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#### GROUND WATER RECHARGE RATES CALCULATED FROM THE ISOTOPIC CONTENT OF GROUND WATER: A PILOT STUDY

by

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The **St. Johns River Water Management District** (SJRWMD) was created by the Florida Legislature in 1972 to be one of five water management districts in Florida. It includes all or part of 19 counties in northeast Florida. The mission of SJRWMD is to manage water resources to ensure their continued availability while maximizing environmental and economic benefits. It accomplishes its mission through regulation; applied research; assistance to federal, state, and local governments; operation and maintenance of water control works; and land acquisition and management.

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## **EXECUTIVE SUMMARY**

This pilot study was conducted to determine if recharge rates derived by using radioactive isotopes to age-date ground water are accurate enough to be used in other areas of the St. Johns River Water Management District where hydrogeologic data are not available. The pilot study area is located in north-central Florida. Five sites were selected for study, one in Clay County and four in Volusia County. Site 1 is located near Brooklyn Lake, in the Keystone Heights area of southwest Clay County. Sites 2 and 3 are located at the Seville fire tower and the Pierson airport, respectively, on the Crescent City Ridge in northwest Volusia County. Site 4 is located at the Tomoka fire tower in the Daytona Beach area of Volusia County. Site 5 is the area surrounding production well 45 of the Daytona Beach wellfield.

Recharge to the Upper Floridan aquifer was estimated for the Volusia County sites using the radioactive isotope tritium (<sup>3</sup>H, or T) to age-date the ground water. Isotopic recharge rates were not estimated for the area near Brooklyn Lake (Clay County) because the analyses using the stable isotopes, deuterium (<sup>2</sup>H, or D) and oxygen-18 (<sup>18</sup>O), indicate that the surface water from the lake has moved vertically and laterally into the Floridan aquifer system. Recharge rates at Brooklyn Lake (Site 1) could not be attributed to ground water flowing sequentially through aquifer systems.

The isotopic analyses at the four sites in Volusia County indicate that the Upper Floridan aquifer contains water with a mixture of ages. The initial T and carbon-14 (<sup>14</sup>C) content of recharge waters has been diluted by mixing within the aquifer. The T content indicates that the Upper Floridan aquifer contains water that probably recharged the aquifer after 1953. The <sup>14</sup>C analyses, corrected for geochemical reactions, indicate that the Upper Floridan aquifer contains water that is approximately 2,800 years older than the water in the surficial aquifer system at the Tomoka fire tower, approximately 6,000 years older than the water in the surficial aquifer system near production well 45 of the Daytona Beach wellfield, and approximately 9,400 years older than water in the surficial aquifer system at the Pierson airport. The disparity in ages between the T and <sup>14</sup>C analyses and the disparity within the <sup>14</sup>C analyses were not surprising because the Upper Floridan aquifer wells at the Pierson airport, the Tomoka fire tower, and near production well 45 penetrate 80, 158, and 159 feet, respectively, into the aquifer. In addition, the Upper Floridan aquifer is comprised of carbon-12, which dissolves and dilutes the <sup>14</sup>C concentrations in recharge water, thereby giving anomalous old dates. The T age-date value of 38 or 39 was used to estimate recharge (i.e., water that has recharged the Floridan aquifer since 1953).

Recharge rates estimated using isotopes were greater than or equal to 5.8, 11.7, 8.1, and 8.4 inches per year at the Seville fire tower, the Pierson Airport, the Tomoka fire tower, and near production well 45, respectively. These recharge rates are remarkably similar to those previously published, which are based on leakance values. The agreement between these two methods implies that recharge rates estimated from the isotopic composition of ground water can be determined reliably in other areas of the St. Johns River Water Management District where hydrogeologic data, used in determining leakance values, are missing. Site-specific recharge to the Upper Floridan aquifer can be estimated reliably using the T isotope. Care should be taken, however, when selecting Upper Floridan aquifer wells for measurement. The potential for mixing different-aged waters is greatest when an Upper Floridan well has a large open-hole interval. Because of this potential, only Upper Floridan aquifer wells with small open-hole intervals that penetrate less than 26 feet of the aquifer should be used.

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## INTRODUCTION

This pilot study was conducted to determine if recharge rates estimated using radioactive isotopes (tritium [<sup>3</sup>H, or T] and carbon-14 [<sup>14</sup>C]) to age-date ground water are accurate enough to be used in other areas of the St. Johns River Water Management District (SJRWMD) where hydrogeologic data (such as the presence and thickness of confining layers) are not available. The natural recharge rates for the Upper Floridan aquifer were determined at point locations on the Crescent City Ridge and in the Daytona Beach area (Figure 1) by using radioactive isotopes to age-date ground water. Stable isotopes (deuterium [<sup>2</sup>H, or D] and oxygen-18 [<sup>18</sup>O]) were used to determine the origin of water in the aquifer systems. The accuracy of using isotopes to estimate recharge was assessed by comparing these recharge rates with those obtained from leakance calculations. Isotopic analyses were conducted in the Keystone Heights area (Site 1, Figure 1); however, natural recharge rates were not determined because the criteria for good estimates of age were not met.

The remainder of this chapter covers introductory material regarding recharge, such as definition, mechanics, and rates.

#### **DEFINITION OF RECHARGE**

Recharge is the addition of water to a saturated zone. For the purposes of this report, recharge is the percolation of water in a downward direction from the ground surface to the water table and from the water table to underlying aquifers. Areas where additions of meteoric water to ground water occur are called recharge areas. Recharge occurs naturally as part of the hydrologic cycle. Rainfall is the ultimate source for all recharge.

#### **MECHANICS OF RECHARGE**

Rainfall and surface water that reach the water table through recharge become ground water. Ground water can move



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#### Figure 1. Pilot study area showing site locations

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vertically from one aquifer to another. This movement is controlled by the difference in hydraulic head between two aquifers. Hydraulic head is defined as the water level elevation with respect to mean sea level (msl). When water level elevations in the water table are higher than in an underlying aquifer, water moves downward and the underlying aquifer is recharged. Conversely, ground water moves toward the water table when the water level elevation in an underlying aquifer is higher than the water table—discharge occurs from the underlying aquifer into the ground water table. Ground water flows from recharge areas to discharge areas that are normally in topographically low places, such as stream valleys, lakes, wetlands, and the sea.

In this study area, recharge generally occurs in topographically high areas with well-drained, sandy soils, that have high vertical permeability. Conversely, recharge is retarded in fine-grained deposits of clay and silt, which have low vertical permeability. The presence of these deposits in the subsurface greatly retards downward percolation of water and commonly results in a perched water table, a condition in which unconfined ground water is separated from an underlying aquifer by an unsaturated zone.

#### **RATE OF RECHARGE**

Recharge rates usually are calculated from hydrogeologic data such as leakance values and the differences in hydraulic head between aquifer systems. The rate of recharge is directly proportional to the difference in hydraulic head between aquifers and the leakance value. Leakance is defined as the vertical hydraulic conductivity of confining units, such as clays, divided by the thickness of the confining units. This rate does not rely on the age of ground water.

The rate of recharge estimated using isotopes is directly proportional to the distance between the depth to the top of the Floridan aquifer system and the water table and inversely proportional to the age of ground water. The distance is easily measured. Age is an unknown—it is the time that has lapsed since recharge.

In this pilot study, age was determined by measuring the concentration of radioactive isotopes T and <sup>14</sup>C. Tritium was used because it identifies water that is less than 70 years old. Carbon-14 was used because it identifies water that is less than 50,000 years old.

In addition to radioactive isotopes, the concentrations of the stable isotopes D and <sup>18</sup>O were measured. The concentrations of the stable isotopes D and <sup>18</sup>O identify the origin of ground water. These latter isotopes were used to determine that only one source of ground water was present and that water was moving vertically downward through the aquifer systems.

## **PILOT STUDY AREA**

The pilot study area is located in north-central Florida. Five sites were selected for study, one in Clay County and four in Volusia County. Site 1 is located near Brooklyn Lake, in the Keystone Heights area of southwest Clay County. Sites 2 and 3 are located at the Seville fire tower and the Pierson airport, respectively, on the Crescent City Ridge in northwest Volusia County. Site 4 is located at the Tomoka fire tower in the Daytona Beach area of Volusia County. Site 5 is the area surrounding production well 45 of the Daytona Beach wellfield. These sites were selected because the locations were in known recharge areas for the Upper Floridan aquifer (Figure 2) and because most of the sites already contained a cluster of observation wells screened or open to different aquifers.

The rate of recharge is influenced by topography, climate, and the hydrogeologic framework. The key parameters to recharge depend on the depth of the water table, the depth to the top of the Floridan aquifer system, the presence and thickness of the confining unit, and the amount of rainfall. Rainfall generally maintains the water table. The water table is generally a subdued reflection of the topography and may lie a few to several tens of feet below land surface.

#### TOPOGRAPHY

The topography of the Keystone Heights, Crescent City Ridge, and Daytona Beach areas is characterized by a series of terraces, or step-like surfaces of increasing elevation, which are the result of wave erosion and deposition during the retreat of sea level during the ice ages of the Pleistocene Epoch. These marine terraces have been dissected by varying degrees of erosion and are capped by thin surficial sands. The terraces, as described by Cooke (1945) and Healy (1975), are the Silver Bluff (0-10 feet [ft] above msl), the Pamlico (10-25 ft above msl), the Talbot (25-42 ft

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Figure 2. Amount of recharge to the Floridan aquifer system in the pilot study area (in inches per year) (modified from Boniol et al. 1993). Site 2 is located in a recharge area of 8-12 inches/year, an area too small to be distinguishable on the map.

