Water Treatment Plant (Site 3)

Three wells were constructed at the Fiveash WTP in east-central Broward County (site 3) by March 1998 (table 2), and seven test cycles were conducted between October 1999 and August 2004 (fig. 8). Storage period lengths were short (0 to 3 days) for all cycles except subcycle 3a, which had an unintended 433-day storage period because of well pump failure (table 7). Potable water recovery efficiency per cycle ranged from about 5 to 61 percent for the seven cycles, with an average value of 28 percent. Cumulative recovery efficiency was about 19 percent.

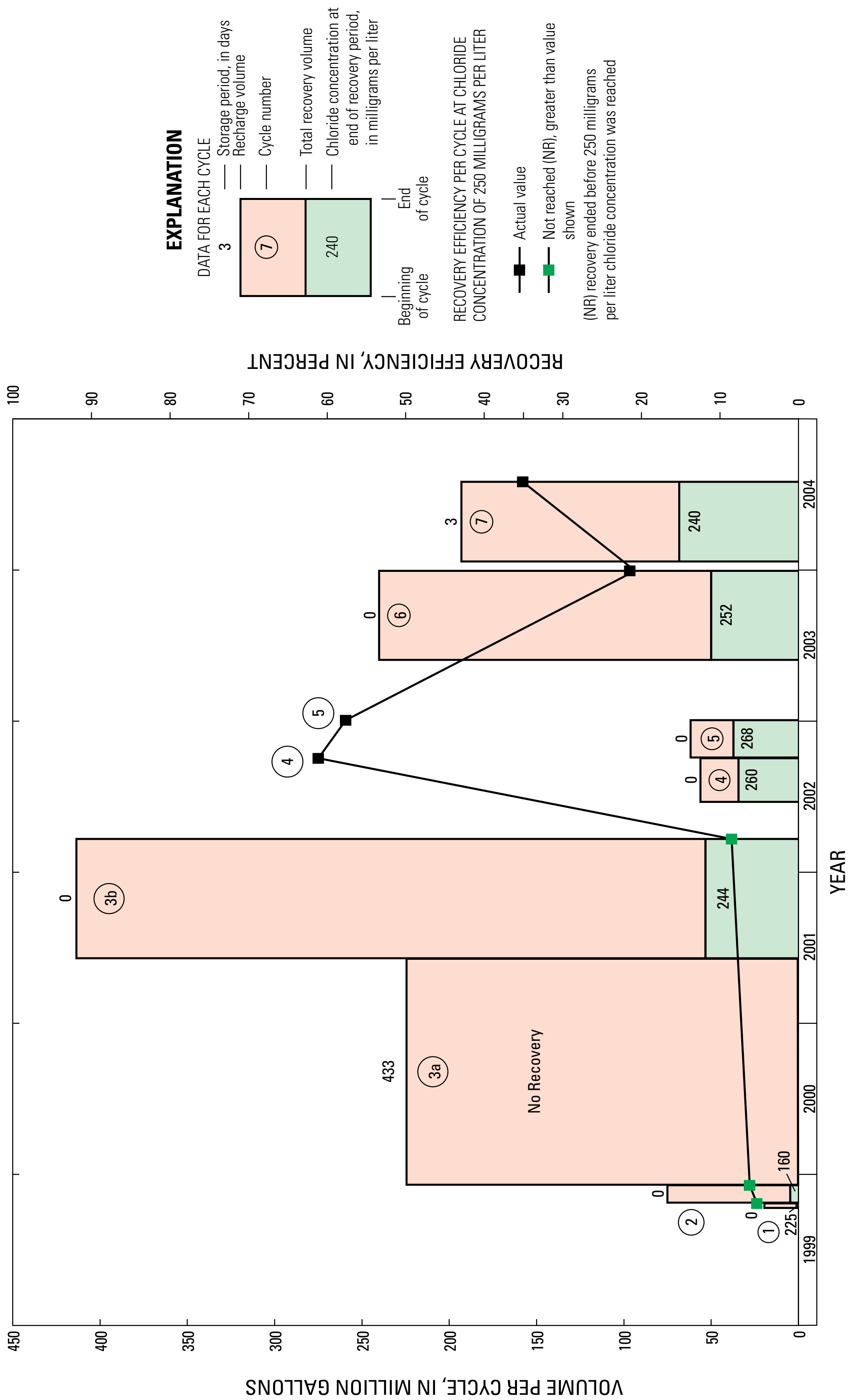


Figure 8. Relation of volumes recharged and recovered, time, and percent recovery for each cycle at the Fiveash Water Treatment Plant (Site 3).

Table 7. Cycle test data from the Fiveash Water Treatment Plant (site 3).

[Potable water chloride concentration limit of 250 mg/L (milligrams per liter). Cumulative recovery efficiency extracted from table 6; all other data extracted from table 5. Values have been rounded off. Mgal, million gallons; >, greater than; --, no data]

Cycle	Storage period (days)	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water		Cumulative recovery efficiency (percent)
				Recharge water (mg/L)	Recovered water (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
1	0	20	1	60	212	5	--	>5	5
2	0	75	5	55	160	6	--	>6	6
3 (a+b)	433	638	54	55	244	9	--	>9	8
4	0	56	34	60	260	61	34	61	12
5	0	62	37	54	268	60	36	58	15
6	0	240	50	58	252	21	50	21	17
7	0	193	68	63	240	35	68	35	19

Relatively small volumes were recharged during cycles 1 and 2 (fig. 8 and table 7). Large volumes were recharged during subcycles 3a and 3b (totaling 638 Mgal); however, because the pump failed during subcycle 3a, recovery was not attempted until subcycle 3b. Recovery efficiency at the end of the entire third cycle was about 9 percent (table 7), and for subcycle 3b it was only about 13 percent. Shortly after cycle 3 (with its large recharge volume), however, in what appears to be a water-banking approach, smaller volumes were recharged for cycles 4 and 5, and recovery efficiency increased to about 60 percent.

For cycles 4 and 5, the recovery rate was reduced to 0.45 and 0.63 Mgal/d, respectively, as opposed to the greater than 1-Mgal/d rate used previously (Hazen and Sawyer P.C., 2003), and the increased recovery efficiency for these cycles may be due, in part, to reduced velocity of water entering the well and mixing within the borehole. “This allowed the stored water to remain more intact and minimized upconing of native water during recovery” (Hazen and Sawyer, P.C., 2003). Ambient water salinity is indicated to increase with depth below the storage zone at this site based on water samples collected from known intervals (app. 1). An alternate explanation for the improvement in cycles 4 and 5 is the flushing of ambient ground water caused by the very large recharge volume in cycle 3. Although the lower recovery rate was used with a much larger recharge volume in cycle 6 (240 Mgal compared to about 60 Mgal for each of the two previous cycles), recovery efficiency fell to about 21 percent (table 7). This reduction in recovery efficiency may have been caused by the almost 5-month period of inactivity between cycles 5 and 6, and the total time (14 months) between cycle 3 with its large recharge volume and cycle 6. Recovery efficiency for cycle 7 increased to about 35 percent, even with an increase in the recovery rate to almost 1 Mgal/d. The decrease in the volume recharged from cycle 6 to 7 and short intercycle and storage period times could have accounted for this increase in recovery efficiency.

Springtree Water Treatment Plant (Site 4)

Construction of well ASR-1 at the Springtree WTP in east-central Broward County was completed by July 1997, and seven cycles were conducted between July 1999 and August 2003 (fig. 9). Cycle 8 began on October 1, 2003, but the recovery phase has not yet been conducted. Storage period lengths for the seven cycles ranged from 0 to 131 days (table 8). Potable water recovery efficiency per cycle ranged from about 19 to 62 percent, with an average value of 36 percent. Cumulative recovery efficiency was about 31 percent.

Recharge volume for cycles 1 to 4 ranged from 20 to 41 Mgal, and was increased to 121 and 187 Mgal, respectively, for cycles 5 and 6 (table 8). Recovery efficiency decreased from about 40 percent for cycles 3 and 4, to about 31 and 19 percent for cycles 5 and 6, respectively. The decreased recovery efficiency for cycle 6 may partly be due to its lengthy storage period (131 days) when compared to previous cycles (about 30 days or less). The per-cycle recovery efficiency increased to over 62 percent for cycle 7; however, this cycle did not have a storage period, and the large volume recharged in cycle 6 may have flushed out some of the ambient ground water near the well. Cycle 8 began in September 2003 and recharge ended in February 2004; however, by the end of 2004, recovery for this cycle had not yet begun.

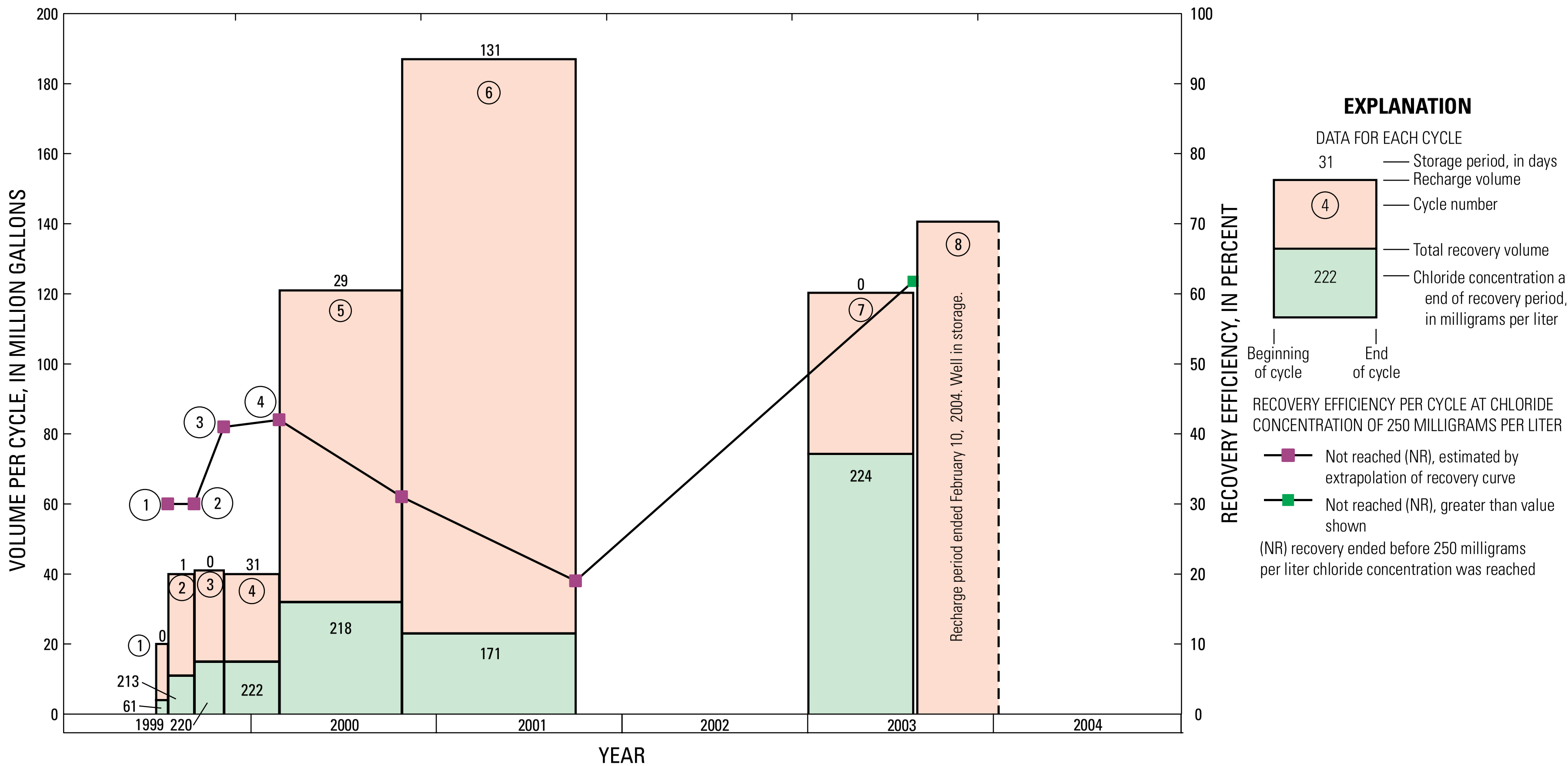


Figure 9. Relation of volumes recharged and recovered, time, and percent recovery for each cycle at the Springtree Water Treatment Plant (Site 4).

