Detection and Quality of Previously Undetermined Floridan Aquifer System Discharge to the St. Johns River, Jacksonville, to Green Cove Springs, Northeastern Florida

by Rick M. Spechler

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
	Flow	
foot per year (ft/y)	0.3048	meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per second (gal/s)	3.785	liter per second
gallon per minute (gal/min)	0.06309	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
	Leakance	
foot per day per foot [(ft/d)/ft]	1.000	meter per day per meter

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Equations for temperature conversion between degrees Celsius (°C) and degrees Fahrenheit (°F):

$$°C = 5/9\ (°F - 32)$$
$$°F = 9/5\ (°C) + 32$$

Altitude, as used in this report, refers to distance above or below sea level.

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

Additional abbreviations

Hz	hertz	μm	micrometer
kHz	kilohertz	μS/cm	microsiemens per centimeter at 25 degrees Celsius
μg/L	micrograms per liter	mg/L	milligrams per liter

Acronyms

PVC	polyvinylchloride	SJRWMD	St. Johns River Water Management District
RASA	Regional Aquifer-System Analysis	USGS	United States Geological Survey
SCUBA	Self-Contained Underwater Breathing Apparatus		

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Abstract

Potentiometric surface maps of the Upper Floridan aquifer show two depressions around the St. Johns River from the city of Jacksonville south toward Green Cove Springs. These depressions, depending on their locations, are the result of withdrawals from agricultural, industrial, domestic and public-supply wells, diffuse upward leakage, and discharge from springs.

Submerged springs that discharge into the St. Johns River between Jacksonville and Green Cove Springs have been thought to exist, but locating and evaluating these springs had not been attempted before this investigation. Thermal infrared imagery, seismic reflection, and numerous interviews with local residents were used to locate springs.

An airborne thermal infrared survey was conducted along a section of the St. Johns River in northeastern Florida during February 1992 to detect possible sources of ground-water discharge to the river. An infrared image displayed one thermal anomaly in the St. Johns River which is associated with a previously unknown spring discharge from the Floridan aquifer system. Thermal anomalies also were observed at six locations where municipal facilities discharge treated wastewater to the river.

Results of seismic reflection surveys indicate the presence of collapse and other karst features underlying the St. Johns River. These features indicate that the surficial deposits and the Hawthorn Formation that underlie the river probably do not consist of continuous beds. The collapse or deformation of the Hawthorn Formation or the presence of permeable sediments of localized extent could create zones of relatively high vertical leakance. This could provide a more direct hydraulic connection between the Upper Floridan aquifer and the river.

Water samples collected from the only submerged spring in the St. Johns River within the Jacksonville-Green Cove Springs reach indicate that the source of the water is the Floridan aquifer system. Chloride and sulfate concentrations were 12 and 340 milligrams per liter, respectively. Specific conductance was 826 microsiemens per centimeter and the temperature of the water discharging from the spring was 25.1 degrees Celsius. The ratio of ^{87}Strontium/^{86}Strontium also indicates that the springwater has been in contact with rock materials of Eocene age, providing additional evidence that the springwater is derived from the Floridan aquifer system.

INTRODUCTION

Little is known about the quantity and quality of natural ground-water discharge to the lower St. Johns River in the reach from Jacksonville to Green Cove Springs. The lack of information about natural discharge from the Floridan aquifer system through springs or diffuse upward leakage to the lower St. Johns River has made efforts to model the ground-water flow system in this area difficult.

Maps of the potentiometric surface of the Upper Floridan aquifer show two depressions; one along the St. Johns River south of the city of Jacksonville, and the other near the city of Green Cove Springs. These depressions indicate that water is moving upward from the Upper Floridan aquifer to discharge into the St. Johns River. The known volume of water being discharged from wells in the Green Cove Springs area and the discharge from Green Cove Springs (2.5 to 5 ft^3/s) is insufficient to cause the observed depression in the potentiometric surface.

Natural spring flow from the Upper Floridan aquifer or upward diffuse leakage from the aquifer could be the cause of the potentiometric surface depressions, although the presence of relatively thick confining beds in the area hydraulically isolate the Upper Floridan aquifer from overlying aquifers and surface-water bodies. However, the presence of these potentiometric surface lows indicates some loss of water from the Upper Floridan aquifer most commonly associated with either pumping, diffuse upward leakage, or spring discharge.

The U.S. Geological Survey (USGS), in cooperation with the city of Jacksonville and the St. Johns River Water Management District (SJRWMD), began a 2-year study in 1992 to locate and determine the quality of water being discharged from the Floridan aquifer system as springs or upward diffuse leakage. This study was the first attempt to locate submerged springs in the St. Johns River between Jacksonville and Green Cove Springs (fig. 1).

Purpose and Scope

This report presents the results of efforts to locate submarine springs in the lower St. Johns River between Jacksonville and Green Cove Springs, Florida, and describes the quality of water being discharged from both newly located and previously documented springs.

The methods employed to locate submarine springs are described in this report. A description of the thermal infrared imagery and seismic reflection equipment used in this study, a brief overview of the principles, and the interpretation of the data collected also are presented. The quality of water discharged from springs in the area is described, and the source of water to the springs was determined.