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above msl), the Penholloway (42–70 ft above msl), the Wicomico (70–100 ft above msl), and the Sunderland (100–170 ft above msl).

Many small lakes occur in southwest Clay County. Many of these lakes occupy sinkholes formed by the dissolution of limestone in the underlying formations (Fairchild 1977). This type of topography is called karst, and drainage is to the subsurface (Bentley 1977). Karst is a term applied to topography that describes any landscape conspicuously influenced by subsurface dissolution of rock. Brooklyn Lake is one of the many small lakes. Site 1 occurs approximately 100 ft from the edge of Brooklyn Lake and has a surface elevation of approximately 145 ft above msl.

The Crescent City Ridge also exhibits karst topographic features resulting from the dissolution of the underlying limestone formations. Such areas are characterized by high relief; a lack of surface drainage features; and the presence of subsurface drainage, sinkholes, and sinkhole-related lakes. Surface elevations at the Seville fire tower and the Pierson airport (Sites 2 and 3) are approximately 42 and 62 ft above msl, respectively.

Karst topography does not occur in the Daytona Beach area. In eastern Volusia County, there are few lakes and no sinkholes. Surface elevations at the Tomoka fire tower (Site 4) and the production well (Site 5) are approximately 43 and 25 ft above msl, respectively.

#### CLIMATE

The climate of the study area is humid subtropical, with a mean annual temperature of 71°F. The average rainfall for the period 1951–80 was 52.84, 53.57, and 48.46 inches/year (in/yr) at the National Oceanographic and Atmospheric Administration stations in Gainesville, Crescent City, and Daytona Beach, respectively. Most of the rainfall was due to convective thundershowers from June through September. Winters are mild and are drier than summers. Most of the rainfall in winter results from frontal activity rather than from convective thunderstorms.

#### HYDROGEOLOGIC FRAMEWORK

The hydrogeologic units in the Keystone Heights, Crescent City Ridge, and Daytona Beach areas are the surficial aquifer system, the intermediate aquifer system or intermediate confining unit, and the Floridan aquifer system (Table 1). Detailed information about the geology and hydrology of these systems can be found in Clark et al. (1963), Bentley (1977), Bermes et al. (1963), Ross and Munch (1980), and Wyrick (1960).

Epoch	Stratigraphic Unit	General Lithology	Hydrogeologic Unit
Holocene Pleistocene	Surficial sands and terrace deposits	Sand, clayey sand, and clay, with some shell locally	Surficial aquifer system
Pliocene	Undifferentiated deposits	Sand, clay, and shell	Intermediate aquifer system or
Miocene	Hawthorn Group	Phosphatic clay, silt, sand, dolomite, and limestones	intermediate confining unit
Eocene	Ocala Limestone	Limestones and dolomitic limestones	Floridan aquifer system
	Avon Park Limestone	Limestones and dolomite	
	Oldsmar Limestone	Limestones and dolomite	
Paleocene	Cedar Keys Formation	Dolomite, some limestone; anhydrite	Floridan aquifer system
		occurs in lower two- thirds of formation	Lower confining unit

 Table 1. Hydrogeologic framework for the pilot study area

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#### Surficial Aquifer System

The sediments of the surficial aquifer system are composed of Holocene and Pleistocene sand, clayey sand, clay, and some shell and Pliocene sand, shell, and clay deposits. Sand and shell deposits have high horizontal and vertical permeability, while clay deposits have low horizontal and vertical permeability. The sand and shell layers vary in thickness, extending from the land surface down to the uppermost areally extensive clay layer, which is less permeable.

Water in the surficial aquifer system is generally unconfined, and its level is free to rise and fall. This unconfined surficial aquifer system is tapped by wells for small to moderate amounts of water, widely used for lawn and garden irrigation. The surficial aquifer system is recharged primarily by rainfall. In coastal areas, the surficial aquifer system also is recharged by upward movement of water from underlying aquifers. Water leaves the system through evapotranspiration, seepage to lakes, discharge to streams and wetlands, leakage to underlying aquifers, and pumpage from wells.

The lithology, texture, and thickness of deposits in the surficial aquifer system vary laterally as well as vertically. The surficial sediments generally range from 20 to 40 ft thick and may be over 90 ft thick in some higher elevations in the sandy ridges (Bermes et al. 1963). The unconsolidated to poorly consolidated sediments generally grade from sand to clayey sand to clay, and the shell beds may have a matrix of sand and/or clay. The clay layers can vary in extent, thickness, and permeability, and thus do not significantly retard the downward movement of water.

#### Intermediate Aquifer System

Directly below the surficial aquifer system lies the intermediate aquifer system. The intermediate aquifer system in the pilot study area consists of Pliocene sand, silt, and clay as well as the phosphatic sand, silt, clay, dolomite, and limestone of the Hawthorn Group of the Miocene Epoch. The intermediate aquifer system is composed of thin, discontinuous layers or lenses of sand, shell, or limestone and yields moderate amounts of water to domestic supply wells. Water in the intermediate aquifer system is confined. The intermediate aquifer system is recharged from the overlying surficial aquifer system or the underlying Floridan aquifer system, depending on hydraulic pressure relationships and the degree of confinement of the intermediate aquifer and Floridan aquifer systems.

The clays within the Pliocene sediments and the Hawthorn Group act as confining units and retard the vertical movement of water among the surficial aquifer, the intermediate aquifer, and the Floridan aquifer systems. The Hawthorn Group is 100 to 150 ft thick at Site 1 and less than 50 ft thick at the other sites (Figure 3). This group contains less than 10% clay units at Site 1 (Scott 1983). No information is available on the thickness of clays within Pliocene sediments or within the Hawthorn Group at the other sites.

#### Floridan Aquifer System

Directly below the intermediate aquifer system lies the Floridan aquifer system. The Floridan aquifer system is the principal source of fresh ground water in SJRWMD and is capable of supplying large quantities of water to wells. Wells drilled into the Floridan aquifer system derive water from fissures and cavities created by the dissolution and fracturing of limestones. The limestones that comprise the Floridan aquifer system act as a single hydrologic unit because the limestones are relatively homogeneous and permeable. Water is confined in the Floridan aquifer system in the study area. The Floridan aquifer system consists of the Ocala, Avon Park, and Oldsmar formations of the Eocene Epoch and part of the Cedar Keys Formation of the Paleocene Epoch. The top of the Floridan aquifer system is 0 to 100 ft below msl at all sites (Figure 4).



Figure 3. Thickness of the Hawthorn Group (in feet)

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Figure 4. Elevation of the top of the limestones of the Floridan aquifer system (in feet below or above mean sea level)

## PROCEDURES

In this pilot study, the procedures involved selecting recharge areas, constructing observation wells where needed, sampling the ground water at each site, and processing the ground water samples for carbon-13 ( $^{13}$ C) and  $^{14}$ C.

#### LOCATING AND DRILLING WELLS

The five study sites are in known recharge areas and in areas where many wells have been drilled into the surficial aquifer system, intermediate aquifer system, or Floridan aquifer system (Table 2). Wells drilled into the Floridan aquifer system were used in this pilot study only if the wells penetrated the upper portion of the Floridan aquifer (Upper Floridan aquifer). These wells penetrated and had an open-hole interval of less than 160 ft of the Upper Floridan aquifer.

If a site did not already have wells for sampling each aquifer system, wells were drilled as needed to provide samples for all three systems. These wells were drilled using the mud-rotary method. Shelby tube samples were collected from clayey layers and sent to Westinghouse Environmental and Geotechnical Services in Altamonte Springs, Florida, for porosity and permeability measurements. These measurements were used to determine the extent to which clay layers act as confining units and to verify leakance values used to calculate recharge rates. Each well was geophysically logged using the gamma ray tool.

#### SAMPLING GROUND WATER

Each well was purged prior to sampling. Purging continued until the temperature, pH, and conductivity did not change by more than 10% between two successive well volumes or until the well was pumped dry. Each well volume equalled the quantity of water in the casing of the well. The number of well volumes taken during the purging generally varied between three and

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Site	Well Number	Aquifer System	Total Well Depth (feet)	Casing Depth (feet)	Land Surface Elevation (feet above sea level)	Water Level (feet above mean sea level)	Sampling Date	Approximate Age (years)
			Keysto	one Helgh	ts Area			
1—Brooklyn Lake	C-0452	Surficial	70	60	145.00	94.22	7/1/91	
						93.96	3/2/92	
						93.70	3/9/92	
	C-0116	Intermediate	144	80	144.74	82.91	3/2/92	
	C-0120	Floridan	250	193	145.16	79.31	7/30/91	Ø
						79.26	9/19/91	
						78.09	3/2/92	
	 					78.23	3/9/92	
			Cres	cent City	Ridge			
2—Seville fire tower	V-0566	Intermediate	52	42	42.00*	24.70	4/1/92	
						<b>24</b> .54⁺	4/13/92	
	V-0184	Floridan	105	80*	41.83	24.09	4/13/92	<39*
3Pierson airport	V-0528	Surficial	23	13	62.26*	59.21	11/19/91	
						59.02*	2/18/92	
	V-0557	Intermediate	98	88	62.10	33.27	2/18/92	
	V-0531	Floridan	210	130*	62.10	24.77	2/18/92	<39*
			Dayto	ona Beach	n Area			
4—Tomoka fire tower	V-0529	Surficial	26	13	43.00*	36.71*	10/28/91	
	V-0546	Intermediate	57	48	43.00	34.39	10/28/91	
1	V-0192	Intermediate	80	60	42.85	32.69	10/15/91	
	V-0188	Floridan	250	92*	42.83	19.68	10/15/91	<38*

#### Table 2. Wells sampled in this pilot study

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#### Table 2—Continued

Site	Well Number	Aquifer System	Total Well Depth (feet)	Casing Depth (feet)	Land Surface Elevation (feet above sea level)	Water Level (feet above mean sea level)	Sampling Date	Approximate Age (years)
		1	Daytona Be	each Area	-continued			
5—Near production well 45 (Daytona Beach wellfield)	V-0543	Surficial	17	7	25.00*	17.87*	8/27/91	
						17.41	10/29/91	
	V-0544	Intermediate	50	40	25.00	18.81	8/27/91	
						18.11	10/29/9	
	V-0545	Intermediate	80	60	25.00	18.48	8/27/91	
						17.84	10/29/91	
	V-0559	Floridan	255	96*	25.00	^	8/27/91	<38*
							10/29/91	

@Not calculated.