Table 8. Cycle test data from the Springtree Water Treatment Plant (site 4).

[Potable water chloride concentration limit of 250 mg/L (milligrams per liter). Cumulative recovery efficiency extracted from table 6; all other data extracted from table 5. Values have been rounded off. Mgal, million gallons; >, greater than; --, no data]

Cycle	Storage period (days)	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water		Cumulative recovery efficiency (percent)
				Recharge water (mg/L)	Recovered water (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
1	0	20	4	70	61	20	--	30	20
2	1	40	11	65	213	28	--	30	25
3	0	41	15	60	220	37	--	41	30
4	31	40	15	60	222	38	--	42	32
5	29	121	32	65	218	26	--	31	29
6	131	187	23	65	171	12	--	19	22
7	0	120	74	69	224	62	--	>62	31
8	--	141	--	65	--	--	--	--	--

Shell Creek Water Treatment Plant (Site 6)

Well ASR-1 was constructed at the Shell Creek WTP in northeastern Charlotte County in 1997, and was originally completed in the upper part of the Suwannee Limestone. However, results from a single-well constant-rate pump test (table 3) and subsequent cycle testing indicated that the transmissivity was unacceptably low in this zone for ASR operational considerations. The well was recompleted in April 1999 to its deeper, present open interval (764 to 933 ft below land surface) in the lower part of the Suwannee Limestone (app. 1; Montgomery Watson, 2000a). Three additional ASR wells (wells ASR-2, ASR-3, and ASR-4R) were constructed in late 2001 and early 2002. Later in 2002 (prior to their initial use), ASR-3 and ASR-4R were back plugged to depths of 912 and 915 ft below land surface, respectively, to improve recovery efficiency potential by "reducing the dispersivity in the open-hole section of the wells" (Water Resources Solutions, Inc., 2002e; 2003d). The storage zone thickness in both wells was reduced from about 200 to 100 ft (table 2). Well ASR-2 (app. 1, CH-316) was not modified and has not been used because of unconsolidated sand entering the well bore during production (Water Resources Solutions, Inc., 2003d).

Reported transmissivity (6,000 ft^2/d) for the Shell Creek WTP (fig. 5) was determined from a multiwell test that used ASR-3 as the production well prior to being back plugged (table 3). The open interval for ASR-3 during this test extended from a depth of 810 to 1,000 ft.

Three test cycles were performed at the site between July 1999 and February 2000, and five operational cycles were completed between some time in 2000 and June 2004 (fig. 10). OnlyASR-1 was utilized during the first six cycles; the last two cycles were multiwell cycles. The first multiwell cycle (OP-4) used wells ASR-1, ASR-3, and ASR-4R, and the second cycle (OP-5) used ASR-3 and ASR-4R. Storage period lengths ranged from 0 to 166 days for cycles 1, 2, 3, OP-4, and OP-5, with no storage period for cycles 1 and 2 (table 9). Potable water recovery efficiency per cycle ranged from greater than 1 to about 47 percent, with an average value of about 21 percent. Cumulative recovery efficiency was about 24 percent.

Potable water recovery efficiency generally was low for the first six cycles (greater than 1 to about 37 percent), even though a large recharge volume of 199 Mgal was used on the sixth cycle (OP-3); however, the recharge water chloride concentration for cycle 3 was high (180-230 mg/L) and unreported for cycles OP-1, OP-2 and OP-3 (table 9). For the first multiwell cycle (OP-4), potable recovery efficiencies for wells ASR-3 and ASR-4R were about 51 and 65 percent, respectively. Recovery efficiency for ASR-1 remained low (about 15 percent) for this cycle; however, although more than 70 percent of the recharge water was injected into this well during the cycle (158 Mgal as opposed to about 30 and 33 Mgal for ASR-3 and ASR-4R, respectively). Well ASR-1 was not used for cycle OP-5, and the combined recovery efficiency at the end of the cycle for ASR-3 and ASR-4R was about 49 percent,

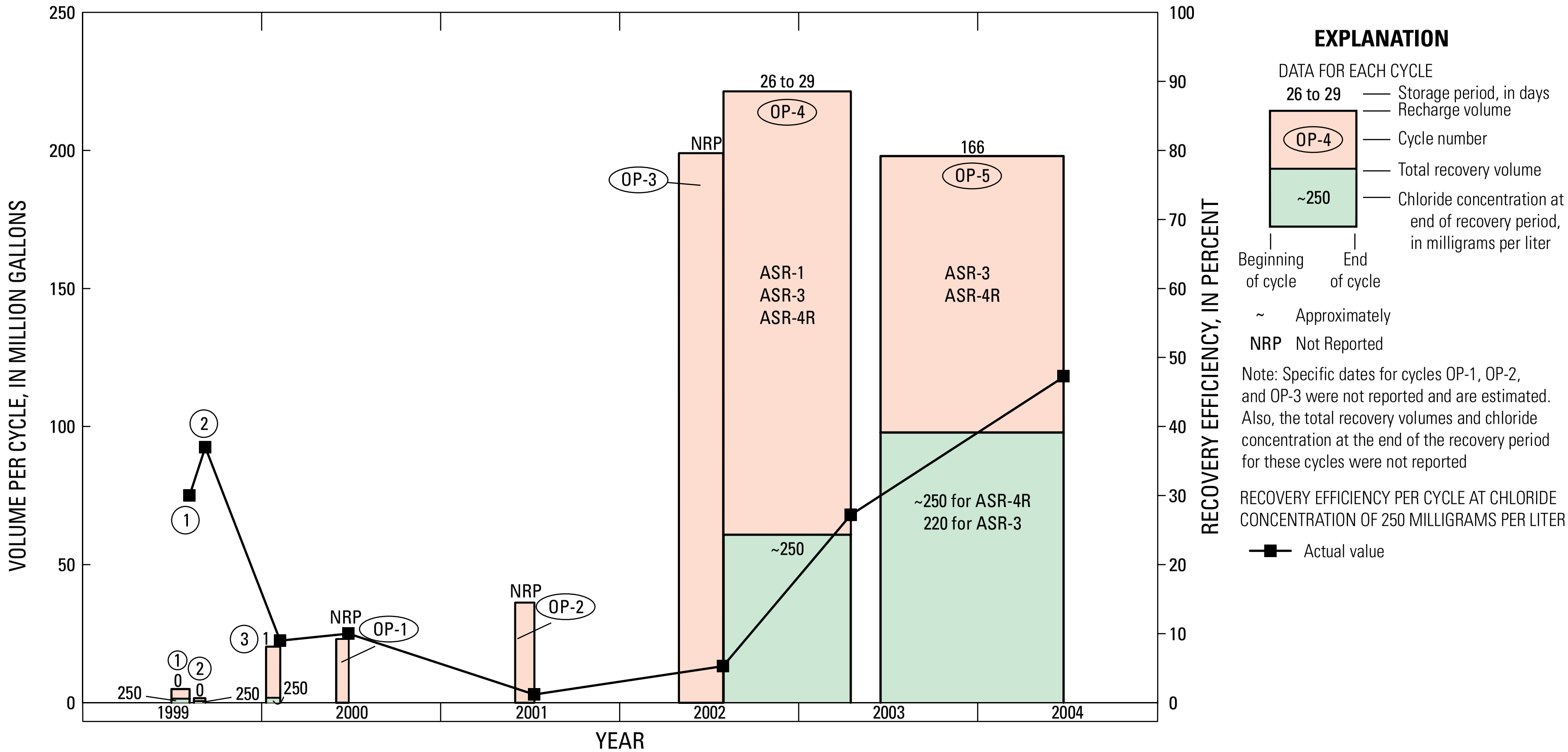


Figure 10. Relation of volumes recharged and recovered, time, and percent recovery for each cycle at the Shell Creek Water Treatment Plant (site 6). Multiple well cycles are labeled by well identifiers. Earlier cycles used only well ASR-1.

Table 9. Cycle test data from the Shell Creek Water Treatment Plant (site 6).

[Potable water chloride concentration limit of 250 mg/L (milligrams per liter). Cumulative recovery efficiency extracted from table 6; all other data extracted from table 5. Values have been rounded off. Mgal, million gallons; < less than; >, greater than; --, no data]

Cycle	Storage period (days)	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water		Cumulative recovery efficiency (percent)
				Recharge water (mg/L)	Recovered water (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
1	0	5	>1	100	250	30	>1	30	30
2	0	2	<1	75	250	37	>1	37	32
3	1	20	<2	180-230	250	9	<2	9	14
OP-1	--	23	--	--	--	--	>2	10	12
OP-2	--	36	--	--	--	--	<1	>1	8
OP-3	--	199	--	--	--	--	10	5	6
OP-4	26-29	221	61	94-107	242-252	28	60	27	15
OP-5	166	198	97	94-95	250-270	49	93	47	24

even with the long storage period used (166 days). The poor recovery for ASR-1 is believed to be caused, at least in part, by the presence of an area of fractured dolomites overlying the storage zone to the south of ASR-1 (Water Resources Solutions, Inc., 2003d). Some of the recharged water in ASR-1 may be moving above the storage zone through the fractured dolomite because of buoyancy effects, even though the ambient chloride concentration at the site is not high (900 mg/L).

