

Prepared in cooperation with the City of Tallahassee

Depth-Dependent Groundwater Quality Sampling at City of Tallahassee Test Well 32, Leon County, Florida, 2013



Open-File Report 2014–1255

Cover. Well drillers installing submersible pump in well 32. Photograph by W. Scott McBride, USGS.

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By W. Scott McBride and Michael A. Wacker

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Open-File Report 2014–1255

**U.S. Department of the Interior
U.S. Geological Survey**

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SALLY JEWELL, Secretary

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Suzette M. Kimball, Acting Director

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Conversion Factors and Datums

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi ²)	2.590	square kilometer (km ²)
Flow rate		
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$$

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 1983 (NAD 83).

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter ($\mu\text{g}/\text{L}$).

Abbreviations

ABI	acoustic borehole imager	OBI	optical borehole imager
bls	below land surface	per mil	parts per thousand
cps	counts per second	SF ₆	sulfur hexafluoride
CW32	test well 32	⁸⁶ Sr	strontium-86
$\delta^{18}\text{O}$	delta oxygen-18	⁸⁷ Sr	strontium-87
$\delta^2\text{H}$	delta hydrogen-2	SFM	spinner flowmeter
EM	electromagnetic	TU	tritium units
² H	deuterium	USGS	U.S. Geological Survey
³ H	tritium	WQT	water-quality tool
KHz	kilohertz		

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Depth-Dependent Groundwater Quality Sampling at City of Tallahassee Test Well 32, Leon County, Florida, 2013

By W. Scott McBride and Michael A. Wacker

Abstract

Public-supply wells sometimes produce water of less than desirable quality because contaminants can migrate to the open interval of wells through preferential pathways. If these pathways can be identified, zones that produce poor quality water can be excluded during the well-construction process. The U.S. Geological Survey has developed geophysical testing methods that can be used to delineate zones of high permeability in test wells. Once the highly permeable zones are identified, water-quality data can be collected from each zone to identify whether any of the zones produce water of poor quality. The zones producing poor quality water can then be cased off in the final well design so that they do not contribute flow to the production well, reducing subsequent water-treatment costs.

A test well was drilled by the City of Tallahassee to assess the suitability of the site for the installation of a new well for public water supply. The test well is in Leon County in north-central Florida. The U.S. Geological Survey delineated high-permeability zones in the Upper Floridan aquifer, using borehole-geophysical data collected from the open interval of the test well. A composite water sample was collected from the open interval during high-flow conditions, and three discrete water samples were collected from specified depth intervals within the test well during low-flow conditions. Water-quality, source tracer, and age-dating results indicate that the open interval of the test well produces water of consistently high quality throughout its length. The cavernous nature of the open interval makes it likely that the highly permeable zones are interconnected in the aquifer by secondary porosity features.

Introduction

Public-supply wells are vulnerable to water-quality issues due to the movement of contaminants through short-circuit pathways that can be induced by pumping and other processes (Landon and others, 2009). Large costs can be associated with the installation and maintenance of a public-supply well used

to provide a clean, safe, and reliable source of drinking water. Treatment costs can be minimized if the spatial distribution of zones of substantial flow and high-quality water can be delineated in test wells prior to the construction of a public-supply well.

The City of Tallahassee operates 28 water-supply wells throughout the city and surrounding areas that draw water from the Upper Floridan aquifer (Davis and Katz, 2007). In general, high-quality groundwater is being withdrawn; however, problems have been identified in a few of the wells, with slightly elevated concentrations of iron, manganese, arsenic, nitrate, and tetrachloroethylene. To meet a growing demand for additional public water supply, the City of Tallahassee plans to complete a new public-supply well north of the city. Test well 32 (CW32) was drilled to confirm the suitability of the water in the open interval for public water supply (fig. 1).

The U.S. Geological Survey (USGS) has developed depth-dependent sampling techniques that can be used to collect water-quality samples and flow-rate data from discrete depth intervals within public-supply wells and boreholes during pumping and non-pumping conditions.

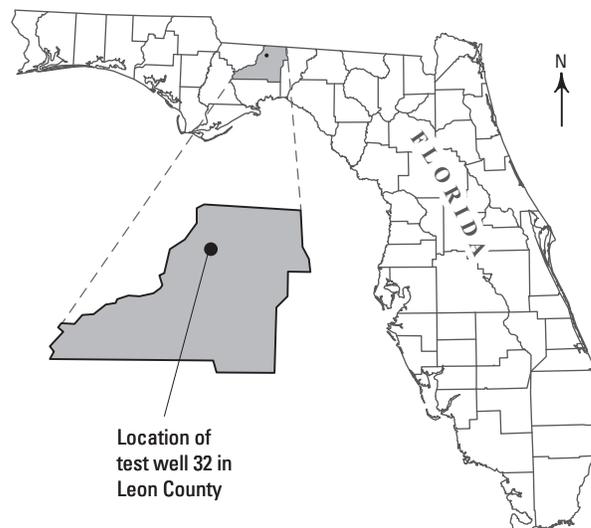


Figure 1. City of Tallahassee test well 32 in Leon County, Florida.

Depth-dependent flow and water-chemistry profiles in pumped wells are useful for understanding sources and pathways for contaminants to supply wells (Collar and Mock, 1997; Gossell and others, 1999; Izbicki and others, 1999, 2005, 2008; Danskin and Church, 2005).

Purpose and Scope

The purpose of this report is to present the findings of a study conducted by the USGS, in cooperation with the City of Tallahassee, to (1) delineate high-permeability zones in the Upper Floridan aquifer at test well CW32 that have substantial rates of groundwater flow and (2) to characterize changes in water quality with depth in the CW32 borehole. Delineation of the high-permeability zones in the Upper Floridan aquifer was determined using a suite of geophysical logging tools. Composite water samples were collected from the open interval, and discrete depth-dependent samples were collected from each of the three productive zones in CW32. Data were collected during December 2013. Water samples were analyzed for a variety of water-quality constituents including major ions, nutrients, dissolved organic carbon, trace elements, volatile organic compounds; natural tracers including isotopes of oxygen, hydrogen, and strontium; and age-dating indicators including tritium and sulfur hexafluoride.