\*Values used in recharge calculation (Equation 3).

\*Water level in the surficial aquifer was 24.64 feet above mean sea level on 4/13/92. This value was used in Equation 3. \*Well head is inside a building, so a measurement was not possible. Water samples were taken from a pump outside the building. five. The total volume of water purged prior to sampling ranged from 9 to 555 gallons. Well V-0529 at the Tomoka fire tower (Site 4) was pumped dry twice, and well V-0566 at the Seville fire tower (Site 2) was pumped dry once. If a well was pumped dry, it was considered purged. Well V-0559 (Site 5) was not formally purged; it had been pumping more than 24 hours prior to sampling.

Purging and sampling were done with the same pump. A submersible pump was used when the depth to the water was greater than or equal to 15 ft. A centrifugal pump was used when the depth to the water was less than 15 ft. Initially, a 2-inch submersible pump was not available for purging well C-0452 at Brooklyn Lake (Site 1). The well was purged and sampled using a 1-litre (L) Teflon bailer in July 1991. Subsequent sampling in March 1992 was done with a 2-inch submersible pump.

After purging, water samples were collected for analysis of the following:

Calcium	Ca	Sulfate	$SO_4$ $SiO_2$ $NO_x$ $PO_4-P$ $TDS$ $^{13}C$ $^{14}C$ $D$ $^{18}O$
Magnesium	Mg	Silica	
Sodium	Na	Nitrate and nitrite nitrogen	
Potassium	K	Ortho-phosphate phosphorus	
Chloride	Cl	Total dissolved solids	
Strontium	Sr	Carbon-13	
Barium	Ba	Carbon-14	
Iron	Fe	Deuterium	
Fluoride	F	Oxygen-18	
Fluoride	F	Oxygen-18	<sup>18</sup> O
Alkalinity		Tritium	T

Water samples collected to measure metals (Ca, Mg, Na, K, Sr, Ba, and Fe), anions (alkalinity, Cl,  $SO_4$ ,  $NO_x$ , F,  $PO_4$ -P),  $SiO^2$ , TDS, and isotopes (D, <sup>18</sup>O, and T) first were filtered through 0.45-micron ( $\mu$ ) filters. Nitric acid was then added to preserve the metals. Sample containers for metals, anions,  $SiO_2$ , and TDS were placed on ice until arrival at the SJRWMD laboratory. Also, two 35-millilitre (mL) glass vials were filled with filtered water for D,

<sup>18</sup>O, and T analyses. Samples were filtered for D, <sup>18</sup>O, and T because many surficial and intermediate aquifer samples were milky and contained suspended material. These vials were kept at room temperature (approximately 23°C) until analysis.

Alkalinity was measured in the field on filtered samples to determine the volume of water to be collected for the <sup>13</sup>C and <sup>14</sup>C analyses. A sufficient volume was collected to generally yield approximately 1 gram of carbon. Samples for <sup>13</sup>C and <sup>14</sup>C analyses were collected in 50-L carboys. A minimum of one and a maximum of eight carboys of water were collected from each well.

A control test was conducted to determine if filtering alters the <sup>13</sup>C and <sup>14</sup>C content of the samples. Two Upper Floridan aquifer wells, C-0120 (Site 1) and V-0559 (Site 5), were chosen for the test sampling of <sup>13</sup>C and <sup>14</sup>C. Samples were collected in July 1991 from well C-0120 and in October 1991 from well V-0559. At well V-0559, replicate water samples were taken. Unlike the other samples collected as part of this pilot study, the control samples were not filtered during processing.

#### **PROCESSING SAMPLES**

Water samples were collected from the surficial aquifer and intermediate aquifer systems and the Upper Floridan aquifer for <sup>13</sup>C and <sup>14</sup>C analyses. Most of the samples from the surficial aquifer and intermediate aquifer systems were milky and contained suspended solids; therefore, the samples from all three aquifers were filtered through 0.45-µ glass fibers at the SJRWMD laboratory prior to precipitating the carbonate. The samples were filtered as soon as possible after collection—no more than 9 days elapsed between sample collection and filtration. As soon as each carboy was filtered, sufficient sodium hydroxide (NaOH) pellets were added to adjust the pH to above 12. Adding NaOH to each carboy was done to convert all the dissolved bicarbonate to carbonate. The carbonate then was precipitated by adding a 2-normal (2N) solution of barium-chloride-bihydrate (BaCl<sub>2</sub>·2H<sub>2</sub>O) to each carboy. Additional 2N solution was added to 50-mL

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aliquots from each carboy. If the sample was cloudy, more 2N solution was added to the carboy. This iterative process was performed until the 50-mL aliquots ceased to precipitate material. The amount of 2N solution of  $BaCl_2 \cdot 2H_2O$  added to each carboy ranged from a minimum of 200 mL to a maximum of 800 mL.

The precipitated carbonate was collected by decanting off most of the overlying fluid and then transferring the carbonate solution into a 1-L bottle. This collection was done as soon as possible after addition of the 2N solution of  $BaCl_2 \cdot 2H_2O$ . A minimum of one and a maximum of 19 days elapsed between carbonate precipitation and collection. Most samples were held for less than 19 days.

The 1-L carbonate solutions and the remaining water samples for each well, which did not require processing, were sent by nextday delivery to the Geochron Laboratories Division of Krueger Enterprises in Cambridge, Massachusetts. The water samples from each well were shipped in two 35-mL glass bottles. Geochron Laboratories analyzed T, D, <sup>18</sup>O, <sup>13</sup>C, and <sup>14</sup>C for each sample, reporting maximum errors of ±2.4 tritium units (a tritium unit is one T atom in 10<sup>18</sup> atoms of hydrogen) for T analyses and ±1.8% for <sup>14</sup>C activity.

The control samples for <sup>13</sup>C and <sup>14</sup>C at the two Upper Floridan aquifer wells were not filtered prior to precipitation of the dissolved carbonate. These samples were processed in the same way as the filtered samples. The control sample at well V-0559 (Site 5) was a replicate sample. The other sample was not a control sample and was filtered.

All laboratory results were reviewed to make sure that the results appeared accurate, that is, that no data seemed odd or out of range. The analyses of the one replicate-sample were compared to verify that the results did not differ by more than the reported error of the analyses.

## **ISOTOPES**

Isotopes are atoms of the same element that differ in mass because of a difference in the number of neutrons in the nucleus. There are two types of isotopes: stable and radioactive. Stable isotopes, such as D and <sup>18</sup>O, are used in hydrologic studies to identify sources of water and to learn more about hydrologic processes such as recharge, evaporation, mixing, and water-rock interactions. Radioactive isotopes, such as T and <sup>14</sup>C, are generally used for age-dating the ground water because these isotopes decay over a period of time and the concentrations decrease. The isotopes monitored in this pilot study are D, T, <sup>13</sup>C, <sup>14</sup>C, and <sup>18</sup>O (Table 3).

Element	Isotope	Average Terrestrial Abundance (atom %)	Radioactive Half-Life (years)
Hydrogen	D	0.015	
	Т	<10 <sup>-14</sup>	12.43
Carbon	<sup>12</sup> C	98.90	
	<sup>13</sup> C	1.10	
	<sup>14</sup> C	<10 <sup>-10</sup>	5,715
Oxygen	<sup>16</sup> O	99.762	
	<sup>18</sup> O	0.200	

Table 3.	Radioactive half-life of tritium and carbon-14
	and average terrestrial abundance of some
	common isotopes

Source: Coplen 1993

Half-life is a fundamental property of radioactive isotopes, a measure of decay (the time for a concentration of the isotope to decrease by one-half), and unique for each radioactive isotope.

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The longer the half-life, the older the age that can be determined; that is, the half-life of an isotope determines its utility as a measure of age of ground water.

Other methods recently used for dating ground water rely on measuring the T, helium-3, and helium-4 concentrations, chlorofluorocarbon concentrations, or krypton-85 concentrations (Plummer et al. 1993). Only the radioactive isotopes T and <sup>14</sup>C are measured in this pilot study. Tritium was used because it can identify water that is less than 70 years old. Carbon-14 was used because it can identify water that is less than 50,000 years old.

#### **DEUTERIUM AND OXYGEN-18**

Deuterium and <sup>18</sup>O generally are used to determine the origin of water or to learn more about hydrologic processes. Deuterium and <sup>18</sup>O isotopic ratios have been used to date ground waters between 1,000 and 40,000 years old because long-term climatic changes are reflected in delta ( $\delta$ )-D and  $\delta$ <sup>18</sup>O values (Buchardt and Fritz 1980). For different hydrologic processes, such as evaporation, silicate hydrolysis, and geothermal exchange, the relationship between  $\delta D$  and  $\delta^{18}O$  changes (Figure 5).