Marco Lakes (Site 7)

Construction of three ASR wells began at the Marco Lakes site in western Collier County during 1996. Well ASR-1 was completed in July 1996, and wells ASR-2 and ASR-3 were completed in November 1999. Six single-well cycles (ASR-1) were conducted between June 1997 and June 2001, and three multiwell cycles (1E, 2E, and 3E) using all three ASR wells were conducted between October 2001 and July 2004 (fig. 11). Cycles have been conducted on an annual basis since the start of the fourth cycle in 1998, and the recharge period for these cycles has been initiated between July and September every year. Storage period ranged from 3 to 181 days (table 10). Potable water recovery efficiency per cycle ranged from about 4 to 68 percent, with an average value of 33 percent. Cumulative recovery efficiency was about 34 percent.

With the exception of cycle 2, potable-water recovery efficiency increased from about 22 to 44 percent during cycles 1 to 6 (table 10). Recharge water chloride concentration was comparatively high relative to other sites, ranging from 98 to 136 mg/L for the first six cycles. On the basis of numerical simulation, the erratic recovery curve and poor recovery efficiency for cycle 2 (about 4 percent) has been attributed to preferential well plugging during recharge of one of two receiving intervals in the storage zone (Water Resources Solutions, Inc., 1999c). Precipitate formation probably caused this plugging, and acidification of the recharge water prior to injection has minimized or eliminated the problem in later cycles.

Beginning with cycle 2E, operation at this site may have followed a water-banking approach. A large recharge volume (about 670 Mgal) was injected during cycle 2E (table 10), and recovery was stopped when chloride concentrations in the wells were low (110-150 mg/L). This buildup of a buffer zone in the aquifer, followed by a much smaller recharge volume for cycle 3E (about 246 Mgal), apparently resulted in a high combined recovery efficiency (greater than 68 percent) in cycle 3E, even though a long storage period (181 days) was used and recovery ended when chloride concentrations ranged from only 130 to 200 mg/L (fig. 11 and table 10).

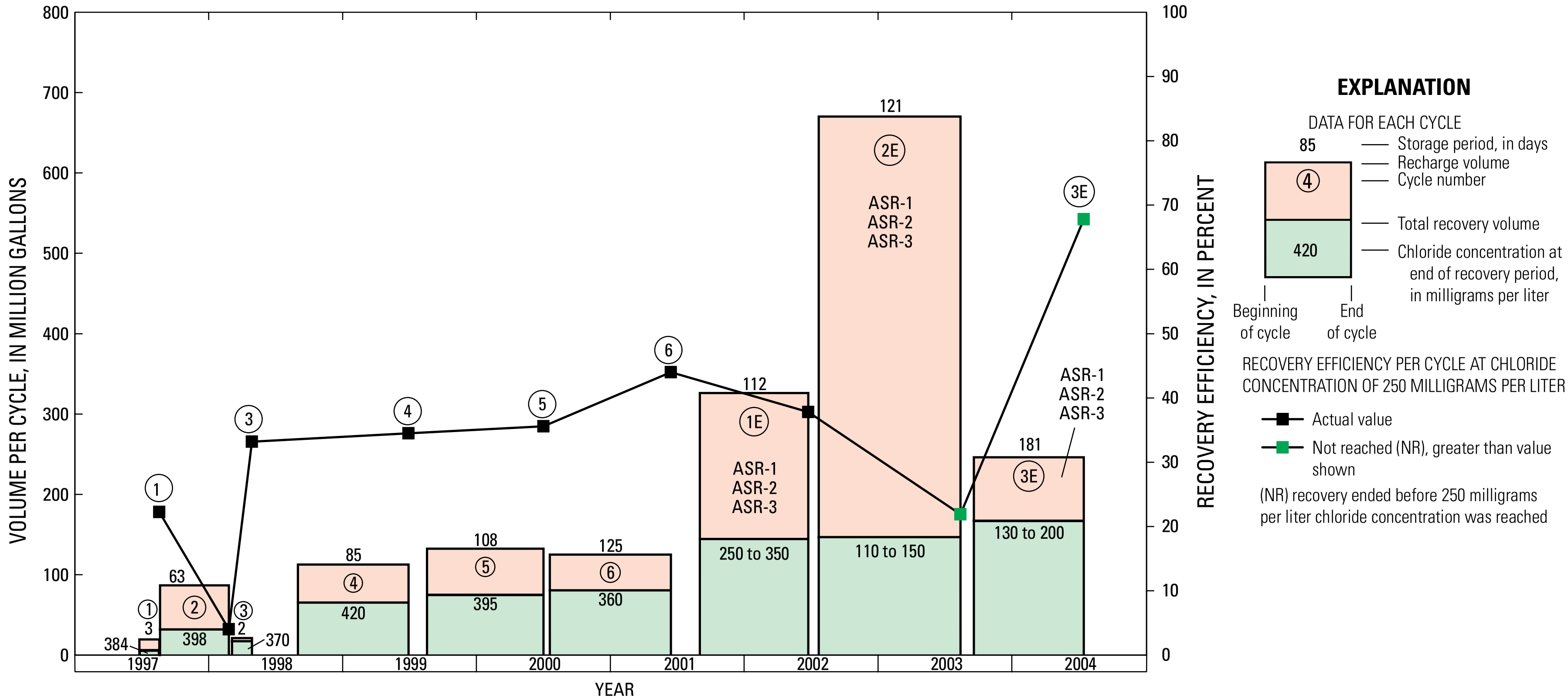


Figure 11. Relation of volumes recharged and recovered, time, and percent recovery for each cycle at the Marco Lakes facility (site 7). Multiple well cycles are 1E, 2E, and 3E.

Table 10. Cycle test data from the Marco Lakes facility (site 7).

[Potable water chloride concentration limit of 250 mg/L (milligrams per liter). Cumulative recovery efficiency extracted from table 6; all other data extracted from table 5. Values have been rounded off. Mgal, million gallons; <, less than; >, greater than; --, no data]

Cycle	Storage period (days)	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water		Cumulative recovery efficiency (percent)
				Recharge water (mg/L)	Recovered water (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
1	3	19	6	98	384	31	>4	22	31
2	63	87	32	115	398	37	<4	4	9
3	2	21	17	13	370	82	7	33	13
4	85	113	65	130	420	58	39	34	23
5	108	132	75	118	395	57	47	36	28
6	125	125	80	136	360	64	55	44	32
IE	112	326	145	105	250-350	44	123	38	34
2E	121	670	147	88	110-150	22	--	>22	29
3E	181	246	167	56	130-200	68	--	>68	34

Boynton Beach East Water Treatment Plant (Site 23)

Construction of well ASR-1 was completed at the Boynton Beach WTP in southeastern Palm Beach County by April 1992, and 21 cycles were completed between October 1992 and July 2004 using ASR-1. Cycles 1 to 4 were conducted over a 7-month period, cycles 5 to 18 were conducted at a rate of almost two per year, and subsequent cycles have been conducted on an annual basis (fig. 12). Storage period lengths ranged from 0 to 174 days; data were unavailable for cycle 17 (table 11). Potable water recovery efficiency per cycle ranged from about 27 to 96 percent, with an average value of about 64 percent. Cumulative recovery efficiency was about 63 percent.

Potable recovery efficiency increased rapidly during the first four cycles to about 90 percent (fig. 12 and table 11), but the high frequency and short storage periods of these cycles may have contributed to the rapid rise. Compared to the preceding two cycles, the low volume of recharge for cycle 4 (about 18 Mgal) also probably contributed to the high recovery for this cycle.

Potable water recovery efficiency decreased to about 27 percent during cycles 5 to 7, probably because of more extended storage periods; for example, the storage period for cycle 7 was 124 days (table 11). Most subsequent storage periods were shorter. Except for cycle 15, recovery efficiency for cycles 8 to18 ranged from about 40 to 96 percent. Cycle 14 recovery continued until chloride concentration increased to about 1,000 mg/L, which probably contributed to a lower projected recovery efficiency for cycle 15. Presumably, to replenish the system, the recovery for cycle 15 ceased at about 34 percent recovery efficiency and a chloride concentration of only about 146 mg/L. On a plot of percent recovery and recovered water chloride concentration during each cycle, the data points for cycle 15 are shifted to substantially lower recovery percentages at the same chloride concentration than for cycles 9 to14 (Reese, 2002, fig. 13).

At about 85 percent, the potable water recovery efficiency for cycle 16 is one of the best obtained for site 23 (table 11). The storage period for cycle 16, however, was only 4 days, and the recovery efficiency for this cycle probably benefited from the incomplete recovery for cycle 15. At least 73 Mgal of water injected during cycle 15 was not recovered. For cycle 19, the first annual cycle, recharge volume was increased to about 201 Mgal (about 4 times the amount for most previous cycles) and the storage period was increased to 86 days, yet the recovery efficiency for this cycle remained relatively high (about 63 percent). Recovery efficiencies for cycles 20 and 21 were about 81 and 77 percent, respectively, with lower recharge volumes (about 104 and 119 Mgal, respectively) than for cycle 19.