Previous Investigations

Numerous investigations have contributed to an understanding of the geology, hydrology, and ground-water resources of the study area. The geology of the study area has been described in reports by Vernon (1951), Puri (1957), Puri and Vernon (1964), Chen (1965), and Miller (1986). Ground-water resources were described by Bermes and others (1963), Clark and others (1964), Leve (1966), Bentley (1977), Fairchild (1977), and Spechler and Hampson (1984). The quality of water from the Floridan aquifer system in the study area was described in reports by Bermes and others (1963), Leve (1966), and Spechler (1994).

Reports describing the regional geology, hydrology, and geochemistry of the Floridan aquifer system include those by Stringfield (1966) and various Regional Aquifer-System Analysis (RASA) reports by Miller (1986), Bush and Johnston (1988), Johnston and Bush (1988), Krause and Randolph (1989), Sprinkle (1989), and Tibbals (1990).

Few reports deal with the subject of spring discharge to the St. Johns River. Related reports such as Rosenau and others (1977) describe more than 250 springs in Florida, including two found in the study area. The USGS annually publishes the "Water Resources Data for Florida Report" which includes discharge measurements and chemical analyses of selected springs throughout the State.

Description of the Study Area

The lower St. Johns River is a 101-mi long reach that begins at the confluence with the Ocklawaha River and ends where the river discharges into the Atlantic Ocean at Mayport. The study area includes an approximately 20-mi long reach of the lower St. Johns River that extends from the Main Street Bridge in downtown Jacksonville southward to the Shands Bridge near Green Cove Springs (fig. 1). Within the study area, the river ranges in width from 1 to 3 mi, and a navigation channel is maintained by the U.S. Army Corps of Engineers at about 13 ft deep. However, depths of up to 25 ft occur in numerous areas near the center of the river. Depths of less than 10 ft generally occur outside of the channel.

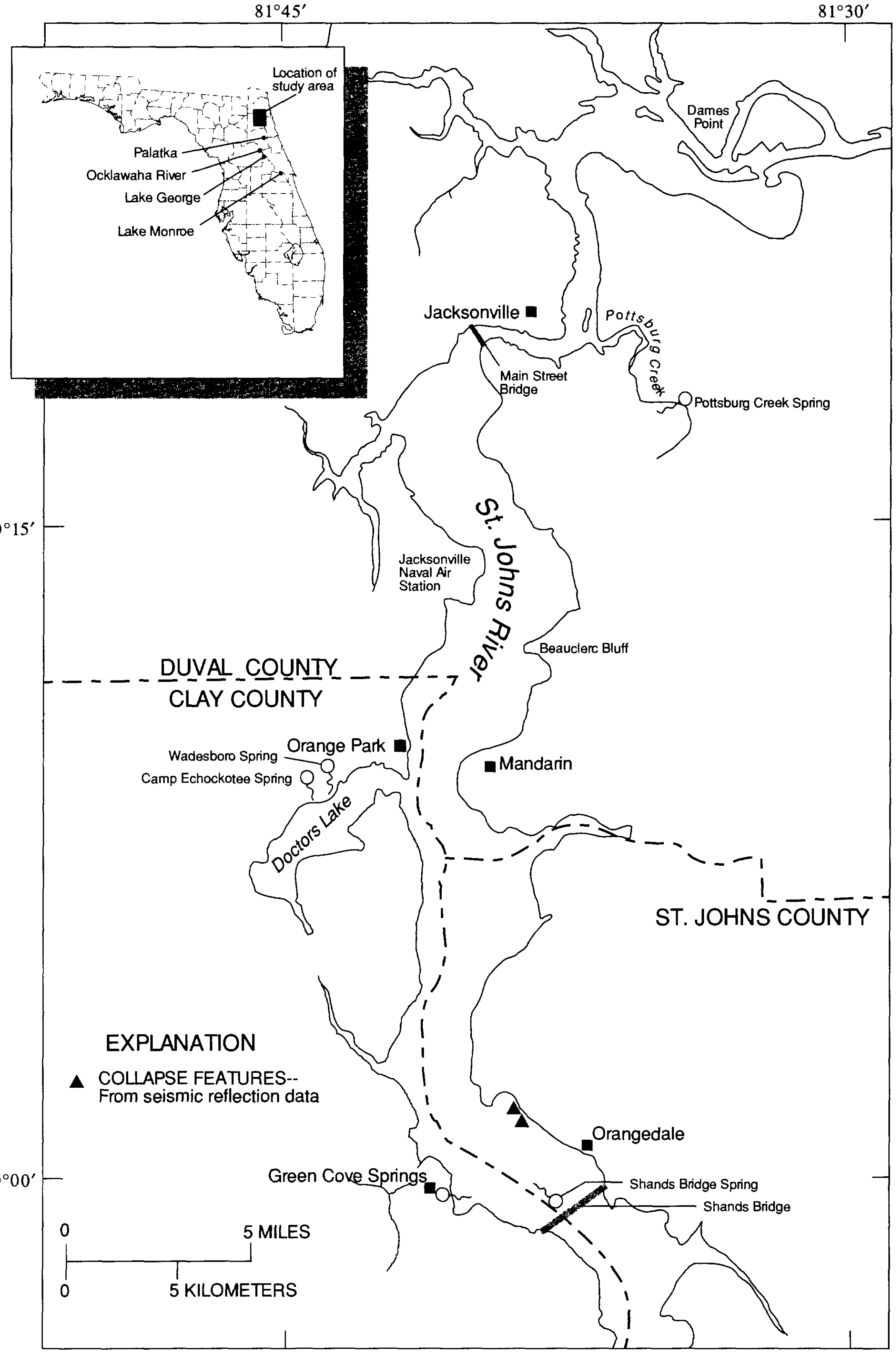

Figure 1. Location of study area.