The stable isotope content of samples generally is measured as a ratio and reported as a  $\delta$ -value, that is, these isotopes are compared to a standard (Equation 1).

$$\delta = \left[\frac{R_x}{R_{standard}} - 1\right] \mathbf{1},000 \tag{1}$$

where:

δ	=	delta values for a given stable isotope "x" in
		parts per thousand or per mil (‰), relative to a
		standard
R	_	ratio of isotone "x" in the sample (e.g. ${}^{2}H ^{1}H$

$$R_x$$
 = ratio of isotope "x" in the sample (e.g., <sup>2</sup>H|<sup>1</sup>H,  
<sup>18</sup>O|<sup>16</sup>O, or <sup>13</sup>C|<sup>12</sup>C)

= ratio of isotope "x" in the standard (e.g.,  ${}^{2}H|^{1}H$ , R<sub>standard</sub>  $^{18}O|^{16}O$ , or  $^{13}C|^{12}C$ )



Isotope standards represent the concentrations found in specific substances. The standard used for oxygen and hydrogen isotopic values of water is the Vienna Standard Mean Ocean Water (VSMOW). By convention,  $\delta D$  and  $\delta^{18}O$  of VSMOW are assigned a value of 0‰. Carbon-isotope ratios are reported relative to the PeeDee belemnite (PDB) standard. A water sample that had been measured for oxygen isotopes, for example, might be labeled with a  $\delta$ -value of +2‰. The positive  $\delta$ -value means that the sample is enriched in <sup>18</sup>O relative to the standard; in other words, the sample is isotopically "heavy" relative to the standard. A negative  $\delta$ -value indicates the sample is depleted in the isotope relative to the standard; the sample is isotopically "light" relative to the standard.

Different physical, chemical, and biochemical processes affect isotopes differently. Isotopes are fractionated by physical processes, such as diffusion and evaporation, and chemical processes, such as precipitation and dissolution, in proportion to the differences in mass. For example, evaporation concentrates the light isotopes in the vapor and the heavy isotopes in the liquid. Hence, the D and <sup>18</sup>O concentrations of lake water are enriched with the heavier isotopes. By comparing the isotopic composition of a substance to a standard, information about the processes operating on the substance can be obtained.

The Global Meteoric Water (GMW) line represents the relationship between  $\delta D$  and  $\delta^{18}O$  values contained in meteoric water worldwide. Equation 2 represents the GMW line (Craig 1961).

$$\delta D = 8 \cdot \delta^{18} O + 10 \tag{2}$$

where:

 $\delta D$  = delta value for deuterium  $\delta^{18}O$  = delta value for oxygen-18

If values for samples fall on this line, the water originated from rainwater.

Evaporation, evapotranspiration, geothermal reactions, and low temperature silicate hydrolysis produce different  $\delta D$  and  $\delta^{18}O$ relationships compared to the GMW line. Evaporation from surface water bodies is a nonequilibrium process that enriches D and <sup>18</sup>O in the water. Evaporation is represented as a change in the slope of the GMW line from 8 to 3–6 (Coplen 1993). Because of the difference in mass between water containing D and <sup>18</sup>O and water not containing these isotopes, evapotranspiration also enriches ground water in D and <sup>18</sup>O. The enrichment of ground water in D and <sup>18</sup>O due to evapotranspiration has not been quantified but is assumed to be similar to that of evaporation. Of the above processes, evaporation and evapotranspiration are most likely the only processes that have affected the  $\delta D$  and  $\delta^{18}O$ relationship in ground water samples in Florida.

Most samples collected in this pilot study have  $\delta D$  and  $\delta^{18}O$  values that fall along the GMW line (Figure 6 and Table 4). Many samples are connected with a line. The line connecting symbols for each sample indicates the range in values that can be obtained from the same sample by the analysis. Duplicate analyses were performed on the same sample on different days.

The range in values (from 0 to +6 for  $\delta D$  and from -0.1 to -0.8 for  $\delta^{18}O$ ) is striking for samples 4, 5, and 6, which were taken from the same well, C-0120 at Site 1, in different months (Figure 6 and Table 4). These ranges indicate that the  $\delta D$  and  $\delta^{18}O$  content of the Upper Floridan aquifer at Brooklyn Lake could vary monthly.

Site 1

A comparison of the  $\delta D$  and  $\delta^{18}O$  content of samples 1–6 indicates that the Upper Floridan aquifer samples 4–6 (well C-0120) were significantly enriched in the heavier isotopes (by approximately +20 in  $\delta D$  and +4 in  $\delta^{18}O$ ; Figure 6 and Table 4). Ground water analyses were practically identical for samples from the surficial aquifer system (samples 1 and 2 from well C-0452) and samples from the intermediate aquifer system (sample 3 from well C-0116). The enrichment of the Upper Floridan aquifer in the heavier isotopes indicates that evaporation from surface water

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#### GROUND WATER RECHARGE RATES CALCULATED FROM ISOTOPES

Site	Well Number	Sampling Date	Delta Carbon-13 (‰)	Carbon-14 (pmc)	Delta Deuterium (‰)	Delta Oxygen-18 (‰)	Tritium (TU)	Sample Number (Figure 6)
1Keystone Heights	C-0452	7/1/91	-17.6	104.5	-19 -20	-3.9 -3.9	12.5	1
(Brooklyn Lake)	C-0452	3/9/92	-24.6	116.7	-16 -17	-4.3 -4.2	9.9	2
	C-0116	3/2/92	-15.8	81.3	-18 -16	-4.3 -4,2	10.2	3
	C-0120	7/30/91 Unfiltered	-11.4	49.1	0	-0.3	11.2	4
	C-0120	9/19/91	-12.5	50.8	6	-0.8	10.5	5
	C-0120	3/9/92	-12.0	51.3	4 3	-0.2 -0.1	12.0	6
2Seville fire tower	V-0566	4/1/92	-12.9	51.2	-16 -18	-3.4 -3.3	9.7	7
	V-0184	4/13/92	-7.2	54.5	-15 -16	-3.1 -3.3	12.4	8
3—Pierson airport	V-0528	11/19/91	-25.1	85.1	-18	-4.0 -4.1	10.1	9
	V-0557	2/18/92	2.7	11.8	-18 -19	-4.4 -4.3	3.9	10
	V-0531	2/18/92	-10.0	23.2	-13 -11	-3.0 -2.9	9.1	11
4Tomoka	V-0529	10/28/91	-23.3	84.0	-17	-3.2	8.3	12
fire tower	V-0546	10/28/91	-12.4	54.2	-17	-3.0	6.0	13
	V-0192	10/15/91	-10.7	49.2	-16 -14	-2.9	6.4	14
	V-0188	10/15/91	-8.7	31.0	-9 -9	-2.1	6.5	15
5Near	V-0543	10/29/91	-13.2	86.7	-14	-2.8	13.1	16
production well 45 (Daytona Beach	V-0544	10/29/91	-12.1	49.7	-12	-2.1	0.1	17
	V-0545	8/27/91	-9.3	42.3	-9	-2.6 -2.6	4.6	18
wellfield)	V-0559	10/29/91	-9.3	37.2	-9	-2.0	7.7	19
	V-0559	10/29/91 Unfiltered	-9.2	35.7	-10 -11	-2.2	7.3	19

#### Table 4. Isotopic analyses for ground water samples collected in this pilot study

Note: % = parts per thousand or per mil

pmc = percent modern carbon

TU = tritium unit

Cells with two numbers indicate values obtained by analyzing samples on successive days.

bodies probably plays a significant role in the origin of Upper Floridan aquifer water at Site 1. Climatic conditions in the past 50 years probably would not produce an enrichment in the heavier isotopes in the surficial aquifer and intermediate aquifer systems of a magnitude recorded in this pilot study. The most likely source of water enriched in the heavier isotopes comes from nearby Brooklyn Lake. Brooklyn Lake and the Floridan aquifer system are hydraulically connected, and Brooklyn Lake recharges the Floridan aquifer system (Clark et al. 1963). No samples were collected from Brooklyn Lake.

Evapotranspiration from the surficial aquifer system also could enrich water in this system with the heavier isotopes before this water recharges the Upper Floridan aquifer. However, because the water level in the surficial aquifer system near Brooklyn Lake is approximately 50 ft below land surface (land surface elevation minus water level, Table 2), evapotranspiration is assumed to be negligible. Little or no evapotranspiration occurs from the surficial aquifer system when the depth to water is greater than 15 ft (Tibbals 1990).

#### Sites 2-5

An analysis of samples 9–19 indicates that there is a small isotopic shift (change in  $\delta D$  and  $\delta^{18}O$ ) toward heavier isotopes when comparing samples at a site from the surficial aquifer and intermediate aquifer systems and the Upper Floridan aquifer at the Pierson airport (Site 3), the Tomoka fire tower (Site 4), and near production well 45 (Site 5). At the Pierson airport (Site 3), the surficial aquifer system (sample 9 from well V-0528) and the intermediate aquifer system (sample 10 from well V-0557) have similar  $\delta D$  and  $\delta^{18}O$  values. The Upper Floridan aquifer (sample 11 from well V-0531) was enriched in the heavier isotopes. The same trend was observed at Site 4 near the Tomoka fire tower (compare samples 12–15). Near production well 45 (Site 5), the intermediate aguifer system and the Upper Floridan aguifer have similar  $\delta D$  and  $\delta^{18}O$  values but the surficial aquifer system (sample 16) from well V-0543) was enriched in the lighter isotopes. The water level in the surficial aquifer at Sites 3, 4, and 5 was generally less than 8 ft below land surface (land surface elevation minus water level, Table 2). At the Seville fire tower (Site 2), the difference was very minor between the  $\delta D$  and  $\delta^{18}O$  values for the intermediate aquifer system (sample 7)

from well V-0566) and the Upper Floridan aquifer (sample 8 from well V-0184). The different  $\delta D$  and  $\delta^{18}O$  values, when comparing samples at a site from the different aquifer systems, suggest that the aquifer systems were recharged under different climatic conditions and hence indicate that the samples were of different ages.