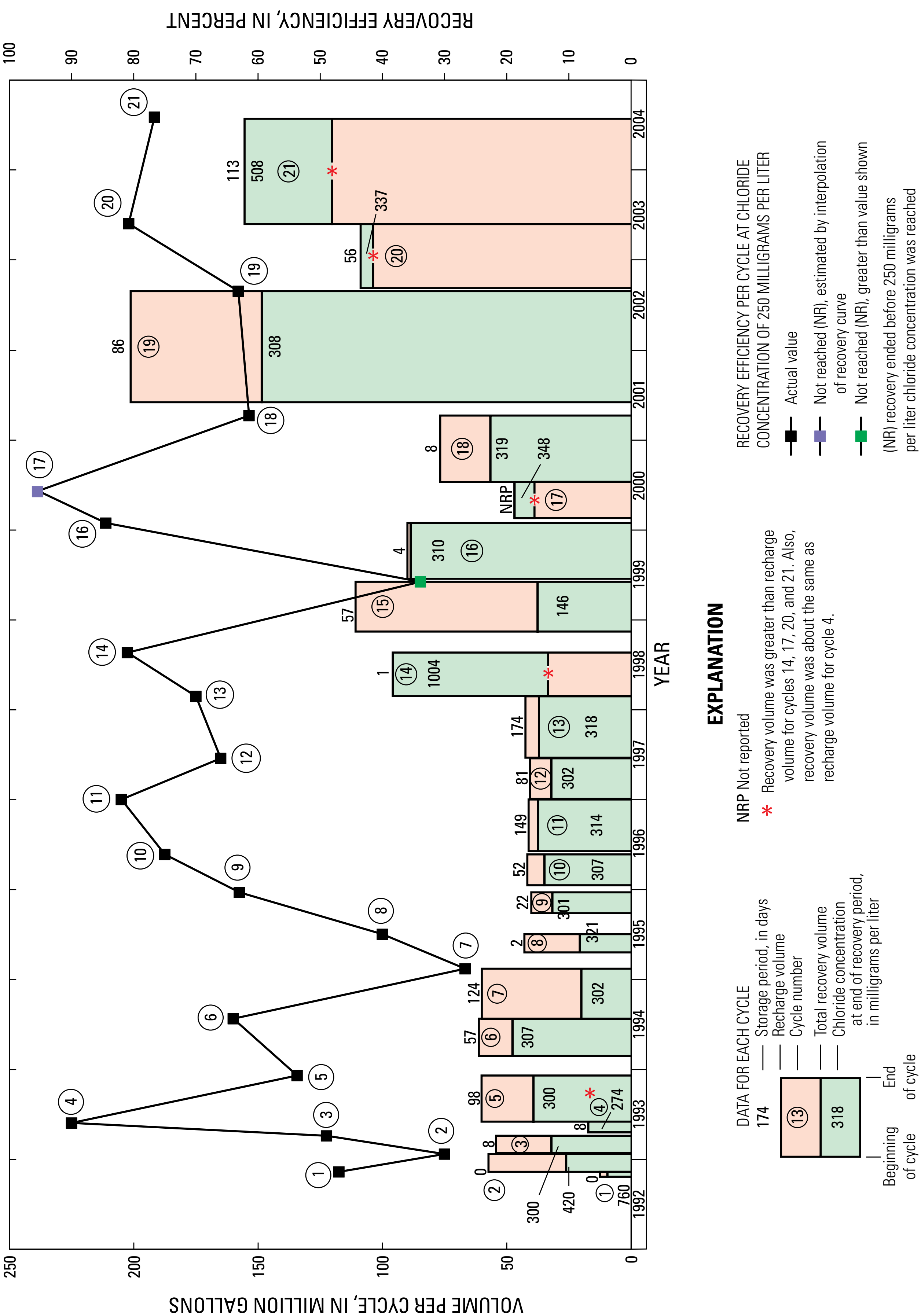


Figure 12. Relation of volumes recharged and recovered, time, and percent recovery for each cycle at the Boynton Beach East Water Treatment Plant (site 23).

Table 11. Cycle test data from the Boynton Beach East Water Treatment Plant (site 23).

[Potable water chloride concentration limit of 250 mg/L (milligrams per liter). Cumulative recovery efficiency extracted from table 6; all other data extracted from table 5. Values have been rounded off. Mgal, million gallons; >, greater than; --, no data]

Cycle	Storage period (days)	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water		Cumulative recovery efficiency (percent)
				Recharge water (mg/L)	Recovered water (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
1	0	13	10	60	760	77	6	47	47
2	0	57	26	50	420	46	17	30	33
3	8	54	32	47	300	59	27	49	40
4	8	18	17	51	274	97	16	90	46
5	98	60	39	46	300	65	32	54	49
6	57	61	48	47	307	78	39	64	52
7	124	60	20	48	302	33	16	27	47
8	2	43	21	52	321	48	17	40	47
9	22	40	32	52	301	79	25	63	48
10	52	42	35	48	307	83	31	75	51
11	149	41	37	41	314	91	34	82	53
12	81	41	32	49	302	79	27	66	54
13	174	43	37	48	318	87	30	70	55
14	1	33	96	62	1,004	287	27	81	57
15	57	111	38	46	146	34	--	>34	53
16	4	90	89	--	310	99	76	85	57
17	--	39	47	--	348	121	37	96	59
18	8	77	57	--	319	74	47	61	59
19	86	201	149	--	308	74	127	63	60
20	56	104	109	--	337	105	84	81	61
21	113	119	156	--	508	131	91	77	63

Delray Beach North Storage Reservoir (Site 24)

Construction of well ASR-1 at the Delray Beach North Storage Reservoir in southeastern Palm Beach County was completed by August 1996. Six test cycles were completed between May 2000 and November 2001; a seventh cycle failed to be completed due to pump failure during recovery (fig. 13). Storage period lengths ranged from 0 to 118 days (table 12). Potable water recovery efficiency per cycle ranged from about 16 to 94 percent, with an average value of about 61 percent (including cycle 7). Cumulative recovery efficiency was about 44 percent.

A TSV of about 250 Mgal was estimated for ASR-1 to support a 50-Mgal recovery volume, and this TSV was recharged at the beginning of cycle testing (CH2M HILL, 2002a). This recharge volume is included in cycle 1, and recharge continued without interruption until the total recharge volume for cycle 1 was 313 Mgal (table 12). Recovery efficiency for cycle 1 was likely adversely affected by a 118-day storage period caused by recovery pump failure; recovery efficiency for cycle 1 was 16 percent at a chloride concentration of 225 mg/L at the end of the cycle. About 50 Mgal per cycle were recharged during cycles 2 and 3, and recovery efficiencies were high (about 94 and 79 percent, respectively). Recovery efficiency decreased to about 53 percent for cycle 4, but recovery was stopped at a chloride concentration of only 185 mg/L. Recovery efficiency improved to almost 80 percent for cycles 5 and 6. With the exception of the first cycle, recovery efficiencies at site 24 were high; however, the storage period length for cycles 2 to 7 averaged only about 1 day, intercycle time was short (usually 2 days or less), and cycles were short (about 2 months or less each).

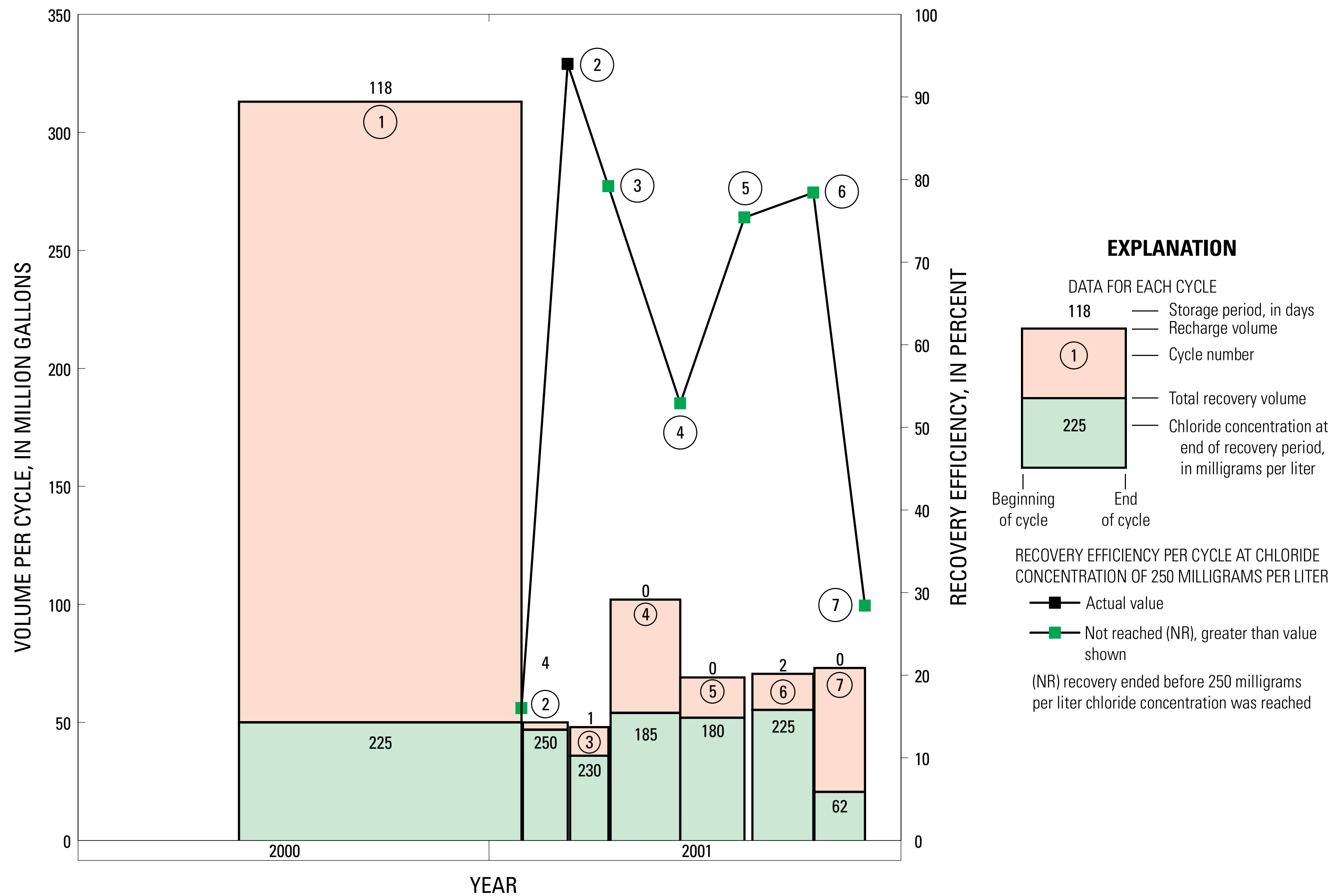


Figure 13. Relation of volumes recharged and recovered, time, and percent recovery for each cycle at the Delray Beach North Storage Reservoir (site 24).

Table 12. Cycle test data from the Delray Beach North Storage Reservoir (site 24).

[Potable water chloride concentration limit of 250 mg/L (milligrams per liter). Cumulative recovery efficiency extracted from table 6; all other data extracted from table 5. Values have been rounded off. Mgal, million gallons; >, greater than; --, no data]

Cycle	Storage period (days)	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water		Cumulative recovery efficiency (percent)
				Recharge water (mg/L)	Recovered water (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
1	118	313	50	40	225	16	--	>16	16
2	4	50	47	40	250	94	47	94	27
3	1	48	38	40	230	79	--	>79	33
4	0	102	54	40	185	53	--	>53	37
5	0	69	52	40	180	75	--	>75	41
6	2	71	55	--	225	78	--	>78	45
7	0	73	21	--	62	28	--	>28	44

West Palm Beach Water Treatment Plant (Site 29)

Construction of well ASR-1 at the West Palm Beach Water Treatment Plant in northeastern Palm Beach County was completed by January 1997, and five ASR test cycles were completed between October 1997 and November 1998 (fig. 14). Storage period lengths ranged from 0 to 3 days (table 13). Recharge volumes per cycle ranged from about 103 to 146 Mgal. Potable water recovery efficiency per cycle was low, ranging from about 3 to 7 percent (table 5). Cumulative recovery efficiency was about 4 percent.

Recovery for cycle 1 was stopped at a chloride concentration of only 133 mg/L (about 4 percent recovery), and recovery efficiency would have been higher if recovery had continued to the potable water level (table 13). Cycle 2 followed immediately and recovery went well beyond the potable water level; however, potable water recovery efficiency was only about 3 percent. Recovery efficiency increased to about 6 to 7 percent for cycles 3 and 4. Recovery efficiency for cycle 5 decreased to only about 3 percent, even though the recharge volume was similar to those used during the previous four cycles. This decrease may have been caused by the 2-month period of inactivity between cycles 4 and 5 (fig. 14). Recovery for cycles 2 to 5 continued until chloride concentrations of about 800 mg/L were reached, thereby eliminating some of the fresher water buffer zone around the well that could have improved recovery efficiency for cycles 3 to 5.