The St. Johns River is affected by tides as far upstream as Lake George, about 106 mi from its mouth. Occasionally, combined drought, wind, and tidal effects can influence river stages and flow at Lake Monroe, about 161 miles upstream (Anderson and Goolsby, 1973, p. 9). The tidal range averages about 1.2 ft at Jacksonville and varies unequally upstream because of channel geometry. Normal tidal range is about 0.7 ft at Orange Park; however from Orange Park south, the amplitude of the tidal wave increases gradually to about 1.2 ft at Palatka (Anderson and Goolsby, 1973, p. 9). Based on 22 years of record, the average discharge of the St. Johns River at the Main Street Bridge is estimated to be about 5,700 ft^3/s (U.S. Geological Survey, 1992, p. 132).

The water quality of the St. Johns River in the study area varies significantly with changing flow conditions. The flow, hence the water quality of the river, is affected by ocean tides, wind, precipitation, surface-water runoff, and evapotranspiration. The extent to which these factors can affect the flow is primarily controlled by channel geometry and the available storage capacity of the river. However, ocean tides have the greatest effect on the quality of water in the river. Saltwater from the Atlantic Ocean advances up the St. Johns River during each incoming tide and recedes during each outgoing tide, forming a transition zone where ocean water mixes with freshwater. The length of the transition zone varies with each tidal cycle and with the amount of freshwater entering the river upstream.

Acknowledgments

The author gratefully acknowledges the assistance of Gary Weise with the Groundwater Resources Management Branch, city of Jacksonville; Timothy Perkins with the Water Division, city of Jacksonville; and Douglas Munch, David Baggett, and Russell Tharin with the St. Johns River Water Management District. Special thanks also are extended to Russell Noles, U.S. Army Corps of Engineers, whose knowledge of the St. Johns River and assistance contributed much to this study, and to Dr. Stephen Snyder and Rich Dentzman, North Carolina State University, for performing the continuous seismic-reflection survey. The author also gratefully acknowledges the assistance provided by many individuals in conjunction with this investigation. The help extended by the following people is sincerely appreciated: Lee Manley and Frank Surface with the St. Johns Archaeological Expeditions, Inc.; Dr. Roger Lloyd, University of Central Florida; and Dr. Doug Pennington, Harry Royce and Noble Enge.

GEOLOGIC FRAMEWORK

The study area is underlain by a thick sequence of sedimentary rocks that overlie a basement complex of metamorphic strata. The primary water-bearing sediments are composed of limestone, dolomite, shell, clay, and sand that range in age from late Paleocene to Holocene. Descriptions of major stratigraphic units and corresponding hydrogeologic units are given in figure 2. Stratigraphic units, in ascending order, are: the Cedar Keys Formation of late Paleocene age, the Oldsmar Formation of early Eocene age, the Avon Park Formation of middle Eocene age, the Ocala Limestone of late Eocene age, the Hawthorn Formation of Miocene age, and the undifferentiated deposits of late Miocene to Holocene age.

Structure contour maps of the top of the Ocala Limestone in northeastern Florida show the surface to be irregular and paleokarstic (Spechler, 1994, pl. 1). Some of the circular depressions on the surface developed when the limestone was exposed to subaerial erosion. Others, however, were probably formed by sinkhole collapse, the result of dissolution of carbonate material by percolating ground water.

Marine seismic-reflection profiles show that the Continental Shelf off the northeastern coast of Florida is underlain by solution-deformed limestone of Late Cretaceous to Eocene age (Meisburger and Field, 1976; Popenoe and others, 1984). Dissolution and collapse features are widely scattered throughout the area and are expressed as sinkholes that presently breach the sea floor, sinkholes that breached the sea floor in the past and are now filled with sand, and collapse structures that originated deep within the section and have deformed the overlying units (Popenoe and others, 1984). The deep dissolution-collapse features are believed to originate in the Upper Cretaceous and Paleocene rocks (Popenoe and others, 1984). Marine seismic-reflection investigations along the St. Johns River in northeastern Florida by Snyder and others (1989), by the USGS in 1989 (Spechler, 1994), by North Carolina State University in 1990, and a joint effort by the USGS and North Carolina State University in 1994 also revealed a number of buried