Description of the Study Area

The study area is in Leon County in north-central Florida (fig. 1). The topography of the study area is characterized by rolling hills and land-surface altitudes that range from 0 to about 200 feet above the National Geodetic Vertical Datum of 1929. The climate is humid, subtropical with relatively large amounts of rainfall. The average annual temperature in Tallahassee is 67 degrees Fahrenheit, and the annual average precipitation is about 66 inches per year. The city water-supply wells are widely distributed, and all 28 existing wells are interconnected through distribution lines. City of Tallahassee test well 32 is located approximately 9 miles north of downtown Tallahassee, about 2.5 miles west of Thomasville Road in the Summerbrooke Subdivision.

Methods of Study

Borehole-geophysical data were collected in the open interval of CW32 to delineate zones of high permeability and flow. Water chemistry data were collected and used to determine the quality of water produced by the high-permeability zones in CW32. Naturally occurring chemical tracers were used to determine whether the high-flow zones in CW32 yield water from similar sources. Transient age-dating tracers were used to determine if water from each of the highly permeable zones in CW32 is of similar age.

Borehole-Geophysical Data Collection

The total depth of the CW32 borehole drilled by the City of Tallahassee is 440 feet (ft) below land surface (bls), with a casing depth of 300 ft and a borehole diameter of 10 inches (in.). Prior to the collection of borehole-geophysical data, the borehole was bridged or collapsed below 413 ft bls, and therefore, borehole data were collected between the base of the casing and 413 ft (natural gamma ray log data were collected from the land surface to 413 ft bls). Borehole-geophysical data from CW32 were collected in two stages on December 2–3, 2013. On December 2, continuous digital borehole images, fluid, caliper, natural gamma, electromagnetic-induction, and acoustic velocity data were collected. WellCAD version 4.4 was used to plot the borehole data and to display the data at different scales (1 to 96 and 1 to 12 scales) to better depict the range of data in the discrete well intervals. This data display was used to plan the subsequent collection of flowmeter data on the following day.

Continuous digital borehole images were obtained using high-resolution optical borehole image (OBI) and an acoustic borehole image (ABI) devices. The ABI data supplement data from the OBI by displaying physical features that may be difficult to distinguish optically (Williams and Johnson, 2004). In addition, the amplitude of the acoustic signal reflects the density and cementation of the rock in the borehole wall (Prensky, 1999; Williams and Johnson, 2004).

Fluid data were collected in the open section of the borehole under ambient flow conditions, using two instruments: (1) a water-quality tool (WQT) that measures fluid temperature, specific conductance, pH, percent oxygen, and oxidation-reduction potential (redox) of the borehole fluid and (2) a fluid probe on the end of a caliper tool that measures borehole-fluid temperature and resistivity.

Other borehole-geophysical data were collected using a three-arm caliper probe, natural gamma tool, electromagnetic (EM) induction tool, and acoustic velocity tool. The three-arm caliper probe was used to measure the diameter of the borehole with depth and to locate zones of potential secondary porosity (Keys, 1990). Natural gamma data typically are used to correlate changes in lithology and stratigraphy between boreholes (Keys, 1990). An electromagnetic induction tool was used to provide bulk electrical conductivity data for the aquifer rock matrix and formation water. These data are influenced by formation porosity, groundwater specific conductance, and temperature (Wacker and others, 2014). Formation resistivity is the reciprocal of conductivity, so EM induction data are comparable to resistivity data (Keys, 1990). Acoustic velocity logs were recorded using full waveform sonic data collected over the open-hole section in two logging runs with one acoustic signal transmitted at 15 kilohertz (KHz; data used for porosity calculations) and a second signal transmitted at 1 KHz (data used for relative permeability).

On December 3, 2013, a spinner flowmeter (SFM) was used, under both ambient and pumping conditions, to measure the relative change in flow as the tool was moved up and down

the borehole. The SFM measures flow using a propeller that spins faster or slower depending on the rate of vertical flow within the borehole. Depths where changes in spin velocity occur, measured in counts per second (cps), indicate locations where inflow and outflow of groundwater to the borehole occurs. Heat-pulse and electromagnetic flowmeters, which measure the actual velocity of flow in the well bore, were not used because these meters require the borehole to be of a uniform diameter. Heat-pulse and electromagnetic flowmeters require that water be routed through a central measuring orifice by way of a rubber diverter. When the borehole wall is not uniform, flow can escape around the diverter, biasing the measurement. The SFM can be used in boreholes that are cavernous, like CW32, because it does not require that flow be confined in order for a measurement to be obtained.

The SFM was first logged up and down the open borehole under ambient flow conditions. After the ambient logging was completed, an electrical submersible pump was installed in the well at 230 ft bls. This was done while the SFM was still in the borehole, because there was insufficient space in the well casing for the pump and SFM to pass one another. The SFM was then moved up and down the borehole as the pump was run at different speeds to measure the vertical flow in the borehole under varying pumping conditions. Fluid data were also collected with the WQT after pumping was completed (and the pump removed) to determine if the borehole fluid had returned to ambient pre-pumping conditions. The WQT was not used during pumping because it would have required the removal of the pump from the test well.

Collection and Analysis of Water Samples

Composite and discrete depth-dependent water samples were collected at CW32 by the City of Tallahassee and the USGS. To collect the composite sample, which represents the quality of water produced by the entire open interval of the test well under pumping conditions, a 6-in.-diameter submersible pump was set at 301 ft near the bottom of the well casing. A sampling port was installed on the side of the pump discharge pipe. Sample water passed through the port into Teflon tubing attached to a sampling chamber that protected the samples from atmospheric contamination during collection. The well was purged three volumes and, during the third volume, water chemistry was monitored for stability using a calibrated multiparameter water-quality instrument. Field readings consisted of specific conductance, pH, temperature, and dissolved oxygen measurements. On December 2, after USGS stabilization criteria were met, both the USGS and the City of Tallahassee collected a composite water-quality sample from the open interval of the test well (300–440 ft bls) while pumping at approximately 550 gallons per minute (gal/min).