Except for the Seville fire tower (Site 2), where a surficial aquifer system well was not sampled, the  $\delta D$  and  $\delta^{18}O$  content of all Upper Floridan aquifer samples was enriched in the heavier isotopes compared to the samples from the surficial aquifer system at the same site. The open-hole interval is 80 ft, 158 ft, and 159 ft at Sites 3, 4, and 5, respectively, but only 25 ft at Site 2 (Table 2). The different  $\delta D$  and  $\delta^{18}O$  values between the surficial aquifer and Floridan aquifer samples at Sites 3, 4, and 5 suggest that the Upper Floridan aquifer samples at these sites were a mixture of waters of different ages.

#### TRITIUM

Tritium is a radioactive isotope of hydrogen (H) which is produced naturally in small amounts by the interaction of cosmic rays with the earth's atmosphere. Cosmogenic T enters ground water by way of rainfall at a concentration of approximately 3–5 tritium units (TU) (Kaufman and Libby 1954; Robertson and Cherry 1989). With the onset of atmospheric nuclear testing in 1953, the T concentration in rainfall at Ocala, Florida (about 75 miles west of Daytona Beach), increased to as high as 700 TU in 1963. Because of the difference in T concentration in rainwater before and after 1953, T has been used as a hydrologic tracer to age-date recent ground water (Coplen 1988). The half-life of T is 12.43 years, which means that the T concentration decreases by a half every 12.43 years. The concentration of T in monthly composite samples of rainfall at Ocala from 1952 to 1988 and its concentration in 1991, corrected for radioactive decay, fluctuated widely but was at a maximum in 1963 (Figure 7). In 1988, the T concentration in rain at Ocala was not measurably different from the estimated pre-1953 concentration. The T concentration was weighted by the amount of rainfall. This annual volume-weighted mean concentration was calculated by summing each monthly rainfall amount multiplied by its T concentration and then dividing the sum by the total rainfall for the year (Katz et al. 1995).



Figure 7. Tritium concentration in rainfall at Ocala, Florida, and its concentration in 1991 after radioactive decay; half-life is 12.43 years (Katz et al. 1995)

Isotopes

In this report, the T concentration in rain at Keystone Heights (Site 1), the Seville fire tower (Site 2), the Pierson airport (Site 3), and Daytona Beach (Sites 4 and 5) was assumed to be similar to that at Ocala. Sites 1–3 are closer to Ocala than to Daytona Beach. Therefore, the T concentration in rain at Daytona Beach may be the most different from that at Ocala. Atmospheric T concentrations are lower near coastal areas and increase inland (Thatcher 1962).

Most ground water samples analyzed in this pilot study were collected in 1991. The T concentrations ranged from 0.1 TU at well V-0544 to 13.1 TU at well V-0543 (both at Site 5) for all aquifers sampled in this pilot study (Table 4). All T concentrations were above 5 TU, except for the intermediate aquifer well (V-0557) at the Pierson airport (Site 3) and the two intermediate aquifer wells (V-0544 and V-0545) near production well 45 (Site 5) in Daytona Beach. The highest concentration (13.1 TU) comes from a surficial aquifer well (V-0543) near production well 45 (Site 5). The well is located approximately 15 ft from a canal. The T concentration in all Upper Floridan aquifer wells was above 6.5 TU.

Tritium concentrations above 5 TU in Upper Floridan aquifer wells at all sites indicated that the Upper Floridan aquifer was recharged after 1953. Because of the variability in the T concentration of rainfall with time since 1953, a more precise age could not be determined. The three samples where the T concentration was below 5 TU, however, were most likely recharged with water prior to 1953, or the samples are a mixture of pre- and post-1953 water. The sample with a T content of 0.1 TU is probably older than 70 years (Swancar and Hutchinson 1992).

### CARBON-14

Carbon-14 is a radioactive isotope of carbon formed by the reaction between cosmic rays and nitrogen in the atmosphere. Carbon-14 combines with oxygen to form carbon dioxide (CO<sub>2</sub>), which is taken up by plants or absorbed by rain and is found in surface water bodies. When plants, animals, and ground water are no longer exposed to the atmospheric CO<sub>2</sub>, the <sup>14</sup>C content begins to decay radioactively. The radiocarbon content of ground water decreases at a rate equal to the half-life of <sup>14</sup>C, which is 5,715 years (Coplen 1993). Therefore, water that has been underground for an extended period of time will have a

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lower concentration of  ${}^{14}C$  than will water that has only recently entered the ground and is isolated from atmospheric CO<sub>2</sub>.

The measured <sup>14</sup>C content of ground water is expressed as a percentage of the modern <sup>14</sup>C content of ground water, or percent modern carbon (pmc). Because the content of <sup>14</sup>C in the atmosphere increased after the above-ground nuclear testing in 1953, 1950 is the base year for modern <sup>14</sup>C. The standard for modern <sup>14</sup>C represents 95% of the activity (reactive concentration) of oxalic acid, as measured by the National Institute of Standards and Technology.

The <sup>14</sup>C content of ground water sampled during this pilot study ranged from 11.8 pmc for an intermediate aquifer well at the Pierson airport (well V-0557, Site 3) to 116.7 pmc for a surficial aquifer well at Keystone Heights (well C-0452, Site 1) (Table 4). The high value (greater than 100 pmc) for <sup>14</sup>C for well C-0452 implies that the water originated from rainfall after 1953. The low value in well V-0557 was probably due to contamination from drilling mud, as evidenced by the  $\delta^{13}$ C of this sample, which was very different from that of the other samples (+2.7 compared to values below –7.0). Therefore, this sample was not used in the <sup>14</sup>C analysis.

The <sup>14</sup>C content of the ground water samples was measured on filtered and unfiltered (control) samples. The maximum difference between a filtered and an unfiltered sample (wells C-0120 and V-0559, Table 4) in the control study was 1.7%. Filtering of the samples did not significantly alter the <sup>14</sup>C content, because the maximum laboratory error of Geochron Laboratories in <sup>14</sup>C analyses was  $\pm 1.8\%$ .

Several computer models calculate the age of ground water from its <sup>14</sup>C content. The age represents the time since a water was last in contact with the atmosphere and is given relative to 1950. Depending on the computer model used, the difference in the age of ground water as calculated by the different models can be as high as 7,000 years. Most models differ on the initial value for <sup>14</sup>C. To ensure consistency, the <sup>14</sup>C age of ground water samples collected as part of this pilot study was obtained using the original data model in NETPATH, an interactive code for modeling net geochemical reactions along a flow path (Plummer et al. 1991). Water is assumed to flow vertically downward

from the surficial aquifer system to the intermediate aquifer system and from the intermediate aquifer system downward to the Floridan aquifer system. The initial value for <sup>14</sup>C used in NETPATH is the measured value of <sup>14</sup>C in the overlying aquifer. The complete geochemistry of the samples, which includes metals (Table 5), anions, and SiO<sub>2</sub> (Table 6), was used to define the possible reactions that may affect the value of <sup>14</sup>C as water flows vertically downward. Differences in water chemistry between aquifers was assumed to be due to chemical reactions that occur as water flows vertically. Lateral transport was assumed to be negligible.

NETPATH uses <sup>13</sup>C data to correct <sup>14</sup>C concentrations through a complex set of equations (Plummer et al. 1991). Some of the parameters used in the equations are the <sup>13</sup>C composition of total dissolved inorganic carbon in the water, the <sup>13</sup>C content of dissolving carbonate, the <sup>13</sup>C content of soil gas (CO<sub>2</sub>), the <sup>14</sup>C content of soil gas (CO<sup>2</sup>), the <sup>14</sup>C content of soil carbonate minerals, and numerous fractionation factors. The correction was done to compensate for the addition of "dead" carbon arising from limestone dissolution. Dead carbon does not contain any <sup>14</sup>C. By adding dead carbon to the system, the <sup>14</sup>C concentration is diluted, which, if uncorrected, would yield an older calculated age for the sample. The most plausible <sup>14</sup>C age corresponds to the one where the difference between computed and measured  $\delta^{13}$ C was minimal (±2‰, Table 7).

Carbon-14 ages ranged from -642 years to 9,423 years (Table 7) for flow from the surficial aquifer system to the intermediate aquifer system and from the intermediate aquifer system to the Floridan aquifer system, using NETPATH. The extreme of -642 years for a <sup>14</sup>C age occurred between wells V-0566 and V-0184 at the Seville fire tower (Site 2). The extreme of 9,423 years for a <sup>14</sup>C age occurred between wells V-0528 and V-0531 at the Pierson airport (Site 3). Negative values for an age (e.g., -642) imply that the flow is recent. A negative value results because the concentration of <sup>14</sup>C increased due to above-ground nuclear testing during the 1950s and 1960s.