<table>
<tr><th>Series</th><th colspan="2">Stratigraphic unit</th><th>Lithology</th><th colspan="3">Hydrogeologic unit</th><th>Hydrologic properties</th></tr>
<tr><td>Holocene to Upper Miocene</td><td colspan="2">Undifferentiated surficial deposits</td><td>Discontinuous sand, clay, shell beds, and limestone</td><td colspan="3">Surficial aquifer system</td><td>Sand, shell, limestone, and coquina deposits provide local water supplies.</td></tr>
<tr><td>Miocene</td><td colspan="2">Hawthorn Formation</td><td>Interbedded phosphatic sand, clay, limestone, and dolomite</td><td colspan="3">Intermediate confining unit</td><td>Sand, shell, and carbonate deposits provide limited local water supplies.
Low permeability clays serve as the principal confining beds for the Floridan aquifer system below.</td></tr>
<tr><td rowspan="5">Eocene</td><td>Upper</td><td>Ocala Limestone</td><td>Massive fossiliferous chalky to granular marine limestone</td><td rowspan="5">Floridan aquifer system</td><td colspan="2">Upper Floridan aquifer</td><td>Principal source of ground water. High permeability overall. Water from some wells shows increasing salinity.</td></tr>
<tr><td rowspan="2">Middle</td><td rowspan="2">Avon Park Formation</td><td rowspan="4">Alternating beds of massive granular and chalky limestone, and dense dolomite</td><td colspan="2">Middle semiconfining unit</td><td>Low permeability limestone and dolomite.</td></tr>
<tr><td rowspan="3">Lower Floridan aquifer</td><td>Upper zone</td><td>Principal source of ground water. Water from some wells shows increasing salinity.</td></tr>
<tr><td rowspan="2">Lower</td><td rowspan="2">Oldsmar Formation</td><td>Semiconfining unit</td><td>Low permeability limestone and dolomite.</td></tr>
<tr><td>Fernandina permeable zone</td><td>High permeability; salinity increases with depth.</td></tr>
<tr><td>Paleocene</td><td colspan="2">Cedar Keys Formation</td><td>Uppermost appearance of evaporites; dense limestone</td><td colspan="3">Sub-Floridan confining unit</td><td>Low permeability; contains highly saline water.</td></tr>
</table>

Figure 2. Generalized geology and hydrogeology of northeastern Florida (modified from Spechler, 1994).

collapse features and other karstic features similar to those observed by Meisburger and Field (1976) and Popenoe and others (1984).

The presence of faults also has been inferred by some investigators. Leve (1966, p. 20, fig. 5; 1978) postulated two generally northward-trending faults located primarily in Duval County. Two small faults west of the St. Johns River in northeastern Clay County also were inferred by Fairchild (1977, p. 23).

HYDROGEOLOGY

The principal water-bearing units in the study area are the surficial and Floridan aquifer systems (fig. 2). The two aquifers are separated by the intermediate confining unit, which contains beds of lower permeability sediments that confine the water in the Floridan aquifer system. In most of the study area, the Floridan aquifer system has three major water-bearing zones (the Upper Floridan aquifer, the upper zone of the Lower Floridan aquifer, and the Fernandina permeable zone), all separated by less permeable semiconfining units. The Fernandina permeable zone is underlain by the sub-Floridan confining unit, which marks the base of the Floridan aquifer system.

Surficial Aquifer System

The surficial aquifer system is the uppermost water-bearing unit in the study area. The aquifer system consists of sand, clay, shell, dolomite, and limestone that range from middle Miocene to Holocene in age. These sediments are discontinuous and result in a surficial aquifer system of variable thickness and permeability. The aquifer generally is unconfined but may be semiconfined where beds of lower permeability are sufficiently thick and continuous. In some areas, the uppermost carbonate beds of the Hawthorn Formation are hydraulically connected with the overlying deposits, forming the lowermost part of the surficial aquifer system. The thickness of the surficial aquifer system in the study area ranges from less than 20 to about 100 ft. However, where there has been channel dredging in the St. Johns River, the surficial aquifer system may be considerably thinner.

The surficial aquifer system generally is not a major source of water in the study area; however, in some places, it is used for public- and domestic-water supply and lawn irrigation. Well yields depend on the thickness and permeability of the aquifer system and range from about 10 to 25 gal/min in the upper part of the aquifer to about 30 to 100 gal/min in the lower part, where permeable dolomite, limestone, and shell beds are present.

Intermediate Confining Unit

The intermediate confining unit, which underlies the surficial aquifer system, primarily consists of the Hawthorn Formation of Miocene age. The unit consists of interbedded clay, silt, sand, limestone and dolomite containing abundant amounts of phosphatic sand, granules, and pebbles. The intermediate confining unit varies in thickness from more than 500 ft in the central part of Duval County to about 200 ft near the Shands Bridge (fig. 3). Throughout most of the area, the clays and silts in the intermediate confining unit serve as an effective confining layer that retards the vertical movement of water between the surficial aquifer system and the underlying Floridan aquifer system.

In some areas, however, permeable sediments of localized extent may occur within the Hawthorn Formation. Also, karst and structural features (buried collapse features) can cause disruptions in overlying confining units. These permeable sediments and breaks in the intermediate confining unit can locally increase the vertical permeability, resulting in a more direct hydraulic connection between the Floridan aquifer system and the river.

Leakance coefficients of the intermediate confining unit are highly variable. RASA model-simulated leakance coefficients reported for the study area range from $1 \mathrm{x} 10^{-8}$ to $1 \mathrm{x} 10^{-5}$ (ft/d)/ft (R.E. Krause, U.S. Geological Survey, written commun., 1993). D. Durden (St. Johns River Water Management District, written commun., 1994) reported simulated leakance values ranging from less than $1 \mathrm{x} 10^{-7}$ to more than $1 \mathrm{x} 10^{-4}$ (ft/d)/ft.

Floridan Aquifer System

The Floridan aquifer system consists of a highly permeable sequence of limestone and dolomite which vary in age from late Paleocene to Eocene. It is the principal source of municipal, industrial, and agricultural water supply for most of northeastern Florida. The Floridan aquifer system in the study area ranges from about 1,800 to 2,100 ft in thickness and includes the following stratigraphic units in descending order: the Ocala Limestone, the Avon Park Formation, the Oldsmar Formation, and the upper part of the Cedar Keys Formation.