Discrete depth-dependent water samples were collected within the open interval of the test well from the highly permeable flow zones that were identified using geophysical logs. On December 3, before sampling began, the drill crew

installed a 4-in.-diameter submersible pump in CW32 capable of pumping about 60 gal/min. The 60-gal/min flow rate was ideal for discrete sampling because it allowed CW32 to be purged in less than 1 hour between samples, but the flow rate was low enough that it was not likely to induce intra-borehole flow over the length of the open interval and cause mixing of waters from each highly permeable zone. Ideally, packers would have been used to isolate each zone during sample collection, but the cavernous borehole precluded their use. The huge volume of water contained in the cavernous borehole makes it highly unlikely that mixing occurred at a flow rate of 60 gal/min. The same sample collection procedures described above for the composite sample were followed for each of the discrete depth-dependent samples. The test well was purged at least three volumes, and field parameter stability was re-established, each time the pump was moved to a new highly permeable zone. Purge volume calculations were based on borehole volume alone, since it was impossible to estimate the volume of water contained in the cavernous portion of the open interval.

Water samples collected by the City of Tallahassee were analyzed for major ions, nutrients, dissolved organic carbon, trace elements, and volatile organic compounds by the City of Tallahassee Water-Quality Laboratory. The USGS collected water samples following methods described in the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). Water samples collected by the USGS were analyzed for tracers (including isotopes of oxygen, hydrogen, and strontium) and age-dating indicators (including tritium and sulfur hexafluoride). The samples collected by the USGS were analyzed at USGS research laboratories, including the Stable Isotope and Groundwater Dating Laboratories in Reston, Virginia, and the Tritium and Radiogenic Isotope Laboratories in Menlo Park, California.

Source Tracers

The stable isotopes of hydrogen ($^2\text{H}/\text{H}$) and oxygen ($^{18}\text{O}/^{16}\text{O}$) are naturally occurring tracers that were used to determine whether the high-flow zones in CW32 produce water from similar sources. Rainfall around the world contains a consistent ratio of $^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/\text{H}$ known as the “global meteoric water line” (GMWL; Craig, 1961). Isotope data are presented using delta (δ) notation, expressed as the ratio of the heavy to the light isotope, normalized to a standard:

$$\delta_{\text{sample}} = 1,000[(R_{\text{sample}}/R_{\text{standard}}) - 1] \quad (1)$$

where R_{sample} and R_{standard} are the ratio of the heavy to the light isotope in the sample and in the standard, respectively. Delta hydrogen-2 ($\delta^2\text{H}$, deuterium) and delta oxygen-18 ($\delta^{18}\text{O}$) are reported relative to Vienna Standard Mean Ocean Water (Coplen and others, 1991). Results are reported in units of per mil (parts per thousand).

The isotopic variability along the GMWL depends on several factors, including the origin of storms, rainfall intensity and amount, and atmospheric temperature (Dansgaard, 1964). After rainfall, water at land surface undergoes varying degrees of isotopic fractionation because of evaporation and other kinetic processes. Fractionation imparts a unique isotopic signature on water molecules that is maintained after recharge and allows groundwater to be traced to its source.

Strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) are another natural tracer that was used to determine the geologic formation from which each highly permeable zone in CW32 yields water. Each formation has a unique range of isotopic ratios that correspond to the $^{87}\text{Sr}/^{86}\text{Sr}$ composition of the shallow seas in which the deposition of aquifer materials occurred. Groundwater reflects the same isotopic ratio as its host rock, so the source formation can be determined by comparing the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of a water sample with the known ratios of each aquifer formation (Katz and Bullen, 1996).

Age Dating

Sulfur hexafluoride (SF_6) and tritium (^3H) data were used to determine the similarity in age of the water from each of the highly permeable zones in CW32, thereby determining the connectedness of the flow system. Groundwater “age” is defined as the length of time a parcel of water has been isolated from the atmosphere, typically when water recharges to the groundwater system. Sulfur hexafluoride is a known greenhouse gas and is primarily used as an electrical insulator in high-voltage switches (Busenberg and Plummer, 2000). The atmospheric concentration of SF_6 has steadily increased since the 1960s, which makes it useful for dating groundwater that has recharged since that time. Atmospheric moisture carries SF_6 from the atmosphere to the surface, where it enters the groundwater system. A sample of water withdrawn from the groundwater flow system can then be dated by comparing the concentration of SF_6 in the sample with known atmospheric concentrations over time (Busenberg and Plummer, 2000).

Tritium (^3H) is a radioactive isotope of hydrogen with a half-life of 12.43 years. Tritium occurs naturally in the Earth’s atmosphere, but levels rose sharply after hydrogen bomb testing began in the 1950s. The concentration of ^3H has steadily declined since 1963, when above-ground testing was banned, and now approaches natural background levels. Rainfall typically contains the same concentration of ^3H as the atmosphere in which the rainfall originated, and this concentration is maintained as it recharges the groundwater. Radioactive decay, however, prevents ^3H from being used, in the absence of other properties needed for corrections, to date groundwater in the way SF_6 is used. Tritium by itself is useful for qualifying whether groundwater contains a mixture of young and old “pre-bomb” water. Water containing no measurable ^3H has been isolated from the atmosphere since at least the mid-1950s (Ingraham, 1998).

Results

Three zones of high permeability were identified in the CW32 borehole. Water-quality, tracer, and age-dating results indicate that the open interval of CW32 produces water of consistent and high quality throughout its length. The cavernous nature of the open interval makes it likely that the highly permeable zones are interconnected in the aquifer by secondary porosity features.

Borehole-Geophysical Data

Borehole-geophysical data collection was completed in CW32 during December 2–3, 2013, to delineate zones of high permeability and support collection of depth-dependent groundwater samples. OBI and ABI data indicated that below 343 ft bls the lithology appeared to be limestone with several large interconnected cavities. On the basis of caliper data, the cavities exceed 26 in. in diameter, the maximum diameter to which the caliper arms can extend. One such cavity is 15 ft long and is located 350 to 365 ft bls (appendixes 1 and 2). On the basis of borehole image and caliper data, the borehole wall above 343 ft bls also appears to be limestone containing strata of varying porosity. In the interval above 343 ft bls, the caliper remained fully engaged with the borehole wall and the diameter was consistently less than 14 in.

Borehole fluid, natural gamma, and electromagnetic-induction data indicated results similar to the image logs, whereby there was a noticeable difference in the data above and below 343 ft (appendixes 1 and 2). Minor changes in fluid properties, a decrease in fluid temperature, and an increase in specific conductance were observed at about 305 and 390 ft bls. Natural gamma and EM induction data had higher values and a greater range that varied with borehole diameter, indicating that the lithology above and below 343 ft bls may be similar and that the differences could be the result of changes in borehole diameter. In the cavernous section below 343 ft, the data from the full waveform sonic tool were unreliable due to borehole diameter, except where the borehole wall was close to the drilled diameter.