The age of the Upper Floridan aquifer water at the Pierson airport (Site 3)—9,423 years—is due probably to mixing of water within the Upper Floridan aquifer or possibly to mixing between the Upper and

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Site	Well Number	Sampling Date	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Strontium (µg/L)	Barium (µg/L)	lron (µg/ L)
1—Keystone Heights (Brooklyn Lake)	C-0452	7/1/91	2	11.2	10	<1.0	<30	NA	133
	C-0452	3/9/92	1	1.1	9	1.4	<30	13	<50
	C-0116	3/2/92	9	3.8	4	<1.0	<30	14	<50
	C-0120	7/30/91 Unfiltered	22	5.2	3	<1.0	<30	NA	512
	C-0120	9/19/91	14	5.1	3	<1.0	<30	47	527
	C-0120	3/9/92	21	5.3	4	<1.0	<30	10	559
2—Seville	V-0566	4/1/92	72	6.7	40	6.5	331	51	<50
fire tower	V-0184	4/13/92	74	2.1	10	1.6	170	13	63
3-Pierson	V-0528	11/19/91	5	2.3	9	3.9	84	27 1	,140
airport	V-0557	2/18/92	28	1.5	16	11.0	239	295	<50
	V-0531	2/18/92	34	7.2	6	1.6	<30	228	<50
4—Tomoka	V-0529	10/28/91	4	1.0	24	3.4	101	17 1	,160
fire tower	V-0546	10/28/91	95	1.3	8	<1.0	601	41	645
	V-0192	10/15/91	105	1.2	8	<1.0	611	80	383
	V-0188	10/15/91	101	9.1	21	1.0	474	39	<50
5Near	V-0543	10/29/91	120	12.1	29	<1.0	707	126 8	,980
production	V-0544	10/29/91	119	7.2	60	1.4	840	47 3	,260
well 45 (Daytona	V-0545	8/27/91	111	6.5	66	1.7	220	NA 1	,420
Beach	V-0559	10/29/91	96	6.9	21	1.1	457	20	204
wellfield)	V-0559	10/29/91 Unfiltered	97	7.0	21	1.0	458	20	211

Table 5. Metal analyses for ground water samples collected in this pilot study

Note: mg/L = milligrams per litre µg/L = micrograms per litre NA = no analysis

> Lower Floridan aquifers. Site 3 is in the middle of the fern-growing area, and drawdowns can be as great as 80 ft during periods of frostand-freeze protection (Bill Osburn, SJRWMD, pers. com.). Deep water in the Upper Floridan aquifer and water in the Lower Floridan aquifer would be older and depleted in <sup>14</sup>C relative to shallower water in the Upper Floridan aquifer. Mixing of waters within the Floridan aquifer

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#### Table 6. Chemical (anion), silica, and total dissolved solids analyses for ground water samples collected in this pilot study

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Site	Well Number	Well Sampling umber Date	Temper- ature (°C)	рН	Conductivity (µmhos/cm)	Alkali Calci Carbo (mg	nity- ium inate /L)	Chloride (mg/L)	Sulfate (mg/L)	Silica (mg/L)	Nitrate and Nitrite as Nitrogen	Fluoride (mg/L)	Phosphate Phosphorus (mg/L)	Total Dissolved Solids (mg/L)													
						Field	Lab				(mg/L)																
1—Keystone	C-0452	7/1/91	22.5	5.56	95	10.8	NA	8	2	5.8	5.360	NA	0.016	73													
Heights (Brooklyn	C-0452	3/9/92	23.2	5.06	70	3.0	<1	10	<1	6.0	2.140	<0.05	0.017	44													
Lake)	C-0116	3/2/92	23.2	6.60	105	33.4	38	8	2	10.0	1.090	0.26	0.768	49													
, –	C-0120	7/30/91 Unfiltered	22.5	7.96	177	80.4	79	6	1	8.6	0.030	NA	0.042	105													
	C-0120	9/19/91	22.5	7.82	178	81.6	79	6	1	10.7	<0.007	NA	0.038	* 246													
	C-0120	3/9/92	22.8	7.81	182	78.8	84	6	2	10.0	0.022	0.13	0.044	101													
2-Seville fire	V-0566	4/1/92	21.8	7.11	538	214.0	268	41	41	NA	0.042	0.46	0.293	384													
tower	V-0184	4/13/92	21.0	7.23	421	192.4	173	17	4	16.0	<0.007	0.12	0.393	249													
3—Pierson	V-0528	11/19/91	25.1	4.94	127	16.4	6	16	17	4.0	<0.007	0.03	0.036	84													
airport	V-0557	2/18/92	22.8	9.49	238	122.0	114	6	1	30.0	0.024	0.37	0.064	116													
	V-0531	2/18/92	23.2	8.17	268	122.8	116	10	5	11.0	<0.007	0.12	0.068	81													
4-Tomoka fire	V-0529	10/28/91	28.3	5.46	218	28.0	28	24	12	8.6	0.009	0.02	0.034	214													
tower	V-0546	10/28/91	23.6	6.85	523	257.6	272	11	4	10.7	<0.007	0.15	0.410	352													
	V-0192	10/15/91	22.3	7.09	562	266.8	274	14	5	15.0	0.018	0.15	0.473	458													
	V-0188	10/15/91	22.3	7.20	661	289.0	293	35	4	17.1	0.017	0.1 <del>9</del>	0.189	356													
5—Near	V-0543	10/29/91	26.0	6.16	917	199.4	177	131	56	8.6	0.016	0.11	0.048	652													
production well 45 (Daytona	V-0544	10/29/91	23.8	6.75	918	358.0	355	86	7	17.1	0.010	0.13	0.103	593													
Beach wellfield)	V-0545	8/27/91	26.1	7.27	906	400.0 372.0	357	76	12	21.4	0.016	NA	0.063	553													
	V-0559	10/29/91	22.4	6.90	641	288.6	293	34	4	17.1	<0.007	0.15	0.199	414													
	V-0559	10/29/91 Unfiltered	22.4	6.90	641	288.6	269	34	4	17.1	<0.007	0.16	0.191	409													

GROUND WATER RECHARGE RATES CALCULATED FROM ISOTOPES

\*Analyzed out of time frame

Note: µmhos/cm = micromhos per centimeter

mg/L = milligrams per litre NA = no analysis

Site	Aquifer Flow	Initial Well	Final Well	<sup>14</sup> C Age (years)	Detta <sup>13</sup> C Values (‰)			
				before 1950	Computed	Measured	Difference	
1-Keystone Heights	Surficial $\rightarrow$ Intermediate	C-0452	C-0116	242	-15.5	-15.8	0.3	
(Brooklyn Lake)	Intermediate $\rightarrow$ Floridan	C-0116	C-0120	55	-12.3	-12.0	-0.3	
				1,412	-12.3	-12.0	-0.3	
2—Seville fire tower	Intermediate $\rightarrow$ Floridan	V-0566	V-0184	-551	-9.3	-7.2	-2.1	
				-642	-9.1	-7.2	-1.9	
3—Pierson airport	Surficial $\rightarrow$ Floridan	V-0528	V-0531	9,423	-10.8	-10.0	-0.8	
4-Tomoka fire tower	Surficial $\rightarrow$ Intermediate	V-0529	V-0546	-477	-13.6	-12.4	-1.2	
	Intermediate → Intermediate	V-0546	V-0192	425	-11.1	-10.7	-0.4	
				42	-10.3	-10.7	0.4	
	Intermediate $\rightarrow$ Floridan	V-0192	V-0188	2,770	-9.6	-8.7	-0.9	
5-Near production	Surficial $\rightarrow$ Intermediate	V-0543	V-0544	4,257	-13.7	-12.1	-1.6	
well 45 (Daytona				4,148	-13.9	-12.1	-1.8	
				4,651	-13.7	-12.1	-1.6	
				4,666	-13.9	-12.1	-1.8	
				3,912	-12.3	-12.1	-0.2	
				3,693	-12.0	-12.1	0.1	
	Intermediate → Intermediate	V-0544	V-0545	1,348	-11.2	-9.3	-1.9	
 	Intermediate $\rightarrow$ Floridan	V-0545	V-0559	1,066	-9.1	-9.3	0.2	

# Table 7. Carbon-14 (<sup>14</sup>C) ages and carbon-13 (<sup>13</sup>C) values calculated for vertical flow using NETPATH

Note: Initial and final wells are used to define the starting and ending chemistry of ground water as it flows vertically from the different aquifers.

‰ = parts per thousand or per mil

system or between the Upper and Lower Floridan aquifers would dilute the <sup>14</sup>C concentration of water from the Upper Floridan aquifer. As a result of diluting the <sup>14</sup>C concentration of Upper Floridan aquifer water, an older age was calculated. For comparison, the T concentration in the Upper Floridan aquifer at this site was 9.1 TU (Table 4). Tritium concentrations above 5 TU indicated that the Upper Floridan aquifer was recharged after 1953.

The Upper Floridan aguifer water at the Tomoka fire tower (Site 4), near production well 45 (Site 5), and at the Pierson airport (Site 3) is approximately 2,800, 6,000, and 9,400 years older than water from the surficial aquifer system at these sites (Table 7). This disparity in ages may be due to the open-hole interval at these sites, which could facilitate mixing of water within the Upper Floridan aquifer, or to the carbonate makeup and chemistry of the Upper Floridan aquifer, or both. The Upper Floridan aquifer wells at the Pierson airport (Site 3), the Tomoka fire tower (Site 4), and near production well 45 (Site 5) penetrate 80, 158, and 159 ft into the aquifer, respectively (total well depth minus casing depth, Table 2). Agricultural and public supply withdrawals from the Upper Floridan aquifer near these sites may have caused the Upper Floridan aquifer to be well mixed. In addition, the limestones of the Upper Floridan aquifer are comprised of carbonate containing no <sup>14</sup>C. This carbonate contains <sup>12</sup>C, which dissolves and dilutes the <sup>14</sup>C concentrations in recharge water, thereby giving anomalous old dates.

#### **COMPARISON OF AGES—TRITIUM VS CARBON-14**

Different age estimates for water in the Upper Floridan aquifer were obtained using T and <sup>14</sup>C. Based on T analyses of ground water in the pilot study area, the water in the Upper Floridan aquifer is less than 39 years old (Table 2). The <sup>14</sup>C analyses of samples from the Seville fire tower (Site 2) agree with the T analysis regarding the recent age for the Upper Floridan aquifer ground water. At the Pierson airport site (3), the Tomoka fire tower site (4), and near the production well 45 site (5), however, the <sup>14</sup>C content indicates that the Upper Floridan aquifer water is thousands of years old. This inconsistency in age-dating is not surprising because the Upper Floridan aquifer wells at the Pierson airport (Site 3), the Tomoka fire tower (Site 4), and near production well 45 (Site 5) penetrate 80, 158, and 159 ft of the aquifer, respectively. At the Seville fire tower site (2), for comparison, the Upper Floridan aquifer well penetrates only 25 ft of the aquifer (Table 2).