The Floridan aquifer system within the study area is divided into the Upper Floridan aquifer and the Lower Floridan aquifer (fig. 2), which are separated by a zone of lower permeability. Two major water-bearing zones exist within the Lower Floridan: the upper part of the Lower Floridan aquifer and the Fernandina permeable zone. These zones are separated by a less permeable unit that restricts the vertical movement of water.

The top of the Floridan aquifer system is defined as the first occurrence of vertically persistent, permeable, consolidated, carbonate rocks. The top of the Floridan aquifer system is highest near Jacksonville Naval Air Station and the Shands Bridge area (fig. 4) where it is about 250 ft below sea level. The top of the aquifer dips to about 600 ft below sea level in parts of central Duval County. The base of the Floridan aquifer system generally corresponds to the beginning of the vertically persistent evaporite deposits present in the upper part of the Cedar Keys Formation (Miller, 1986, B46).

The principal recharge areas of the Upper Floridan aquifer are to the southwest of the study area. Water enters the Upper Floridan aquifer by several means: by downward leakage from the surficial aquifer system in areas where the potentiometric surface of the Upper Floridan aquifer is a below the water table in the surficial aquifer; by lateral inflow from adjacent areas; and through sinkholes and lakes that are connected to the aquifer. Areas of discharge are primarily located along the St. Johns River and adjacent areas. Discharge from the Upper Floridan aquifer occurs by diffuse upward leakage in areas where the potentiometric surface of the Upper Floridan aquifer is above the water table, by spring flow, by lateral outflow, and by pumping and flowing wells.

The potentiometric surface of the Upper Floridan aquifer in the study area during September 1992 is shown in figure 5. September is close to the end of the wet season when water levels usually are near their seasonal high. At this time, the potentiometric surface ranged from more than 60 ft above sea level in the extreme southwestern part of the study area to less than 25 ft above sea level near Green Cove Springs and in a small area just south of Jacksonville. The direction of lateral ground-water movement in the Upper Floridan aquifer is toward the St. Johns River.