Under ambient flow conditions prior to pumping from the well, the SFM was logged both up and down the well bore, and no observable flow was detected. The lack of measurable flow is substantiated by the change in fluid properties with depth, especially the change in fluid conductance. The change in conductance with depth is an indication that no flow or mixing occurs over the length of the open-hole section under ambient conditions.

Under pumping conditions, most of the inflow from CW32 (as indicated by a change in counts per second of the SFM) originated from between 339 and 350 ft bls. This zone accounted for about 38 percent of the total well discharge. This zone of inflow may extend deeper to 365 ft bls, but flow within the cavernous zone cannot be measured with accuracy

(appendixes 1 and 2). Smaller zones of inflow were noted by the SFM data in the intervals 307–311 ft and 387–390 ft bls, with each accounting for about 25 percent of the total discharge. The pumped flow data were collected after an electrical submersible pump was installed in CW32. No testing was performed until after the rate of discharge stabilized. An inline flowmeter was installed on the pump discharge line, but it did not appear to operate properly, perhaps because of cavitation within the line. The flow rate was estimated to be about 550 gal/min using a bucket and stopwatch. Attempts were made to run the pump at varying speeds, but there was no apparent change in the rate of discharge. The lack of apparent change was supported by different logging runs of the SFM, which indicated no difference in flow velocity as the pump speed was varied.

Approximately 3 hours after the pump was stopped and removed from CW32, the WQT was run a second time to determine how quickly fluid properties return to ambient pre-pumping conditions. Higher fluid conductance values were logged in the section above 343 ft bls (316 microsiemens per centimeter ($\mu\text{S}/\text{cm}$) at 25 degrees Celsius versus 260 $\mu\text{S}/\text{cm}$ under ambient conditions) than were recorded prior to the test (appendix 1). These data are an indication that the 550 gal/min pump rate was sufficient to induce flow over the entire open interval of the test well. Minor changes in other borehole fluid properties, including temperature, pH, percent oxygen, and redox potential, were similar to the pre-pumping ambient conditions.

Following analyses of all the borehole-geophysical data, three highly permeable zones were delineated within the logged open interval of CW32 at 307–311 ft, 339–350 ft, and 387–390 ft. Pump placement was limited by the 20-ft length of each section of drop pipe attached to the pump and by the length of the pump housing itself, so it was not always possible to place the pump intake exactly adjacent to a permeable zone. Therefore, discrete depth-dependent water samples were collected at 301, 343, and 385 ft bls.

Water-Quality Data

Water-quality data, including major ions, nutrients, trace elements, and volatile organic compounds, were consistent between samples with the exceptions of lead, copper, zinc, and toluene (tables 1, 2). Stiff diagrams, prepared using major ion data from each of the four samples, are nearly identical in shape (fig. 2). A Stiff diagram graphically displays the proportion of major ions in individual samples in a way that allows rapid visual comparison of the data on the basis of shape. The similarity of the major ion composition of the four samples indicates that the water has followed similar flow paths through the aquifer system.

Concentrations of lead, copper, zinc, and toluene tended to increase with depth, but were below established drinking

water criteria (U.S. Environmental Protection Agency, 2014). It is unlikely that these constituents are present in the aquifer at the concentrations found in the samples. The samples likely were contaminated as the water passed through the drop pipe that supported the submersible pump. The pipe joints were coated with thread lubricant (pipe dope) at the connections, and all four of these substances are common ingredients in this type of lubricant. The galvanized finish on the pipes also may have contributed to sample contamination, especially with zinc, as it is the primary ingredient used in the galvanization process.

Source Tracers

Results for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ tracer data indicate that all four water samples originated from a similar source that is slightly enriched in isotopic composition compared to meteoric waters. Values for $\delta^{18}\text{O}$ ranged from -2.69 to -2.78 per mil, whereas $\delta^2\text{H}$ values ranged from -12.9 to -15 per mil (fig. 3). Water produced by CW32 contains a fraction of water recharged from a standing surface-water source, on the basis of the slightly enriched isotopic signature found in all of the samples collected from the test well. The composite sample was the most enriched of all the samples, likely because this sample contained a relatively large fraction of water recharged from standing surface-water sources. The higher pump rate (550 gal/min) used during the collection of the composite sample likely drew water in from shallower sources. The surface water could originate through a short-circuit pathway such as a sinkhole. Several sinkhole lakes and ponds are upgradient from CW32, including Lake Iamonia in the Summerbrooke Subdivision, and could be a source of this surface water. Alternatively, surface water could be drawn into the aquifer as a consequence of aquifer pumping at a point distant from the test well. This finding is consistent with results inferred for a site near this location and reported by Katz and others (1997), who determined that several City of Tallahassee production wells pumped groundwater mixed with a small percentage of surface water even though the wells were greater than about 200 ft deep.

Results for $^{87}\text{Sr}/^{86}\text{Sr}$ analyses indicate that water from all four samples followed a similar flow path through the Upper Floridan aquifer. Katz and Bullen (1996) analyzed rock cores collected from the Upper Floridan aquifer and determined that $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for Eocene-aged Ocala Limestone vary from 0.7081 to 0.7085 per mil. Isotopic ratios in the four water samples collected at CW32 ranged from 0.70824 to 0.70829 per mil, indicating that the Ocala Formation within the Upper Floridan aquifer is clearly the primary source of water to the test well (fig. 4). This result is expected because the open interval in the test well likely spans all or most of the Ocala Formation according to published estimates of aquifer depth and thickness (Miller, 1986).

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Table 1. Major ions, nutrients, and trace elements in groundwater samples collected at the City of Tallahassee test well 32, (U.S. Geological Survey site 303408084152300 COT 440 ft UFA Test Well at Tallahassee, FL), December 2013.