Evaluation of Site Performance

Potable water recovery performance at all ASR sites in southern Florida is discussed in the subsequent sections. First, analysis of recovery efficiencies is made and relative performance of sites is determined. This relative recovery performance is then compared to four hydrogeologic and design factors.

Recovery Efficiency and Relative Performance

A comparison of potable water recovery efficiencies for each cycle at all of the ASR sites with three or more cycles (including test cycles) was made (fig. 15). Much of the recovery efficiency variability between sites and cycles may be attributed to factors not shown, such as recharge volume per cycle, duration of storage and intercycle periods, and the extent of recovery for each cycle. Eight of the 15 sites had recovery efficiencies of less than about 10 percent for the first cycle (sites 1, 3, 12, 14, 20, 22, 27, and 29). Of these eight sites, three have not yet achieved recoveries exceeding 10 percent, and three failed to achieve a recovery exceeding 30 percent by the third cycle. Conversely, the other seven sites had an initial recovery of about 20 percent or greater and attained more than 30 percent recovery by the second cycle, except for site 7, which had a well-plugging problem during cycle 2 as previously discussed. Recovery efficiencies for the most recent cycles at all sites with data are shown in figure 16. Three sites on the east coast and two on the west coast of Florida achieved recoveries of greater than 60 percent for their most recent cycles.

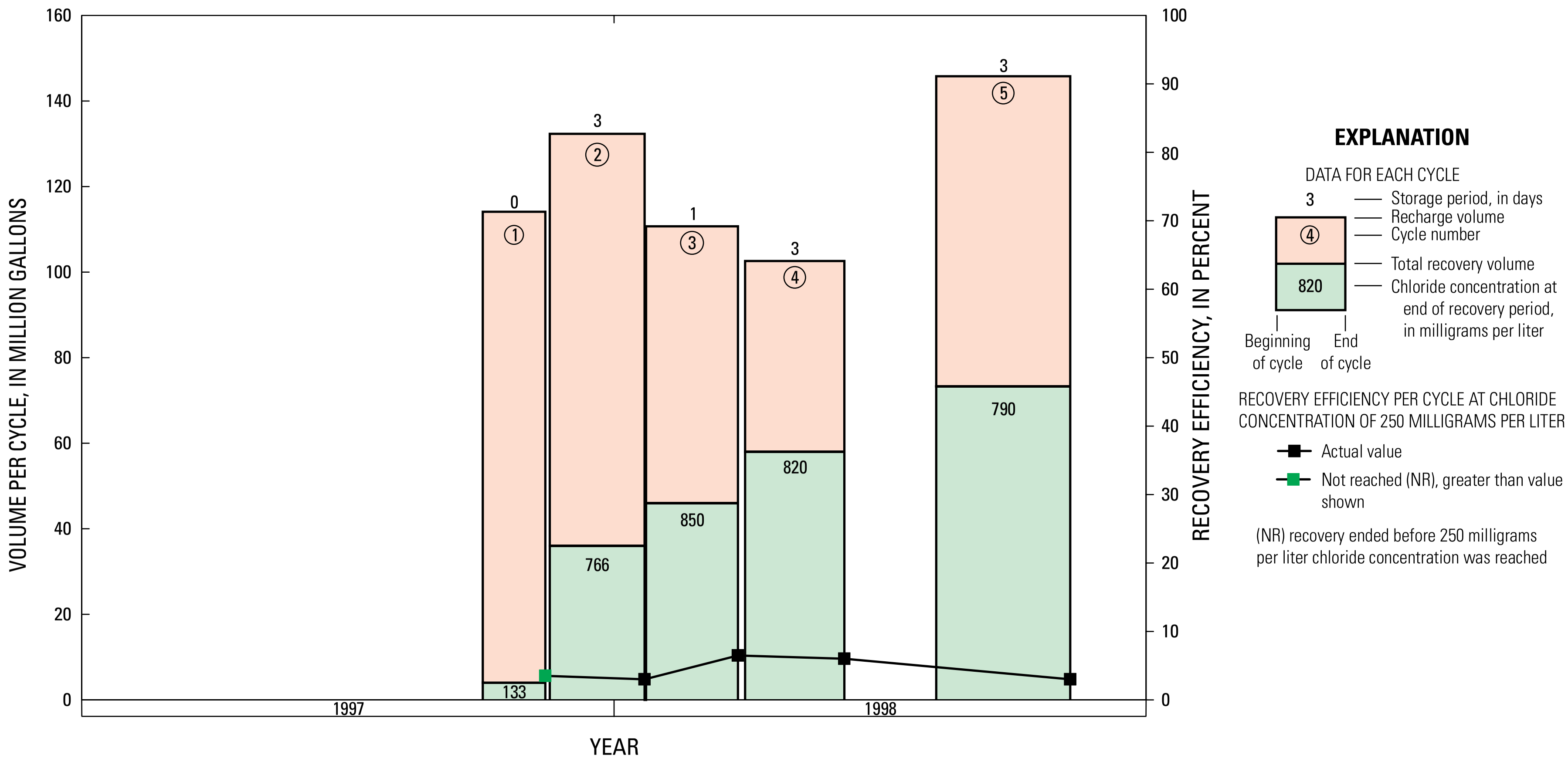


Figure 14. Relation of volumes recharged and recovered, time, and percent recovery for each cycle at the West Palm Beach Water Treatment Plant (site 29).

Table 13. Cycle test data from the West Palm Beach Water Treatment Plant (site 29).

[Potable water chloride concentration limit of 250 mg/L (milligrams per liter). Cumulative recovery efficiency extracted from table 6; all other data extracted from table 5. Values have been rounded off. Mgal, million gallons; >, greater than; --, no data]

Cycle	Storage period (days)	Recharge volume (Mgal)	Recovery volume (Mgal)	Chloride concentration		Recovery efficiency at end of cycle (percent)	Potable water		Cumulative recovery efficiency (percent)
				Recharge water (mg/L)	Recovered water (mg/L)		Recovery volume (Mgal)	Recovery efficiency (percent)	
1	0	114	4	65	133	4	--	>4	4
2	3	132	36	54	766	27	4	3	3
3	1	111	46	50	850	42	7	7	4
4	3	103	58	42	820	57	6	6	5
5	3	146	74	80	790	50	4	3	4

Comparisons of site performance were made using the cumulative recovery efficiencies and cumulative recharge volumes calculated at the end of each cycle in table 6, and these comparisons were used to group sites by performance. The cumulative potable water recovery efficiencies at the end of each cycle for all sites with at least three cycles (fig. 17) display substantially less variability than the per-cycle recovery efficiencies (fig. 15). Much of the variability in per-cycle recovery efficiency apparently caused by water banking, such as at sites 3 (fig. 8), 4 (fig. 9), 7 (fig. 11), and 24 (fig. 13), is eliminated on the cumulative recovery efficiency plot. A comparison of cumulative recharge volume and time at the end of each cycle since the beginning of cycle testing for sites with at least three cycles illustrates large differences in the overall rate of recharge (fig. 18). Sites on this plot can be divided into two groups based on the overall recharge rate. The group with the higher recharge rate includes sites 1, 3, 20, 22, 24, and 29; this group has an overall recharge rate of about 300 Mgal/yr or higher, which is the same as 2 Mgal/d for a 5-month recharge period each year. Three sites in the other group (sites 4, 14, and 23) also had close to this higher rate of recharge, but only for the first few cycles during their first year of operation. A higher overall recharge rate could improve recovery efficiency because of the water-banking effect as previously discussed.

The relative performance of all sites was grouped into "high," "medium," and "low" categories based primarily on their cumulative potable water recovery efficiency during the first seven cycles (fig. 17 and table 14). The cumulative recovery efficiencies were arbitrarily chosen to be 0 to 20 percent for low performance, 20 to 40 percent for medium performance, and greater than 40 percent for high performance. Seven cycles were used because six sites had this number of cycles or greater. For sites with less than seven cycles, the trend of points for the site in figure 17 was projected up to seven cycles. The ratings of three sites, considered borderline, were modified using the overall recharge rate (fig. 18). Site 1 (Broward County WTP 2A) was rated medium instead of high because of a high recharge rate, site 6 (Shell Creek WTP) was rated medium instead of low because of a low recharge rate, and site 7 (Marco Lakes) was rated high instead of medium because of a low recharge rate. Also as previously discussed, the recharge water used at site 7 for cycles 2 to 6 had a substantially higher chloride concentration than the concentration typically used at most other sites, and preferential well plugging occurred during cycle 2. Two sites (sites 11 and 15), not shown in figure 17, also were rated (table 14). Site 11 (Lee County WTP) was rated high based on three cycles with a cumulative recovery efficiency for the third cycle of about 27 percent (table 6) and a low overall recharge rate, and site 15 (Winkler Avenue) was rated low based on one cycle with a recovery efficiency of only 0.5 percent (table 5). Of the 30 sites in this study (table 1), a rating was determined for 17 sites. Seven sites were rated high, five were rated medium, and five were rated low. The remaining 13 sites have not been tested or inadequately tested, and therefore, could not be rated.

Hydrogeologic, Design and Management Factors

Performance at all sites was compared against four of the hydrogeologic and design factors, including thickness, transmissivity, and ambient chloride concentration of the storage zone, and the thickness of the aquifer above the top of the storage zone (table 14). A threshold was chosen for each factor to represent a value above which the factor could adversely affect recovery efficiency. The approximate threshold values chosen for transmissivity and ambient chloride concentration, which were previously identified, are 30,000 ft^2/d and 2,500 mg/L, respectively.