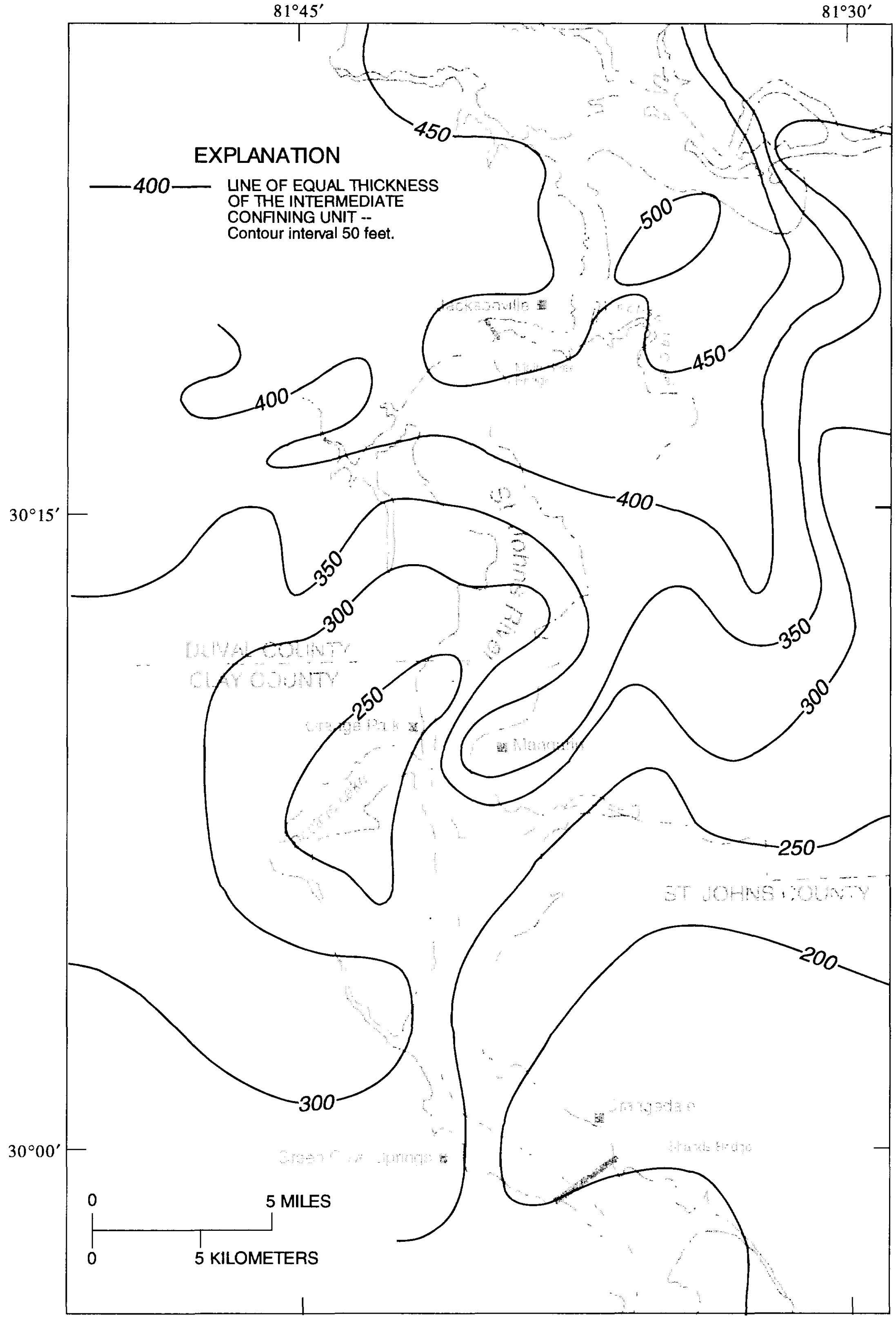

Figure 3. Generalized thickness of the intermediate confining unit.

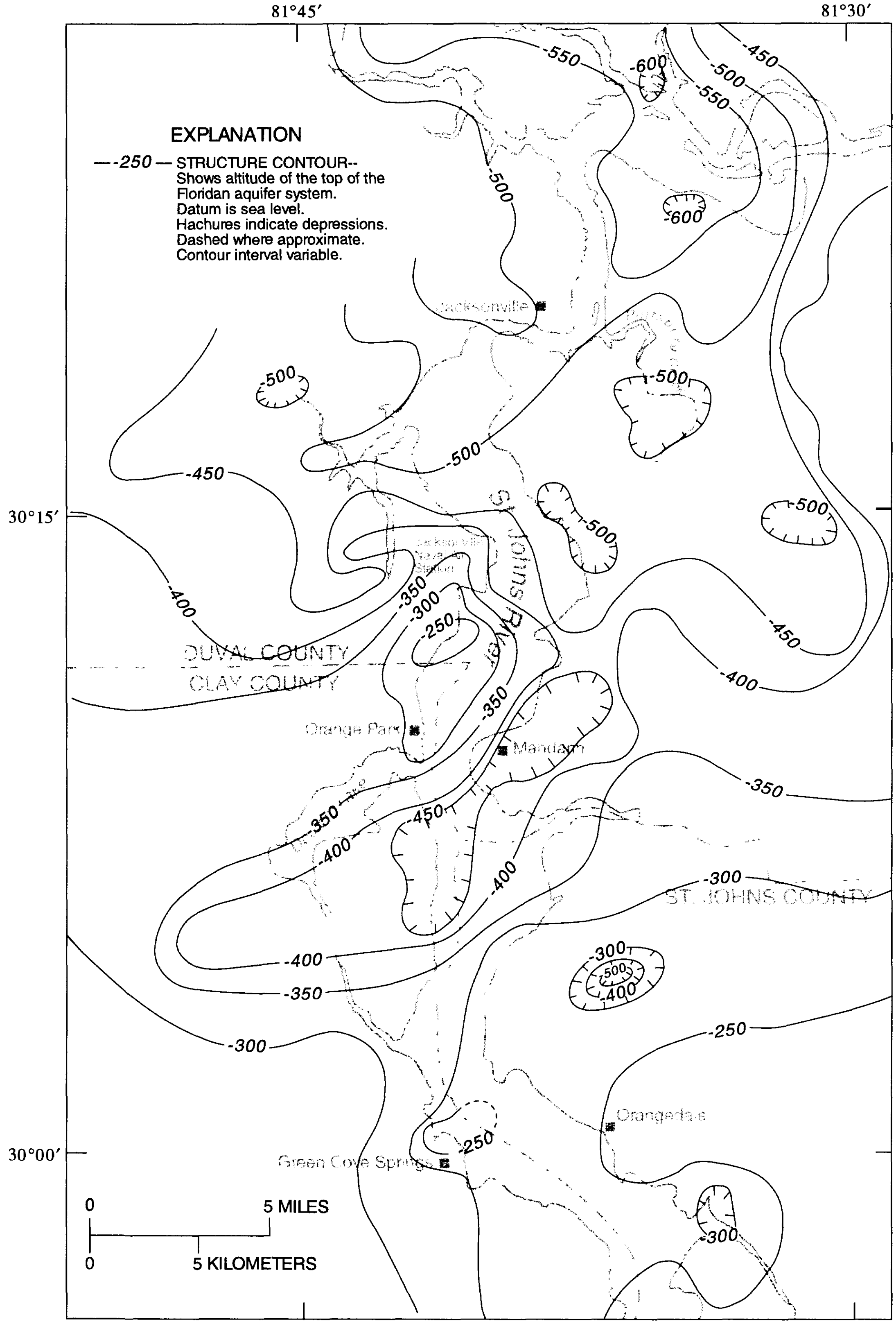

Figure 4. Altitude of the top of the Floridan aquifer system (modified from Spechler, 1994).