[ft, feet; EST, Eastern Standard Time; CaCO₃, calcium carbonate; µg/L, micrograms per liter; <, less than; mg/L, milligrams per liter; CU, color units; ND, no data; N, nitrogen; TON, threshold odor number; NOD, no odor detected; °C, degrees Celsius; Ca, calcium; NTU, nephelometric turbidity units]

Sample description	Composite sample from 300 to 440 ft	Depth-dependent sample at 301 ft	Depth-dependent sample at 343 ft	Depth-dependent sample at 385 ft
Date (EST)	12/3/2013	12/4/2014	12/4/2013	12/4/2013
Time	1600	1500	1400	1200
Alkalinity, mg/L CaCO ₃	ND	176	175	175
Antimony, total, µg/L	<2.49	<2.49	<2.49	<2.49
Arsenic, total, µg/L	<1.39	<1.39	<1.39	<1.39
Cadmium, total	<0.09	<0.09	<0.09	<0.09
Chloride, mg/L	ND	3.8	3.9	3.9
Color, CU	ND	<1	<1	<1
pH	ND	7.7	7.7	7.7
Fluoride, mg/L	ND	<0.20	<0.19	<0.19
Chlorine, free available, mg/L	<0.0	<0.0	<0.0	<0.0
Lead, total, µg/L	<1.32	<1.32	1.87	3.32
Mercury, total, µg/L	<0.42	<0.42	<0.42	<0.42
Aluminum, total, µg/L	<2.68	<2.68	<2.68	<2.68
Barium, total, µg/L	4.93	4.88	4.91	4.82
Beryllium, total, µg/L	<0.15	<0.15	<0.15	<0.15
Calcium, total, mg/L	47.0	47.9	47.9	47.0
Chromium, total, µg/L	2.43	2.21	2.31	2.05
Cobalt, total, µg/L	<0.31	<0.31	<0.31	<0.31
Copper, total, µg/L	<0.36	<0.36	2.05	3.56
Iron, total, µg/L	11.5	9.21	21.4	5.90
Magnesium, total, mg/L	14.2	13.8	13.2	14.4
Manganese, total, µg/L	<1.88	<1.88	<1.88	<1.88
Molybdenum, total, µg/L	<1.17	<1.17	<1.17	<1.17
Nickel, total, µg/L	<1.17	<1.17	<1.17	<1.17
Strontium, total, µg/L	84.1	82.5	81.7	81.9
Vanadium, total, µg/L	1.85	1.57	1.69	1.56
Zinc, total, µg/L	5.81	116	148	172
Nitrogen, nitrate by difference, mg/L as N	ND	0.230	0.240	0.210
Nitrogen, nitrite, mg/L as N	ND	<0.001	<0.001	<0.001
Nitrogen, nitrite plus nitrate, mg/L as N	ND	0.230	0.240	0.210
Odor, threshold, TON	ND	NOD	NOD	NOD
Potassium, total, mg/L	0.50	0.39	0.42	0.34
Selenium, total, µg/L	<0.84	<0.84	<0.84	<0.84
Silica, dissolved, mg/L	ND	15.86	16	15.97
Sodium, total, mg/L	2.52	2.48	2.51	2.45
Sulfate, total, mg/L	ND	1.8	1.8	1.9
Residue, total filterable @ 180 °C, mg/L	ND	202	198	197
Hardness, mg/L as Ca	ND	181	177	183
Carbon, total organic, mg/L	ND	0.4	0.4	0.4
Turbidity, NTU	ND	0.19	0.18	0.10

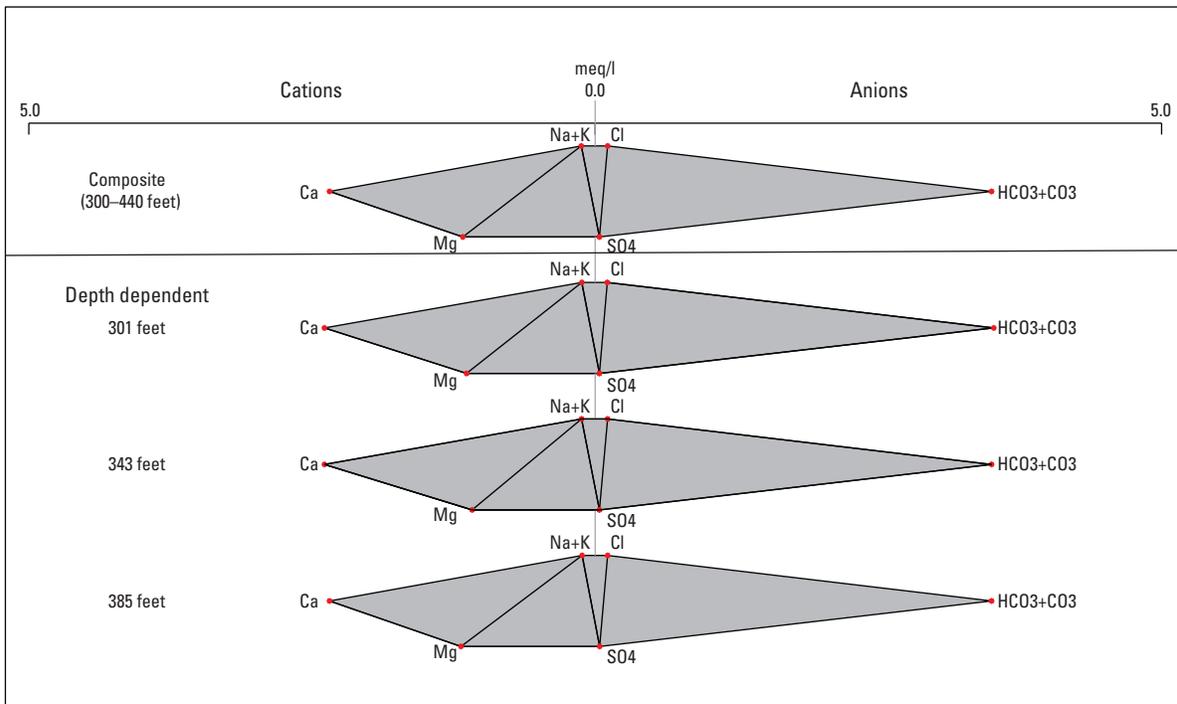


Figure 2. Stiff diagrams comparing the major ion concentrations of four water samples collected at the City of Tallahassee test well 32, December 2013.