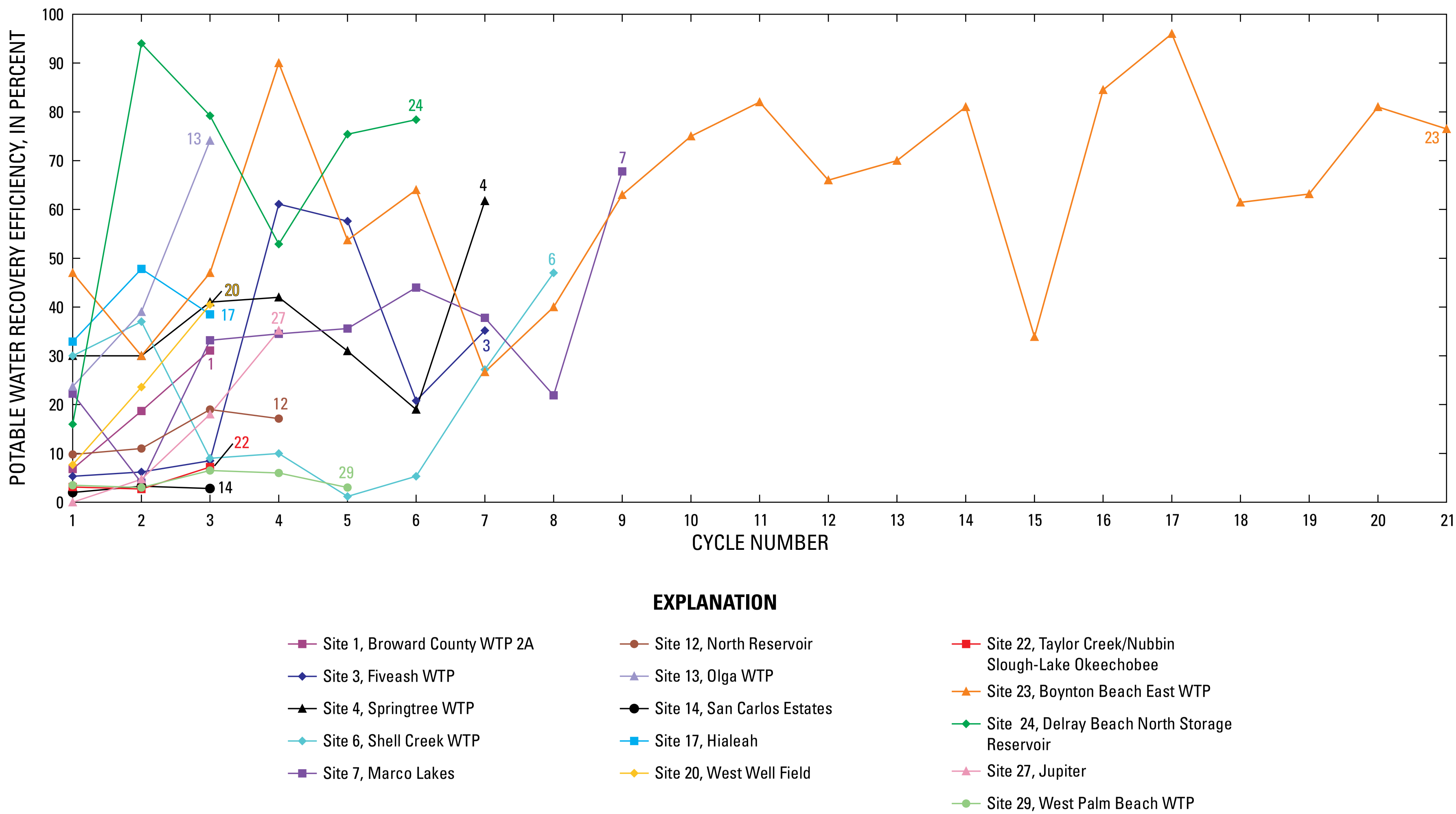
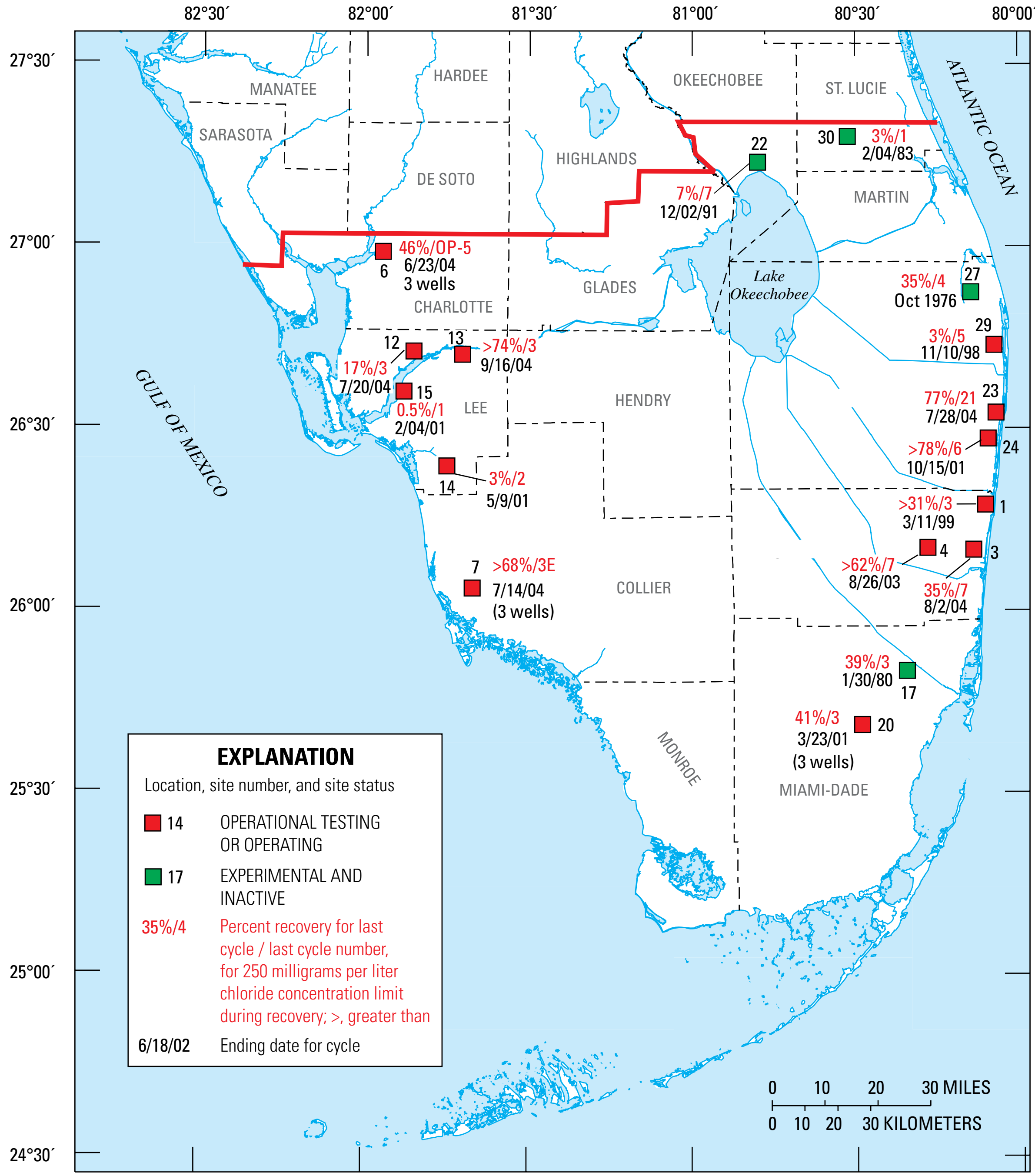


Figure 15. Comparison of potable water recovery efficiencies for each cycle at aquifer storage and recovery sites with three or more cycles (including test cycles). WTP is water treatement plant. Recovery for some cycles did not reach the potable water limit (chloride concentration of 250 milligrams per liter), so recovery efficiency would have been higher.



Base from U.S. Geological Survey digital data
Universal Transverse Mercator projection, Zone 17, Datum NAD 27

Figure 16. Potable water recovery efficiencies for the most recent cycle at aquifer storage and recovery sites in southern Florida. Three sites (indicated) use three wells simultaneously; all other sites use one recharge well.

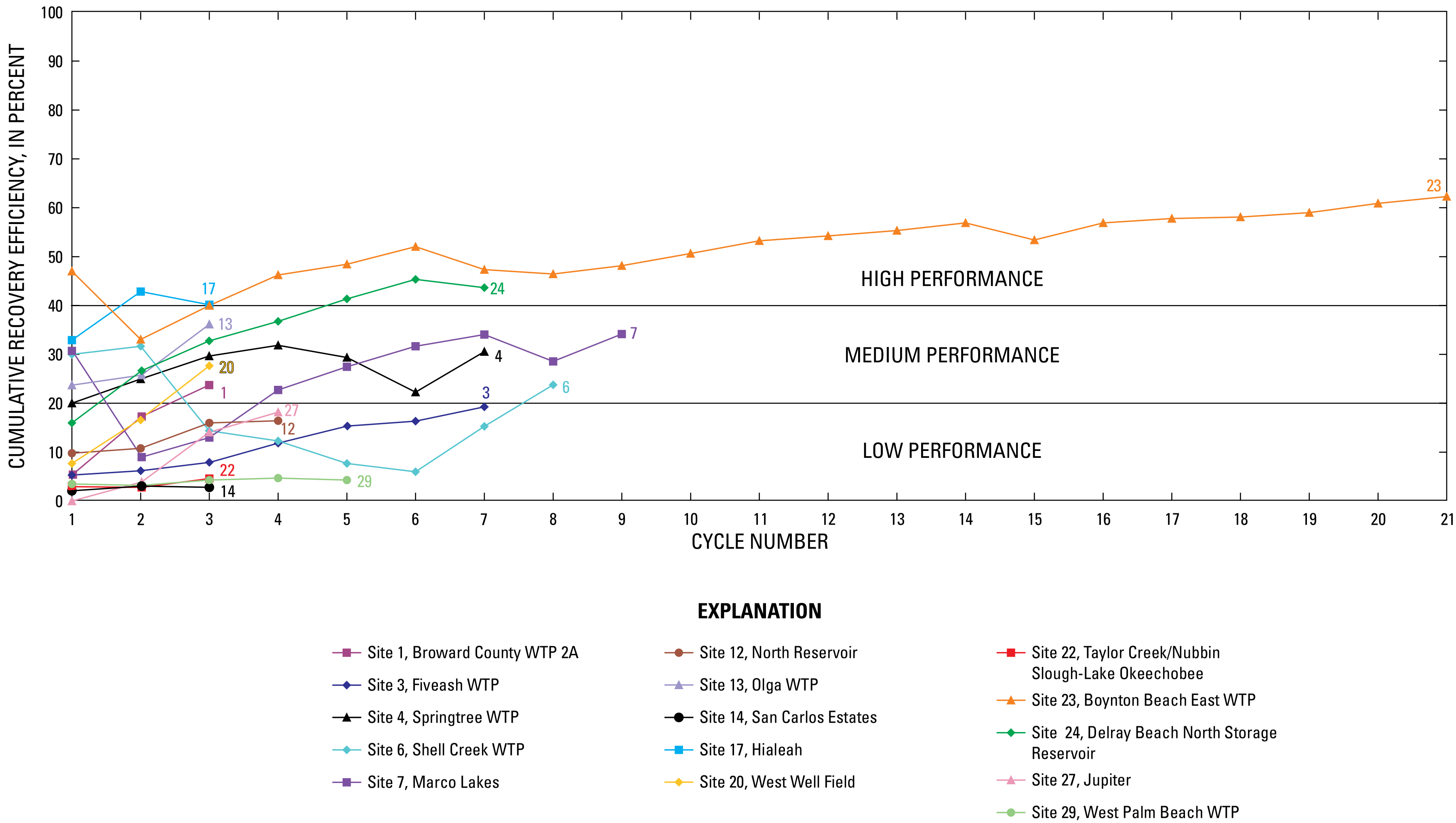


Figure 17. Comparison of cumulative potable water recovery efficiencies for sites with at least three cycles (including test cycles). WTP is water treatment plant. Performance ratings primarily are based on first seven cycles.