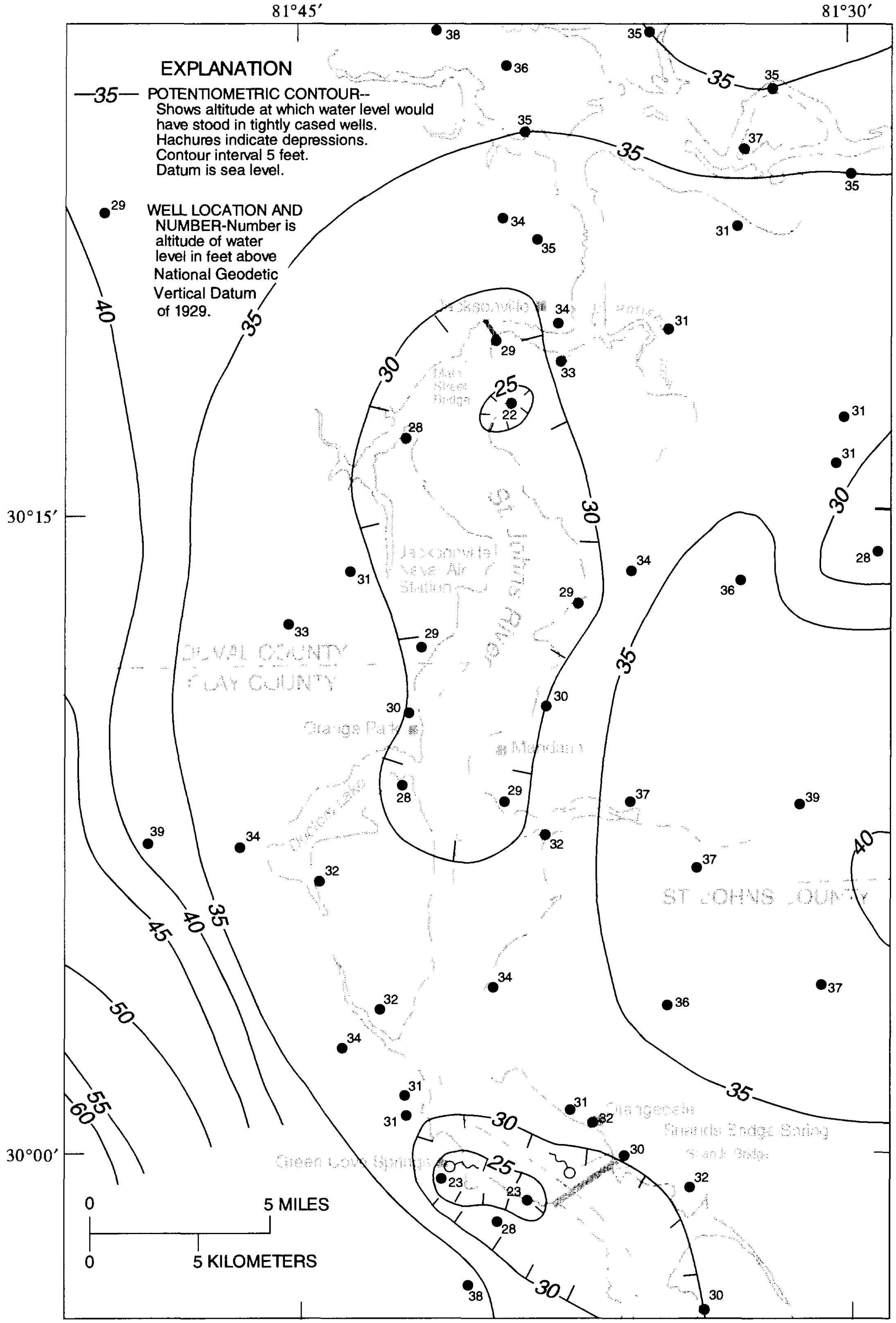

Figure 5. Potentiometric surface of the Upper Floridan aquifer, September 1992 (modified from Murray, 1993).

Two depressions in the potentiometric surface of the Upper Floridan aquifer along parts of the St. Johns River from Jacksonville to Green Cove Springs are shown in figure 5. To better define these depressions, additional wells were added to the well network for the September 1992 potentiometric surface map. The depression in the potentiometric surface from the city of Jacksonville south toward Mandarin is believed to be caused, in part, by withdrawals from industrial and public-supply wells, and possibly by diffuse upward leakage or undocumented spring discharge into the St. Johns River. Springs discharging into the river also are thought to exist in the central and southern part of this depression, near the Jacksonville Naval Air Station and Mandarin. However, to date, none have been located. In the Green Cove Springs area, the depression in the potentiometric surface is the result, in part, of withdrawals from domestic- and public-supply wells and withdrawals for irrigation immediately south of the area. Discharge of water by diffuse upward leakage and from springs in the St. Johns River also contribute substantially to this depression. Discharge from Green Cove Springs is about 2.5 to 5 ft^3/s, which is not enough to cause the observed potentiometric surface depression. However, the recent discovery of one small submerged spring in the St. Johns River near Orangedale indicates that other submerged springs probably exist.

Industrial and agricultural expansion and population growth in northeastern Florida during the last 50 years have resulted in increased water withdrawals from the Floridan aquifer system. In 1965, total pumpage from the Floridan aquifer system in Clay, Duval, Nassau, and St. Johns Counties was estimated at 178 Mgal/d. Total pumpage from the Floridan aquifer system was about 250 Mgal/d in 1990 (Marella, 1992, p. 9). The increase in pumpage over the years has caused a decline in the potentiometric surface of the Upper Floridan aquifer. In much of the study area, water-level declines in wells open to the Floridan aquifer system have averaged about one-third to one-half ft/yr. Declines in the potentiometric surface vary depending on location within the study area. The greatest declines in water levels are in heavily pumped areas in the parts of Duval County where water use for industrial and public-supply demand is greatest. Long-term water-level declines in the Upper Floridan aquifer are smallest toward the southern part of the study area where water demands are less.