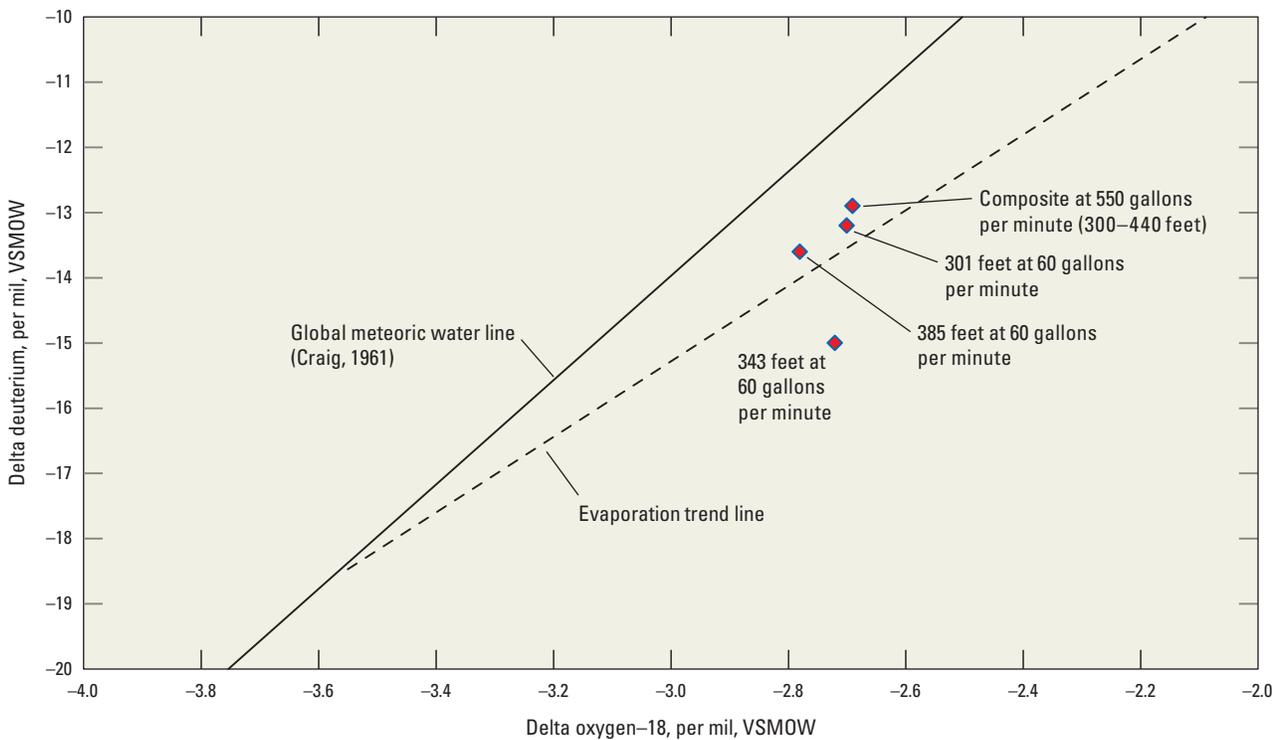


Figure 3. Content of delta deuterium and delta oxygen-18 in water samples collected from the City of Tallahassee test well 32 relative to the global meteoric water line in December 2013.

8 Depth-Dependent Groundwater Quality Sampling at City of Tallahassee Test Well 32, Leon County, Florida, 2013

Table 2. Volatile organic compounds in groundwater samples collected from City of Tallahassee test well 32 (U.S. Geological Survey site 303408084152300 COT 440 ft UFA Test Well at Tallahassee, FL), December 2013.

[EST, Eastern Standard Time]

Sample description	Concentration of organic compounds, in micrograms per liter			
	Composite sample from 300 to 440 feet	Depth-dependent sample at 301 feet	Depth-dependent sample at 343 feet	Depth-dependent sample at 385 feet
Date	12/3/2013	12/4/2013	12/4/2013	12/4/2013
Time (EST)	1600	1500	1400	1200
1,1,1,2-Tetrachloroethane	<0.030	<0.030	<0.030	<0.030
1,1,1-Trichloroethane	<0.030	<0.030	<0.030	<0.030
1,1,1,2-Tetrachloroethane	<0.040	<0.040	<0.040	<0.040
1,1,2-Trichloroethane	<0.030	<0.030	<0.030	<0.030
1,1-Dichloroethane	<0.030	<0.030	<0.030	<0.030
1,1-Dichloroethylene	<0.040	<0.040	<0.040	<0.040
1,1-Dichloropropene	<0.030	<0.030	<0.030	<0.030
1,2,3-Trichlorobenzene	<0.060	<0.060	<0.060	<0.060
1,2,3-Trichloropropane	<0.150	<0.150	<0.150	<0.150
1,2,4-Trichlorobenzene	<0.040	<0.040	<0.040	<0.040
1,2,4-Trimethylbenzene	<0.030	<0.030	<0.030	<0.030
1,2-Dibromo-3-chloropropane	<0.020	<0.020	<0.020	<0.020
1,2-Dibromoethane	<0.070	<0.070	<0.070	<0.070
1,2-Dichlorobenzene	<0.030	<0.030	<0.030	<0.030
1,2-Dichloroethane	<0.030	<0.030	<0.030	<0.030
1,2-Dichloropropane	<0.030	<0.030	<0.030	<0.030
1,3,5-Trimethylbenzene	<0.030	<0.030	<0.030	<0.030
1,3-Dichlorobenzene	<0.040	<0.040	<0.040	<0.040
1,3-Dichloropropane	<0.030	<0.030	<0.030	<0.030
1,4-Dichlorobenzene	<0.040	<0.040	<0.040	<0.040
2,2-Dichloropropane	<0.040	<0.040	<0.040	<0.040
2-Chlorotoluene	<0.020	<0.020	<0.020	<0.020
4-Chlorotoluene	<0.030	<0.030	<0.030	<0.030
Benzene	<0.040	<0.040	<0.040	<0.040
Bromobenzene	<0.030	<0.030	<0.030	<0.030
Bromochloromethane	<0.040	<0.040	<0.040	<0.040
Bromodichloromethane	<0.040	<0.040	<0.040	<0.040
Bromoform	<0.080	<0.080	<0.080	<0.080
Bromomethane	<0.100	<0.100	<0.100	<0.100
Carbon tetrachloride	<0.030	<0.030	<0.030	<0.030
Chlorobenzene	<0.030	<0.030	<0.030	<0.030
Chloroethane	<0.050	<0.050	<0.050	<0.050
Chloroform	<0.100	<0.100	<0.100	<0.100
Chloromethane	<0.080	<0.080	<0.080	<0.080
<i>cis</i> -1,2-Dichloroethylene	<0.030	<0.030	<0.030	<0.030
<i>cis</i> -1,3-Dichloropropylene	<0.030	<0.030	<0.030	<0.030
Dibromochloromethane	<0.040	<0.040	<0.040	<0.040