The difference between T and <sup>14</sup>C ages implies that the Upper Floridan aquifer contains a mixture of waters of different ages. The amount of T and <sup>14</sup>C originally in the surficial aquifer system, which recharges the Upper Floridan aquifer, has been diluted by mixing with the older water from deeper in the Upper Floridan aquifer or from the Lower Floridan aquifer. The apparent <sup>14</sup>C age of this water provides information about mixing.

If the original <sup>14</sup>C content of the Upper Floridan aquifer had been diluted by mixing with older water, the T concentrations also would have been diluted. If the T concentration of the Upper Floridan aquifer were greater than 5 TU, the unmixed concentration would be even higher, because the T concentration in older waters is less than 5 TU. In situations like this where the ages inferred from <sup>14</sup>C and T concentrations differ, only the T age was used to estimate recharge.

## **RECHARGE TO THE UPPER FLORIDAN AQUIFER**

Ground water recharge is the addition of water to a saturated zone and the downward movement of the water into aguifer systems. Nearly all of the water recharging the Floridan aquifer system in SJRWMD comes from rainfall. Other minor sources of recharge include seepage from parts of streams and lakes, deep percolation of irrigation waters, effluent from cesspools and septic tank drainfields, leakage from water and sewage conduits, and wastewater discharged to the ground surface (Vecchioli et al. 1990). Rainfall percolating downward from land surface to the Floridan aquifer system usually passes through the unsaturated soil zone, the surficial aquifer system, and the intermediate aquifer system. In this vertical movement, water moves from an area of higher water level to an area of lower water level. The rate of recharge is governed, therefore, by both the leakance characteristics of intervening units, especially clays, and the hydraulic head between aquifers.

#### **RECHARGE—HYDROGEOLOGY**

Recharge rates are usually calculated from hydrogeologic data such as the leakance values and the differences in water levels (hydraulic head) between aquifer systems. The leakance values generally are estimated from ground water flow models and are verified by comparing model-derived values with those measured from core samples of clayey and silty layers. The rate of recharge by the leakance method is directly proportional to leakance values and hydraulic head.

#### Leakance Values

Leakance is defined as the ratio of rock permeability to the thickness of the rock sample (Table 8). Clay layers were sampled at the Seville fire tower (Site 2), the Pierson airport (Site 3), and near production well 45 (Site 5) in Daytona Beach. Permeabilities of these samples ranged from  $3.1 \times 10^{-1}$  feet/day (ft/d) at the

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Seville fire tower (Site 2) to  $1.8 \times 10^{-5}$  ft/d near production well 45 (Site 5) (Table 8). Leakance values at the same sites were  $1.6 \times 10^{-1}$  and  $9.0 \times 10^{-6}$  (ft/d)/ft, respectively. No wells were drilled in the Keystone Heights area (Site 1), and no samples were collected at the Tomoka fire tower (Site 4).

# Table 8. Porosity and permeability of clayey layers from Shelby tube samples

Site	Depth of Sample (feet)	Porosity Percentage	Permeability (feet/day)	Leakance Values ([feet/day]/foot)						
Crescent City Ridge										
2—Seville fire	13–15	33	3.1 x 10⁻¹	1.6 x 10 <sup>-1</sup>						
tower	30–33	51	4.0 x 10⁻⁴	1.3 x 10 <sup>-4</sup>						
	40–43	34	2.2 x 10 <sup>-2</sup>	7.3 x 10 <sup>-3</sup>						
3—Pierson airport	38–40	73	7.7 x 10⁻⁵	3.9 x 10 <sup>-5</sup>						
	68–69.5	43	3.7 x 10 <sup>-3</sup>	2.5 x 10 <sup>-3</sup>						
	98–100	54	4.5 x 10⁻⁵	2.3 x 10 <sup>-5</sup>						
5—Near production well 45 (Daytona Beach wellfield)	27–29	62	1.8 x 10 <sup>-5</sup>	9.0 x 10 <sup>-6</sup>						

Other scientists have calculated similar leakance values based on similar rock characteristics. Bush and Johnston (1988) reported model-simulated leakance values of  $2.3 \times 10^{-4}$  (ft/d)/ft in semiconfined areas. Ryder (1985) reported leakance values ranging from  $1.0 \times 10^{-7}$  to  $7.0 \times 10^{-4}$  (ft/d)/ft in southwest Florida, and Duerr et al. (1988) reported values of  $1.0 \times 10^{-7}$  to  $7.0 \times 10^{-5}$  (ft/d)/ft in west-central Florida. Boniol et al. (1990) used leakance values ranging from  $1.0 \times 10^{-5}$  to  $1.0 \times 10^{-4}$  (ft/d)/ft

to calculate recharge in the Crescent City Ridge. Boniol et al. (1993) used leakance values ranging from  $6.9 \times 10^{-6}$  to  $1.2 \times 10^{-4}$  (ft/day)/ft to map recharge to the Floridan aquifer system in SJRWMD. The leakance values for the samples collected in this pilot study (Table 8) were in general agreement with these values.

#### Hydraulic Head

Hydraulic head is defined as the elevation of water levels with respect to mean sea level in aquifers or parts of an aquifer at any given location. For the five sites sampled in this pilot study, the direction of water movement is downward. That is, hydraulic head in wells tapping the surficial aquifer system is higher than in wells open to the intermediate aquifer system, which in turn has higher head than in wells open to the Floridan aquifer system (Table 2). At Site 5, however, the hydraulic head in the intermediate aquifer system, well V-0544, was slightly higher than in the surficial aquifer system.

For the five sites sampled in this pilot study, the difference in hydraulic head was the greatest between the surficial aquifer and the intermediate aquifer systems at the Pierson airport (Site 3)—25.75 ft on February 18, 1992 (Table 2). The difference in hydraulic head was the lowest between two intervals of the intermediate aquifer system near production well 45 (Site 5)—0.33 ft on August 27, 1991.

Water levels in each aquifer in the pilot study area fluctuate monthly in response to rainfall and withdrawals (Figures 8–11). At Keystone Heights (Site 1), the available data indicate that water levels in the respective aquifer systems mirror each other (Figure 8). Annual fluctuations in these aquifer systems generally range about 4–5 ft. At the Seville fire tower (Site 2), little or no information was available on water levels in the surficial and intermediate aquifer systems (Figure 9). Annual recorded fluctuations in the Floridan aquifer system at the Seville fire tower can be as high as 20 ft. At the Pierson airport (Site 3), the available data indicate that, throughout most of the period of

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Figure 8. Water level fluctuations in the surficial aquifer and the intermediate aquifer systems and in the Upper Floridan aquifer at Keystone Heights (Site 1)

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Figure 9. Water level fluctuations in the intermediate aquifer system and the Upper Floridan aquifer at the Seville fire tower (Site 2)



Figure 10. Water level fluctuations in the surficial aquifer and the intermediate aquifer systems and in the Upper Floridan aquifer at the Pierson airport (Site 3)



Figure 11. Water level fluctuations in the intermediate aquifer system and the Upper Floridan aguifer at the Tomoka fire tower (Site 4)

record, the water levels from each aquifer generally mirror each other except during the winter months when the Upper Floridan aquifer fluctuates rapidly (Figure 10). These fluctuations do not occur in the overlying aquifers. Annual recorded fluctuations in the Floridan aquifer system at the Pierson airport can be as high as 42 ft. At the Tomoka fire tower (Site 4), recorded water levels were available from only one intermediate aquifer system well and one Upper Floridan aquifer well. The fluctuations in the intermediate aquifer system generally mirror those in the Floridan aquifer system but were not as extreme as those in the Floridan aquifer system. The annual fluctuations were generally as large as 7 ft in the intermediate aquifer system and 13 ft in the Upper Floridan aquifer. No information was available on the annual fluctuations in the three aquifer systems near production well 45 (Site 5).

The rapid fluctuations in the water levels for Upper Floridan aquifer wells at the Seville fire tower (Site 2) and the Pierson airport (Site 3) were in response to frost-and-freeze withdrawals (Figures 9 and 10). The recorded fluctuations approximate 20 ft at the Seville fire tower (Site 2) and 42 ft at the Pierson airport (Site 3). However, measured drawdowns at the Pierson airport (Site 3) have been as large as 80 ft (Bill Osburn, SJRWMD, pers. com.).

#### **RECHARGE—ISOTOPES**

Isotopic recharge rates were estimated using Equation 3.

$$RR \geq \frac{\left[CD - (EL - WT)\right] \cdot 12 \cdot \phi}{A} \tag{3}$$

where:

RR = recharge rate in inches per year

- *CD* = depth at the bottom of the well casing (Floridan aquifer system well) measured in feet
- *EL* = elevation of land surface in feet above mean sea level

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- WT = elevation of the water table in feet above mean sea level, generally the water level in the surficial aquifer system
- 12 = constant to convert feet to inches
- = porosity of stratigraphic column (unitless) ¢
- Α = age of ground water in years, based on isotopes

Several assumptions were made to estimate recharge rates for the Upper Floridan aguifer based on isotopes. The elevation of the bottom of the casing was assumed to be equal to the elevation of the top of the Upper Floridan aquifer, even though many wells had approximately 160 ft of open hole. Recharge water is treated as being added at the top of the aquifer. (The very top of the aquifer could not be sampled because of the manner in which the well had been constructed; however, a portion of the top of the aquifer was sampled.) If the depth to the bottom of the well were used instead of the depth at the bottom of the well casing, the estimated recharge rate using isotopes would be greater. For all recharge calculations, porosity was assumed to be 0.30. This value is reasonable for the Upper Floridan aquifer (Mercer et al. 1986; Dames and Moore 1988). If a lower value of 0.10 were used for porosity, the estimated recharge rate would be a factor of 3 higher. Conversely, if a value of 0.60 were used for porosity, the estimated recharge rate would be a factor of 2 lower. A value of less than 38 or 39 was used for the age of the sample. Based on the T analyses, the Upper Floridan aquifer at all sites contained water that recharged the aquifer after 1953. The age value used was the difference in time between when the samples were collected—either 1991 or 1992—and 1953. If a value smaller than 38 were used for age, the estimated recharge rate would be larger.