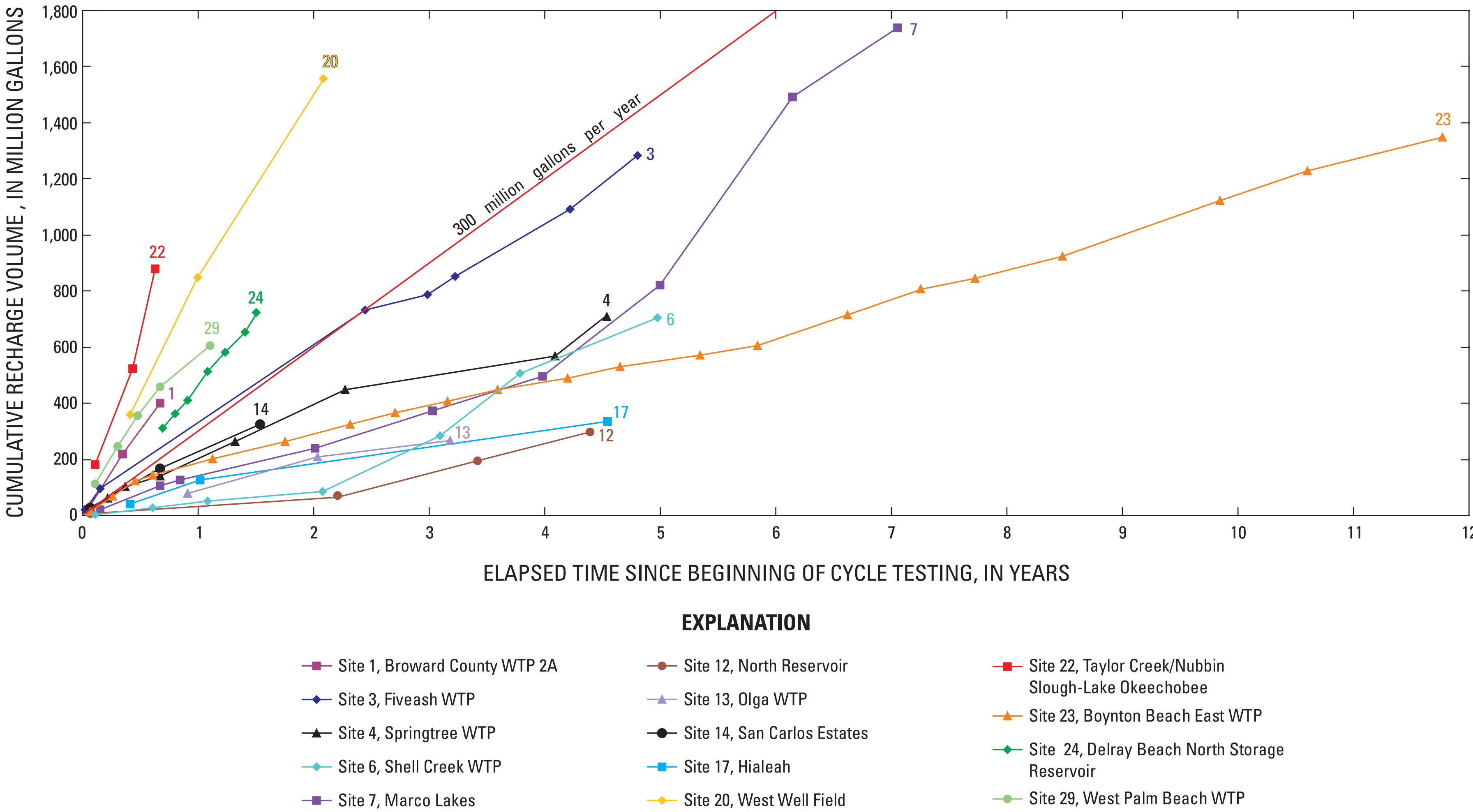


Figure 18. Comparison of cumulative recharge volume and time since the beginning of cycle testing for sites with at least three cycles (including test cycles). WTP is water treatment plant. Points shown by symbols on each line mark the end of each cycle.

Table 14. Comparison of hydrogeologic and design factors that may affect recovery efficiency with aquifer storage and recovery site performance.

[Values for transmissivity and ambient chloride concentration are rounded to two significant figures based on values in tables 3 and 4. Threshold values are shown in brackets in table headings. Values that exceed thresholds are shown in italics. Recovery performance rating based on cumulative recovery efficiency for first seven cycles, or projected to seven cycles if less cycles have been completed. Low is 0 to 20 percent recovery efficiency, medium is 20 to 40 percent recovery efficiency, high is greater than 40 percent recovery efficiency. UFA, Upper Floridan aquifer; MFA, middle Floridan aquifer; ft^2/d, square feet per day; mg/L, milligrams per liter; ND, not determined; ?, recovery performance rating is less certain because of the low number or type of cycles or other reasons]

Site number	Factors that may affect recovery efficiency				Recovery performance indicated by cycle testing (number of cycles completed, including test cycles)
	Storage zone thickness (ft) [*150*]	Transmissivity of storage zone (ft^2/d) [*30,000*]	Ambient dissolved chloride (mg/L) [*2,500*]	Thickness of UFA above top of storage zone (ft) [*50*]	
1	*205*	29,000	1,900	*145*	Medium? (3)
2	*168*	24,000	2,000	50	No testing
3	145	20,000	*3,500*	*85*	Low (7)
4	*160*	5,700	*3,600*	*70*	Medium (7)
5	*188*	4,700	*11,000*	2	No complete cycles
6	*169*	6,000	900	*160*	Medium (8)
7	45	9,100	*2,600*	0	High? (9)
8	61	ND	2,100	*162*	No testing
10	*260*	ND	900	0	No testing
11	*155*	800	500	0	High (3)
12	100	8,300	750	0	Medium (4)
13	61	9,400	1,000	*344*	High (3)
14	51	*70,000*	1,100	0	Low (3)
15	98	27,000	1,300	0	Low? (1)
16	*240*	13,000	700	35	No testing
17	150	11,000	1,200	0	High (3)
18	*470*	11,000	2,200	0	No testing
19	*404*	12,000	1,600	0	Inadequate testing (1)
20	*452*	15,000	2,400	0	High (3)
21	*313*	*40,000*	600	0	No testing
22	*442*	*590,000*	*3,000*	0 for MFA	Low (7)
23	105	9,400	1,900	4	High (21)
24	104	ND	2,300	*86*	High (7)
25	*215*	19,000	2,100	*60*	No testing
26	*210*	8,100	1,800-2,500	30	No testing
27	*290*	ND	1,800	30	Medium (4)
28	90	8,800	2,100	*95*	No testing
29	*215*	*110,000*	*2,800*	*60*	Low (5 test cycles only)
30	*175*	5,900	1,000	0	Inadequate testing (1)

Design factors that concern the thickness and position of the storage zone also were used for comparison. The threshold values that were chosen for these factors, however, are somewhat arbitrary. A value of 150 ft was chosen for the thickness of the storage zone. This value is less than the average storage zone thickness of 183 ft (for all sites with the storage zone in the Upper Floridan aquifer), but is about halfway between the original and reduced storage zone thicknesses for two ASR wells at the Shell Creek WTP (site 6). Both wells had improved recovery efficiency in comparison to the original ASR well at the site, which has a storage zone thickness of 169 ft. Additionally, the average thickness of 183 ft is upwardly biased by sites 19 and 20 in Miami-Dade County with storage zone thicknesses of greater than 400 ft (fig. 4), of which about 300 ft is interpreted to be above the Upper Floridan aquifer. A threshold value of 50 ft for the thickness of the portion of the aquifer above the top of the storage zone was chosen. This value is approximately the average of this thickness determined for all sites with the storage zone in the Upper Floridan aquifer (table 14) using the plots in appendix 1. An aquifer thickness above the top of the storage zone of 50 ft or less could still result in a loss of recharged water due to the buoyancy effect, depending on the vertical hydraulic conductivity of the aquifer and ambient salinity. The four factors were determined for all sites, and the sites exceeding the threshold values were identified for the purpose of comparison with the relative recovery efficiency performance ratings (table 14).

Relative ASR performance, determined at 17 sites, was grouped by rating and compared with the four hydrogeologic and design factors that may affect recovery efficiency (table 15). Some correlation of the ratings with the number of factors exceeding their respective threshold value was found. As the ratings decrease from high to low, the number of sites with two or more factors that exceed threshold values increases. Of the five sites rated low, three sites had two to four factors that exceeded their threshold values, whereas for the sites rated high, none had more than one factor. Three of the sites rated low have storage zone transmissivities above the threshold value of 30,000 ft^2/d, and three have ambient chloride concentrations above the threshold value of 2,500 mg/L. All of the sites that have transmissivities above the threshold value were rated low. Of the eight sites with a storage zone thickness greater than 150 ft, only two had a high rating. A correlation with the factor for the thickness of the Upper Floridan aquifer above the top of the storage zone, however, was not indicated. Sites that exceeded the 50-ft value were relatively evenly distributed among the three performance ratings.

Although not included in the preceding comparison, storage period length or time between cycles also may affect recovery efficiency. This appears to be more likely for sites in southeastern Florida than in southwestern Florida; southeastern Florida has higher ambient salinity, higher apparent vertical hydraulic conductivity in the aquifer, and more storage zones located more than 50 ft below the top of the Upper Floridan aquifer. Ten of the 16 east coast sites have chloride concentrations of at least of 2,000 mg/L, but concentrations at only 2 of the 9 west coast sites exceed this value. Because of the possibility of enhanced vertical hydraulic conductivity in the upper part of the Upper Floridan aquifer in the southeastern coastal area, upward migration of recharged freshwater during long storage or intercycle periods may cause substantial decreases in recovery efficiency. This reasoning tends to be supported by the cycle test data. Seven of the 16 east coast sites have a thickness of the aquifer above the top of the storage zone of greater than 50 ft (table 14). Of these seven sites, four sites—Broward County WTP 2A (site 1), Fiveash WTP (site 3), Springtree WTP (site 4), and West Palm Beach WTP (site 29)—have a low or medium performance rating; one site—Delray Beach North Storage Reservoir (site 24)—has a high rating; and two sites—Hillsboro Canal East (site 25), and System 3 Palm Beach County (site 28)—have had no cycle testing.

Some evidence seems to indicate poor recovery performance can occur in southeastern Florida because of long inactive periods. For example, no potable water was recovered at the Southwest Well Field (site 19) after recharge of 228 Mgal into two wells and storage for 360 days. Additionally, a large reduction in recovery efficiency at the Fiveash WTP (site 3) occurred between cycles 5 and 6 (fig. 8), mostly perhaps because of 8 months of inactivity since cycle 3 with its large recharge volume and the low volumes recharged for cycles 4 and 5.