Table 2. Volatile organic compounds in groundwater samples collected from City of Tallahassee test well 32 (U.S. Geological Survey site 303408084152300 COT 440 ft UFA Test Well at Tallahassee, FL), December 2013.—Continued

[EST, Eastern Standard Time]

Sample description	Concentration of organic compounds, in micrograms per liter			
	Composite sample from 300 to 440 feet	Depth-dependent sample at 301 feet	Depth-dependent sample at 343 feet	Depth-dependent sample at 385 feet
Dibromomethane	<0.030	<0.030	<0.030	<0.030
Dichlorodifluoromethane	<0.030	<0.030	<0.030	<0.030
Ethylbenzene	<0.030	<0.030	<0.030	<0.030
Hexachlorobutadiene	<0.040	<0.040	<0.040	<0.040
Isopropylbenzene	<0.020	<0.020	<0.020	<0.020
Methylenechloride	<0.030	<0.030	<0.030	<0.030
MTBE	<0.050	<0.050	<0.050	<0.050
Naphthalene	<0.040	<0.040	<0.040	<0.040
n-Butylbenzene	<0.020	<0.020	<0.020	<0.020
n-Propylbenzene	<0.030	<0.030	<0.030	<0.030
p-Isopropyltoluene	<0.030	<0.030	<0.030	<0.030
sec-Butylbenzene	<0.020	<0.020	<0.020	<0.020
Styrene	<0.040	<0.040	<0.040	<0.040
t-Butylbenzene	<0.030	<0.030	<0.030	<0.030
Tetrachloroethylene	<0.040	<0.040	<0.040	<0.040
Toluene	<0.030	0.490	1.240	1.740
Total Xylenes	<0.050	<0.050	<0.050	<0.050
<i>trans</i> -1,2-Dichloroethylene	<0.030	<0.030	<0.030	<0.030
<i>trans</i> -1,3-Dichloropropylene	<0.040	<0.040	<0.040	<0.040
Trichloroethylene	<0.030	<0.030	<0.030	<0.030
Trichlorofluoromethane	<0.030	<0.030	<0.030	<0.030
Vinyl chloride	<0.030	<0.030	<0.030	<0.030

10 Depth-Dependent Groundwater Quality Sampling at City of Tallahassee Test Well 32, Leon County, Florida, 2013

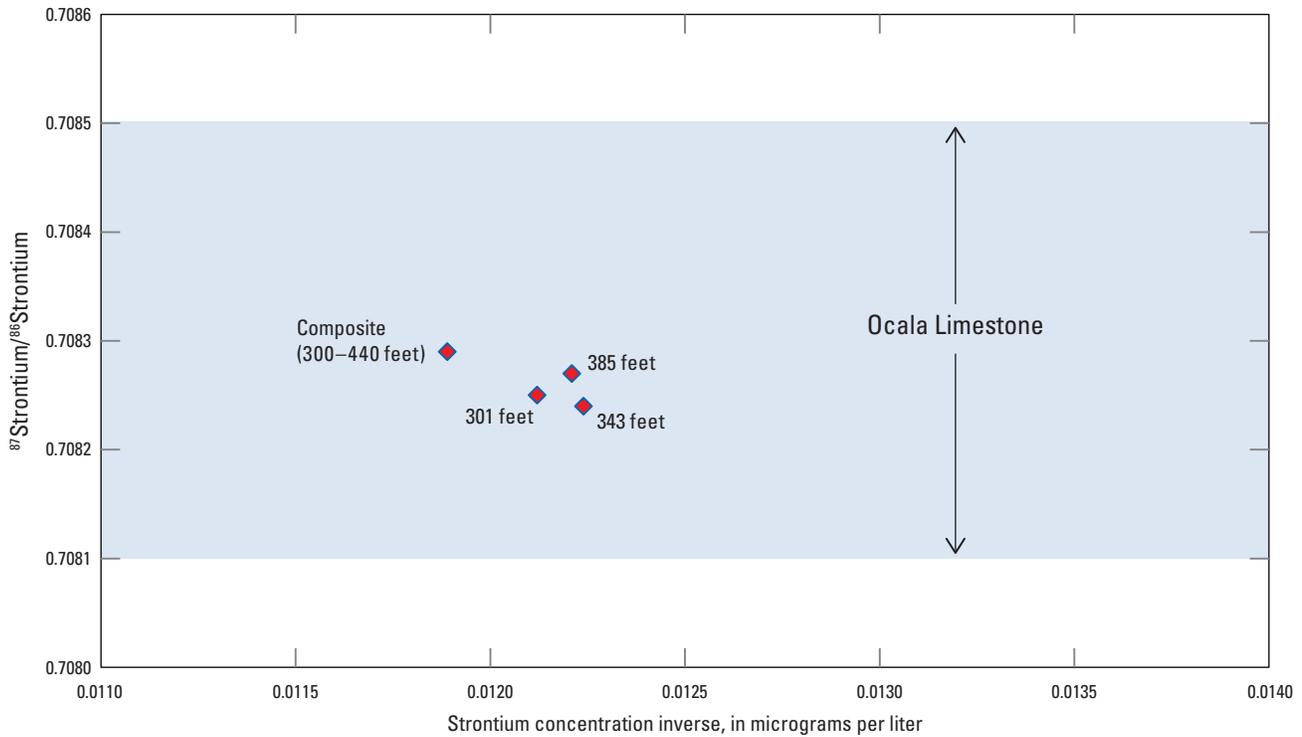


Figure 4. Relation between strontium isotope ratios and the inverse of the strontium concentration in water samples collected at the City of Tallahassee test well 32, December 2013.