Recharge rates were estimated by substituting the appropriate numerical values from Table 2 into Equation 3. Recharge rates are at least 5.8 in/yr at the Seville fire tower (Site 2) and 11.7 in/yr at the Pierson airport (Site 3; Table 9). Recharge rates at the Tomoka fire tower (Site 4) and near production well 45 (Site 5) are at least 8.1 in/yr and 8.4 in/yr, respectively.

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Site	Well Number	Latitude	Longitude	Recharge Rate (inches/year)		
				Isotopes	Hydrogeology <sup>1</sup>	
		Crescent C	ity Ridge			
2—Seville fire tower	V-0184	291941	812942	≥ 5.8	8–12	
3—Pierson airport	V-0531	291448	812749	≥ 11.7	12 or more	
		Daytona Be	ach Area			
4Tomoka fire tower	V-0188	290834	810738	≥ 8.1	8–12	
5—Near production well 45 (Daytona Beach wellfield)	V-0559	291107	810517	≥ 8.4	8–12	

#### Table 9. Recharge rates to the Upper Floridan aquifer calculated using either isotopes or leakance values

<sup>1</sup> Source: Boniol et al. 1993

Recharge rates using isotopes were not estimated for the Keystone Heights area (Site 1) because the D and <sup>18</sup>O analyses indicated that the Upper Floridan aquifer around Brooklyn Lake probably receives recharge directly from the lake as a result of downward seepage and lateral movement of lake water. This conclusion is supported by Clark et al. (1963). An assumption inherent in the recharge calculation is that ground water flows in a downward direction to the surficial aquifer system, then from the surficial aquifer system to the Floridan aquifer system. This assumption was incorrect at Brooklyn Lake, where lake water flows directly into the Floridan aquifer system and then moves laterally.

Estimated ground water recharge rates using isotopes are minimum estimates due to the variability in age as indicated by the T concentration of rainfall. Reducing age by a factor of 2 would increase the estimated recharge rates by 2.

#### **COMPARISON OF RATES**

The estimated recharge rates for the Upper Floridan aquifer using isotopes were compared with previously published recharge rates to determine the reliability of estimating rates based on the T content of ground water. Information on recharge rates in Florida is available only for the Upper Floridan aquifer. Stewart (1980) provided a generalized statewide recharge map of areas with high (10–20 in/yr), low-to-moderate (2–10 in/yr), very low (less than 2 in/yr), and no recharge to the Floridan aquifer system. Phelps (1984) mapped areas of high, low-to-moderate, and no recharge to the Floridan aquifer system in SJRWMD. Aucott (1988) mapped generalized areas of recharge to and discharge from the Floridan aquifer system for Florida. Vecchioli et al. (1990) mapped recharge rates for the Floridan aquifer system of greater than and less than 10 in/yr for Okaloosa, Pasco, and Volusia counties. Boniol et al. (1990) determined recharge rates to the Floridan aquifer system at intervals of 2 in/yr for the Crescent City Ridge area. Boniol et al. (1993) mapped recharge rates for the Floridan aquifer system at intervals of 4 in/yr for the entire SJRWMD.

The recharge rates estimated in this pilot study were within or near the ranges mapped by Boniol et al. (1993) using leakance values (Table 9). For example, recharge rates of at least 5.8, 11.7, 8.1, and 8.4 in/yr were estimated in this pilot study for Sites 2, 3, 4, and 5, respectively. Boniol et al. mapped recharge rates of 8–12 in/yr for Sites 2, 4, and 5 and 12 or more in/yr for Site 3 (Figure 2). The agreement between these two methods implies that recharge rates estimated from the isotopic composition of ground water can be determined reliably in other areas of SJRWMD where hydrogeologic data, used in determining leakance values, are missing. Site-specific recharge to the Upper Floridan aquifer can be estimated reliably using the T isotope. Care should be taken, however, when selecting Upper Floridan aquifer wells for measurement. The potential for mixing different-aged waters is greatest when an Upper Floridan aquifer well has a large open-hole interval. Because of this potential, only Upper Floridan aquifer wells with small open-hole intervals

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that penetrate less than 26 ft of the aquifer should be used. The smaller the amount of aquifer penetrated, the better. Even with a penetration of 26 ft for the Upper Floridan aquifer, there is still the possibility of mixing of waters with different ages, especially during sampling.

## SUMMARY

Both radioactive isotopes (T and <sup>14</sup>C) and stable isotopes (D, <sup>18</sup>O, and <sup>13</sup>C) were measured in this pilot study. The radioactive isotopes were used to determine the age of ground water. The stable isotopes were used to identify the source for ground water and to identify recharge which occurred during different climatic conditions. The stable isotope <sup>13</sup>C was used to correct the <sup>14</sup>C concentrations for the addition of "dead" carbon arising from limestone dissolution. Dead carbon does not contain any <sup>14</sup>C.

Recharge to the Upper Floridan aquifer was estimated at four sites, using radioactive isotopes to estimate the age of ground water. Two of the sites are on the Crescent City Ridge: the Seville fire tower (Site 2) and the Pierson airport (Site 3). The other two sites are in the Daytona Beach area: the Tomoka fire tower (Site 4) and near production well 45 (Site 5).

A fifth site, near Brooklyn Lake in the Keystone Heights area (Site 1) also was sampled. However, the D and <sup>18</sup>O isotope analyses of Upper Floridan aquifer water at Brooklyn Lake confirm that lake water is flowing directly into the Floridan aquifer system and moving laterally. Because of the hydraulic connection between the lake and the Floridan aquifer system, recharge rates using isotopes were not calculated for the Brooklyn Lake site.

The radioactive isotopes at the four sites indicate that the Upper Floridan aquifer contains water with a mixture of ages. The T content indicates that the Upper Floridan aquifer contains water that recharged the aquifer after 1953. The <sup>14</sup>C analyses, on the other hand, indicate that the Upper Floridan aquifer contains water that is approximately 2,800, 6,000, and 9,400 years older than the surficial aquifer system at the Tomoka fire tower (Site 4), near production well 45 (Site 5), and at the Pierson airport (Site 3), respectively. The disparity in ages was not surprising because the Upper Floridan aquifer wells at the Pierson airport (Site 3), the Tomoka fire tower (Site 4), and near production well

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45 (Site 5) penetrate 80, 158, and 159 ft of the aquifer, respectively. In addition, frost-and-freeze withdrawals cause drawdowns as high as 80 ft at Site 3 near the Pierson airport. The large drawdowns probably result in significant mixing within the Upper Floridan aquifer and possibly between the Upper and Lower Floridan aquifers at the Pierson airport (Site 3). As a consequence, the <sup>14</sup>C content was diluted by mixing with water that has a lower <sup>14</sup>C concentration.

The <sup>14</sup>C content also could have been diluted by carbonate dissolution. The Floridan aquifer system is composed of carbonate containing no <sup>14</sup>C. This carbonate contains <sup>12</sup>C, which dissolves, dilutes, and equilibrates with <sup>14</sup>C in recharge water, thereby giving anomalous old dates.

The Upper Floridan aquifer contains recharge water that is less than 39 years old, according to the isotope method. Mixing of recharge and older water in the Upper Florida aquifer would also decrease the T concentration. However, if the T concentration of the Upper Floridan aquifer were greater than 5 TU, the T concentration in recharge water would be higher because older waters contain less than 5 TU of T. Because of the variability in the T concentration of rainfall with time since 1953, a more precise age could not be determined. Therefore, the estimated recharge rates for the Upper Floridan aquifer using T are minimum estimates.

Estimated recharge rates using isotopes ranged from greater than or equal to 5.8 in/yr at the Seville fire tower (Site 2) to greater than or equal to 11.7 in/yr at the Pierson airport (Site 3). At the Tomoka fire tower (Site 4) and near production well 45 (Site 5), these estimated recharge rates were at least 8.1 and 8.4 in/yr, respectively.

These estimated recharge rates are similar to those mapped by Boniol et al. (1993). Boniol et al. mapped recharge rates for the Upper Floridan aquifer in SJRWMD calculated using hydraulic head and leakance values. They mapped recharge rates of 8–12 in/yr for Sites 2, 4, and 5 and 12 or more in/yr for Site 3. The agreement between these two methods implies that recharge rates estimated from the isotopic composition of ground water can be determined reliably in other areas of SJRWMD where hydrogeologic data, used in determining leakance values, are missing. Site-specific recharge rates to the Upper Floridan aquifer can be estimated reliably using the T isotope. Care should be taken, however, when selecting Upper Floridan aquifer wells for measurement. The potential for mixing different-aged waters is greatest when an Upper Floridan aquifer well has a large openhole interval. Because of this potential, only Upper Floridan aquifer wells with small open-hole intervals that penetrate less than 26 ft of the aquifer should be used.

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