Table 15. Aquifer storage and recovery site performance, grouped by rating, and compared with factors that could affect recovery efficiency.

[“X” indicates factor equals or exceeds threshold value. Threshold values are given in table 14. Site ratings are described in the text and in table 14. Sites with insufficient data for ratings are not shown. no., number; --, no exceedence for factor]

Site No.	Storage zone thickness	Storage zone transmissivity	Storage zone chloride concentration	Aquifer thickness above storage zone
		High		
7	--	--	X	--
11	X	--	--	--
13	--	--	--	X
17	--	--	--	--
20	X	--	--	--
23	--	--	--	--
24	--	--	--	X
		Medium		
1	X	--	--	X
4	X	--	X	X
6	X	--	--	X
11	X	--	--	--
12	--	--	--	--
27	X	--	--	--
		Low		
3	--	--	X	X
14	--	X	--	--
15	--	--	--	--
22	X	X	X	--
29	X	X	X	X

Summary

This report completes the second phase of an ongoing investigation to compile and synthesize data on existing aquifer storage and recovery (ASR) sites in southern Florida and to identify specific hydrogeologic, design, and management factors that control the recovery of freshwater recharged into ASR wells. The first report completed in 2002 provided preliminary data inventory, review, and analysis. The current study: (1) compiled new ASR data that have been made available, (2) determined the hydrogeologic framework at each ASR site, and (3) further evaluated performance at each site including a more complete comparative analysis of ASR sites. The focus of the current study is on the Upper Floridan aquifer, which is continuous throughout southern Florida, and generally has good overlying confinement; however, this aquifer contains brackish to saline ground water, which can greatly affect the recovery of the freshwater recharged and stored because of dispersive mixing.

Well data were inventoried and compiled for all wells at existing and historical ASR sites in southern Florida. All of the ASR wells at the 30 sites have been drilled to the carbonate Floridan aquifer system, mostly under the direction of local municipalities or counties in coastal areas. The Upper Floridan aquifer of the Floridan aquifer system is either being used, or is planned for use, at 29 of the sites. Three of the 30 sites are currently operational, 11 are undergoing "operational (cycle) testing," 11 require additional infrastructure development or regulatory approval prior to "operational testing," and 5 are no longer active or abandoned after experimental testing was completed. Five of the more recent sites are pilot or test well sites drilled as part of the Comprehensive Everglades Restoration Plan (CERP), for which ASR has been proposed on a large, unprecedented scale; cycle testing at these five sites has not yet begun.

Many utility-operated, nonexperimental ASR facilities with constructed wells have experienced cycle testing or operational delays because of unresolved regulatory issues; mechanical problems, such as well pump failure; inadequate source-water supply, or other reasons. Out of ten sites with wells constructed in the 1990s, five have conducted only three cycles or less, and cycle testing has not begun at two others.

The hydrogeology of the Upper Floridan aquifer in southwestern Florida differs from southeastern Florida. Confinement between flow zones within the Upper Floridan aquifer in southwestern Florida is generally better than in southeastern Florida, and some zones in southwestern Florida are referred to as separate aquifers or subaquifers. Unconformities are present at formation contacts in the Upper Floridan aquifer, and zones of dissolution can be associated with these unconformities. Because of these unconformities and associated karstification, the vertical hydraulic conductivity in the upper part of the Upper Floridan aquifer may be higher in southeastern Florida than in southwestern Florida. The hydrogeologic framework at each of the 30 ASR sites is delineated in this report; geophysical log traces, lithologic columns, flow zones, geologic and hydrogeologic units, completed open-hole intervals, and ambient water-quality data are illustrated for each site.

Storage zone factors that can affect the efficiency of ASR operation vary widely between sites. The thickness of the open-hole storage zone ranges from 45 to 470 ft, and borehole diameter ranges from 5.125 to 29 in. Twenty-inch or greater diameter ASR wells are required to obtain an injection or withdrawal rate of 5 Mgal/d or greater. Transmissivity of the Upper Floridan aquifer storage zones is reported to range from 800 to 110,000 ft^2/d, but at most sites, transmissivity ranges from about 5,000 to 30,000 ft^2/d. Chloride concentration of ambient ground water in Upper Floridan aquifer storage zones ranges from 500 to 11,000 mg/L, but at most sites, the chloride concentration ranges from about 1,000 to 3,000 mg/L. A high degree of correlation between chloride concentration and salinity (dissolved-solids concentration) in the Floridan aquifer system in southern Florida has been demonstrated in previous studies. Water-quality data obtained from known sampled intervals and inferred from resistivity geophysical logs indicate that ambient salinity and chloride concentration increase with depth below the storage zone at six sites.

Potable water recovery efficiency on a per cycle basis was the primary measure used to evaluate site performance and is defined as the percentage of the volume of freshwater recharged that has been recovered before the chloride concentration of recovered water reaches 250 mg/L. Cycle test data were compiled for 20 ASR sites, and potable water recovery efficiencies were calculated for 18 of these sites. Cumulative recharge volumes and cumulative potable water recovery efficiencies were calculated for each cycle and also were used to evaluate performance. Additionally, total recovery efficiencies or the percent recoveries at the end of each cycle were determined. They can be substantially higher than the potable water recovery efficiencies because of blending of the higher salinity water recovered from the aquifer with low salinity water at the WTP. Total recovery efficiency is the performance measure used in the operation of WTPs.

Potable water recovery efficiencies per cycle vary widely. Eight sites had recovery efficiencies of less than about 10 percent for the first cycle, and three of these sites have not yet achieved recoveries exceeding 10 percent. The highest recovery efficiency achieved for a cycle was 94 percent for cycle 2 at the Delray Beach North Storage Reservoir. Three sites on the east coast of southern Florida and two sites on the west coast have achieved per cycle potable water recovery efficiencies exceeding 60 percent, and three of these sites (two on the west coast and one on the east coast) have achieved good (greater than 60 percent) recovery efficiencies, even with long storage periods (from 174 to 191 days).

Results of cycle testing at several sites appear to support the target storage volume or water-banking approach. For example, at the Delray Beach North Storage Reservoir site, six times more recharge water (313 Mgal) was used during the preceding cycle 1 than in cycle 2 with its high recovery efficiency (94 percent). This method involves recharging a large volume of water in an initial cycle, which flushes out the aquifer around the well and builds up a buffer zone that can maintain high recovery efficiency in the following cycles with much lower recharge volume. Recovery efficiencies at the Delray Beach North Storage Reservoir site remained high for the next five short cycles (about 2 months or less per cycle) conducted, however, except for the first cycle, there were no substantial storage periods and little or no idle time between cycles.

Comparisons of the performance of sites were made using the cumulative potable water recovery efficiencies and cumulative recharge volumes calculated at the end of each cycle. The cumulative potable recovery efficiencies at the end of each cycle display substantially less variability than the per-cycle recovery efficiencies. The per-cycle recovery efficiency variability is caused, in large part, by the practice of water banking in some cycles. A comparison of cumulative recharge volume and time at the end of each cycle since the beginning of cycle testing for all sites illustrates large differences in the overall rate of recharge. A higher overall recharge rate (greater than 300 Mgal/yr) can improve recovery efficiency because of the water-banking effect.

The relative performance of all sites with adequate cycle test data was determined. Performance was grouped into "low," "medium," and "high," categories based primarily on their cumulative recovery efficiency for the first seven cycles, or projected to seven cycles if fewer cycles have been conducted. The cumulative percent recoveries for these categories were arbitrarily chosen to be 0 to 20 percent for low, 20 to 40 percent for medium, and greater than 40 percent for high. The ratings of three sites considered borderline were modified using the overall recharge rate. Of the 30 ASR sites in this study, a rating was determined for 17 sites. The remaining 13 sites have not been tested (or were inadequately tested), and therefore, could not be rated. Of the 17 rated sites, 7 were rated high, 5 were rated medium, and 5 were rated low.

The relative performance of all sites rated was compared with four hydrogeologic and design factors: thickness, transmissivity, and ambient chloride concentration of the storage zone, and the thickness of the portion of the aquifer above the top of the storage zone. Respective threshold values of 150 ft, 30,000 ft^2/d, 2,500 mg/L, and 50 ft, respectively, were chosen for these factors to represent the approximate values above which recovery efficiency could be adversely affected. The values chosen for transmissivity and ambient chloride concentration were identified in previous studies, Increased permeability in a carbonate aquifer, such as the Upper Floridan aquifer, corresponding to increased transmissivity of a storage zone, typically translates to greater dispersive mixing with high salinity ambient ground water. For the other two factors, which are design factors concerning the thickness and position of the storage zone, the threshold values chosen are somewhat arbitrary; however, they are based, at least in part, on their average value for all sites with the storage zone in the Upper Floridan aquifer. High values for storage zone thickness could result in decreased recovery efficiency because of the greater vertical extent of the transition zone along which mixing occurs and because of increased potential for dispersive mixing. An aquifer thickness above the top of the storage zone of more than 50 ft could lower recovery efficiency, depending on the vertical hydraulic conductivity of the aquifer and ambient salinity. The buoyancy of the injected freshwater in saline ambient ground water could cause part of the bubble to migrate above the level of the top of the storage zone (base of casing), where it may be more difficult to recover. The four factors were determined for all sites, and the sites exceeding the threshold values were identified.

Correlation of the performance ratings with the number of factors exceeding their respective threshold value is indicated. As the ratings decrease from high to low, the number of sites with two or more factors that exceed threshold values increases. The best correlation is found with the transmissivity and ambient chloride concentration factors, but some correlation also is indicated with the thickness of the storage zone. The storage zone transmissivity and ambient chloride concentration each exceeded the threshold value at three sites rated low. All of the sites that have transmissivities above the threshold value were rated low. Of the eight sites with a storage zone thickness greater than 150 ft, only two sites were rated high. A correlation with the factor for the thickness of the Upper Floridan aquifer above the top of the storage zone, however, was not indicated.

Long intercycle or storage periods also may affect recovery efficiency. This adverse effect appears to be more likely for Upper Floridan aquifer sites in southeastern Florida than in southwestern Florida; southeastern Florida has higher ambient salinity, higher apparent vertical hydraulic conductivity, and more storage zones located greater than 50 ft below the top of the aquifer. Because of the possibility of enhanced vertical hydraulic conductivity in the upper part of the Upper Floridan aquifer in the southeastern coastal area, upward migration of recharged freshwater during long storage or intercycle periods may cause substantial decreases in recovery efficiency. This reasoning tends to be supported by the cycle test data. Seven of the 16 east coast sites have a thickness of the aquifer above the top of the storage zone of greater than 50 ft; of these 7 sites, 4 sites have a low or medium performance rating, 1 site has a high rating, and 2 sites have had no cycle testing. Additionally, some evidence seems to indicate poor recovery performance has occurred in southeastern Florida for certain cycles because of long storage and intercycle periods.

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