Age Dating

SF₆ data indicate that water produced by the CW32 open interval recharged to the groundwater system from 26.2 to 29.4 years ago. The composite sample collected at 550 gal/min yielded the youngest date—26.2 years. The depth-dependent samples ranged in age from 27.4 to 29.4 years; the samples from the greatest depth had the greatest ages (table 3). The piston-flow model used to relate SF₆ concentration to age assumes that a parcel of water moves through a flow system with no mixing, but that is an unlikely scenario in a karst system. Therefore, the modeled ages most likely represent an average age for the mixture of waters produced by the well. The composite sample likely contains a relatively larger fraction of slightly younger water than from the discrete zones because the higher pump rate used during sample collection may have pulled younger water down from the overlying low permeability Hawthorn Group. This conclusion is supported by the $^{87}\text{Sr}/^{86}\text{Sr}$ data because the isotopic ratio of the composite sample was slightly higher

than that of the discrete samples (fig. 4). The Hawthorn Group is known to have higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than the Ocala Formation (Brewster-Wingard and others, 1997).

Tritium data corroborate the groundwater ages determined by SF₆ dating and verify that most of the water produced by CW32 recharged to the groundwater system after hydrogen-bomb testing began in 1952. Tritium concentrations in the samples varied from 1.15 to 1.4 tritium units (TU; table 3). When the CW32 data are corrected for radioactive decay, using the range of recharge ages calculated from SF₆ data, the concentration of ^3H ranged from 5.0 to 7.0 TU at the time of recharge. The average ^3H concentration in rainfall at Ocala, Fla., was 9.9 TU in 1984 and decreased to 4.7 TU by 1988 (International Atomic Energy Agency, 2014); therefore, ^3H data measured in this study support the calculated dates for SF₆ recharge. Water recharged prior to 1952 would contain ^3H at levels well below the 0.3 TU reporting limit of the analysis because the half-life of ^3H is 12.43 years. CW32 likely produces little or no water recharged prior to 1952.

Table 3. Field measurements, tracer, and age data collected from City of Tallahassee test well 32, (U.S. Geological Survey site 303408084152300 COT 440 ft UFA Test Well at Tallahassee, FL), December 2013.

[EST, Eastern Standard Time; ft blw LSD, feet below land surface datum; gal/min, gallons per minute; min, minutes; °C, degrees Celsius; μS/cm, micro-siemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; NTRU, nephelometric turbidity ratio units; CaCO₃, calcium carbonate; avg, average; fg/kg, femtograms per kilogram; std, standard; δ¹⁸O, oxygen-18 to oxygen-16 ratio; δ²H, hydrogen-2 to hydrogen ratio, reported relative to Vienna Standard Mean Ocean Water (VSMOW); ³H, tritium; TU, tritium units; ⁸⁷Sr/⁸⁶Sr, strontium-87 to strontium-86 ratio]

Sample description	Composite sample from 300 to 440 feet	Depth-dependent sample at 301 feet	Depth-dependent sample at 343 feet	Depth-dependent sample at 385 feet
Date	12/3/2013	12/4/2013	12/4/2013	12/4/2013
Sample start time (EST)	1600	1500	1400	1200
Water level, ft blw LSD	194	194	194	194
Flow rate, gal/min	550	60	60	60
Pumping period, min	55	24	28	60
Sampling depth, ft blw LSD	300	301	343	385
Water temperature, °C	20.9	20.9	21.4	21.3
Specific conductance (field), μS/cm	330	340	339	344
pH (field)	7.4	7.4	7.4	7.5
Dissolved oxygen (field), mg/L	3.9	3.4	0.3	2.8
Turbidity (field), NTRU	1	0.4	0.3	0.3
Alkalinity (field), mg/L as CaCO ₃	176	185	183	184
Bicarbonate (field), mg/L	214	225	222	224
Carbonate (field), mg/L	0.4	0.3	0.3	0.3
Sulfur hexafluoride (SF ₆) (avg), fg/kg	191.5	152.5	146	117.5
Sulfur hexafluoride (SF ₆) piston flow model age (avg), years	26.2	27.4	27.7	29.4
Sulfur hexafluoride (SF ₆) piston flow model recharge year (avg)	1988	1986.5	1986	1984.5
δ ¹⁸ O, VSMOW	-2.69	-2.7	-2.72	-2.78
δ ² H, VSMOW	-12.9	-13.2	-15	-13.6
³ H, TU	1.15	1.40	1.27	1.34
⁸⁷ Sr/ ⁸⁶ Sr	0.708	0.708	0.708	0.708

Summary and Conclusions

The U.S. Geological Survey, in cooperation with the City of Tallahassee, completed a study to delineate high-permeability zones in the Upper Florida aquifer that have substantial rates of groundwater flow and to characterize changes in water quality with depth in the borehole of test well CW32 (CW32). Borehole-geophysical data were used to delineate high-permeability zones in the open interval of CW32. Water-chemistry data were used to determine the quality of water in the test well. Naturally occurring tracers were used to determine whether the high-flow zones in CW32 produce water from similar sources, whereas age-dating was used to determine the approximate date of recharge

(approximately 26 to 29 years ago) and if water from each of the highly permeable zones in CW32 is of similar age.

The open interval in CW32 produces water of similar (consistently) high quality throughout its length. Results of water-quality, tracer, and age-dating analyses indicate that the quality, source, flow path, and age of the water produced by CW32 are comparable in each of the three highly permeable zones identified using geophysical techniques. The cavernous nature of much of the open interval is an indication that the three productive zones are likely interconnected in the aquifer system by secondary porosity features. Changes to the CW32 open interval, as constructed during testing, would likely provide little or no improvement in the high-quality water produced by the well.

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Appendix 1. Comparison of borehole image, geophysical, water quality, flowmeter, and sonic logs showing evidence of three productive intervals in the City of Tallahassee test well 32 at Leon County, Florida, December 2013. Only the data collected in the open interval of the test well are displayed at 1 to 96 scale.

File can be downloaded from <http://pubs.usgs.gov/of/2014/1255/>.

Appendix 2. Comparison of borehole image, geophysical, water quality, flowmeter, and sonic logs showing evidence of three productive intervals in the City of Tallahassee test well 32 at Leon County, Florida, December 2013. The full geophysical log is displayed at 1 to 12 scale.

File can be downloaded from <http://pubs.usgs.gov/of/2014/1255/>.

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Edited by Kay P. Naugle

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For more information concerning this report, contact:

Director

U.S. Geological Survey

Caribbean-Florida Water Science Center

4446 Pet Lane, Suite 108

Lutz, FL 33559

(813) 498-5000

or visit our Web site at:

<http://fl.water.usgs.gov>