METHODS

Detection of Spring Discharge

Several methods were used in an attempt to locate spring discharge to the St. Johns River, including the interpretation of geologic and hydrologic data, extensive interviews with local residents, advertising, and field reconnaissance. Thermal infrared images taken from an airplane provided information on the location of spring vents based on water temperature anomalies. Marine seismic reflection provided indirect indications of spring discharge, based on the underlying geologic structure.

Hydrogeologic Methods and Field Reconnaissance

The compilation and interpretation of new and existing hydrologic and geologic data for the study area provided information on potential areas of spring flow. Stratigraphic units and possible geologic structures were identified and maps were generated. Areas of potential spring discharge also were delineated by identifying potentiometric surface lows from potentiometric surface maps and from locations of existing springs.

During the course of the investigation, about 150 people familiar with the St. Johns River were interviewed. The results of these interviews and subsequent field reconnaissance were instrumental in identifying potential areas of spring discharge. Early in the investigation, hundreds of flyers advertising the search for submerged springs in the St. Johns River were posted in office buildings, fish camps, boat marinas, or passed out to boaters and recreational and commercial fisherman. Short articles also were written and published in some of the local boating, diving, and environmental club newsletters, as well as in local newspapers.

Responses from the various sources produced general locations of possible springs in the St. Johns River, as well as approximate locations of observed springs. Many of these areas were included in the field reconnaissance in an attempt to verify the presence of springs.

Thermal Infrared Imagery

Submerged springs discharging into the St. Johns River between Jacksonville and Green Cove Springs are thought to exist, but locating and evaluating these springs had not been attempted prior to this investigation. Thermal infrared imagery, a remote sensing technique, offered the potential of rapid aerial exploration for thermal anomalies that might indicate such springs.

Thermal infrared imagery is used for measuring a portion of the radiant energy that is emitted from the earth. Infrared detectors are used to measure radiation emitted in the 8–14 micrometer range because that wavelength range is an atmospheric window where absorption of the radiation by water vapor and carbon dioxide is low (Paulson, 1968). The energy of the radiation emitted by an object is primarily a function of its emissivity and temperature. For surfaces having a relatively constant emissivity factor, such as a water surface, any variations in the intensity of radiated energy can be related to variations in the surface temperature (Brereton, 1984, p. 3).

To detect infrared radiation, special detectors have been developed. The infrared-sensing element of these detectors is a solid-state device which converts the incoming infrared radiation into an electrical signal. A continuously rotating mirror scans the ground surface and directs the emitted radiation onto the detector through an optical focusing system. The scanning axis of the mirror is perpendicular to the flight path of the aircraft in which the equipment is mounted, so that as the aircraft moves forward, continuous coverage of the ground target is obtained. The electrical signal generated by the detector is amplified and stored on magnetic tape and then later recorded on photographic film (Brereton, 1984, p. 3).

Detection of springs using thermal infrared imagery depends on the temperature contrast between the potential spring and its surroundings. Ground water in the study area has a nearly constant year-round temperature of about 21.5–23.0 °C. By contrast, the temperature of water in the St. Johns River varies seasonally from a minimum of about 11.5 °C in mid-winter to about 29.5 °C in the summer. It is during these two seasons that the maximum temperature contrast would occur and, therefore, detection of any spring discharge would be more likely.

However, warmer water generated from springs tends to rise to the river surface during the winter making detection easier both in the field and by thermal infrared imagery. Also, the hydraulic head that controls the rate of ground-water discharge is still significantly higher in the winter than in the late spring and early summer, creating maximum spring flows. The head difference between ground water in the Upper Floridan aquifer and in the St. Johns River is further increased during periods of low tide, which may be as much as 1/2 to 1 1/2 ft below the highest tide in the study area.

Salinity also would be expected to be somewhat higher in the river because of decreased rainfall and surface-water runoff during the winter. If the discharging ground water is fresher than the river water, the ground water will tend to rise to the surface because of the difference in water densities, thus providing a better chance of detecting temperature differences at the water's surface.

The best imagery results are obtained during the hours of darkness, at which time the effects of solar heating are minimized. However, weather conditions need to be good (the equipment cannot be operated successfully through clouds, fog, or rain) because infrared radiation is absorbed by water vapor. Additionally, winds need to be relatively calm because strong winds will generate waves which may destroy any thermal anomalies.

Poor weather conditions in early 1992 prevented an areal survey during the period when temperature differences between the river and ground-water discharge were greatest. Windy, foggy, or wet weather conditions prevented an areal survey in January. Windy, wet, and warm weather conditions in early February caused the St. Johns River to begin to warm prematurely.

An aerial thermal infrared imagery survey of the upper reaches of the Jacksonville to Green Cove Springs reach was conducted on the night of February 20 and the morning of February 21, 1992, between the hours of 8:55 p.m. and 3:30 a.m. The areas of coverage for the survey are shown in figure 6. However, the survey was delayed for about 2 hours (around 11:30 p.m.) because some low-lying clouds entered the area. During the flight, the winds were 5 to 10 knots from the north, the skies were clear of clouds and fog, and the surface air temperature ranged from about 6 to 12 °C. At the time of the airborne data collection, river-water temperatures ranged from about 15.7 to 17.0 °C.

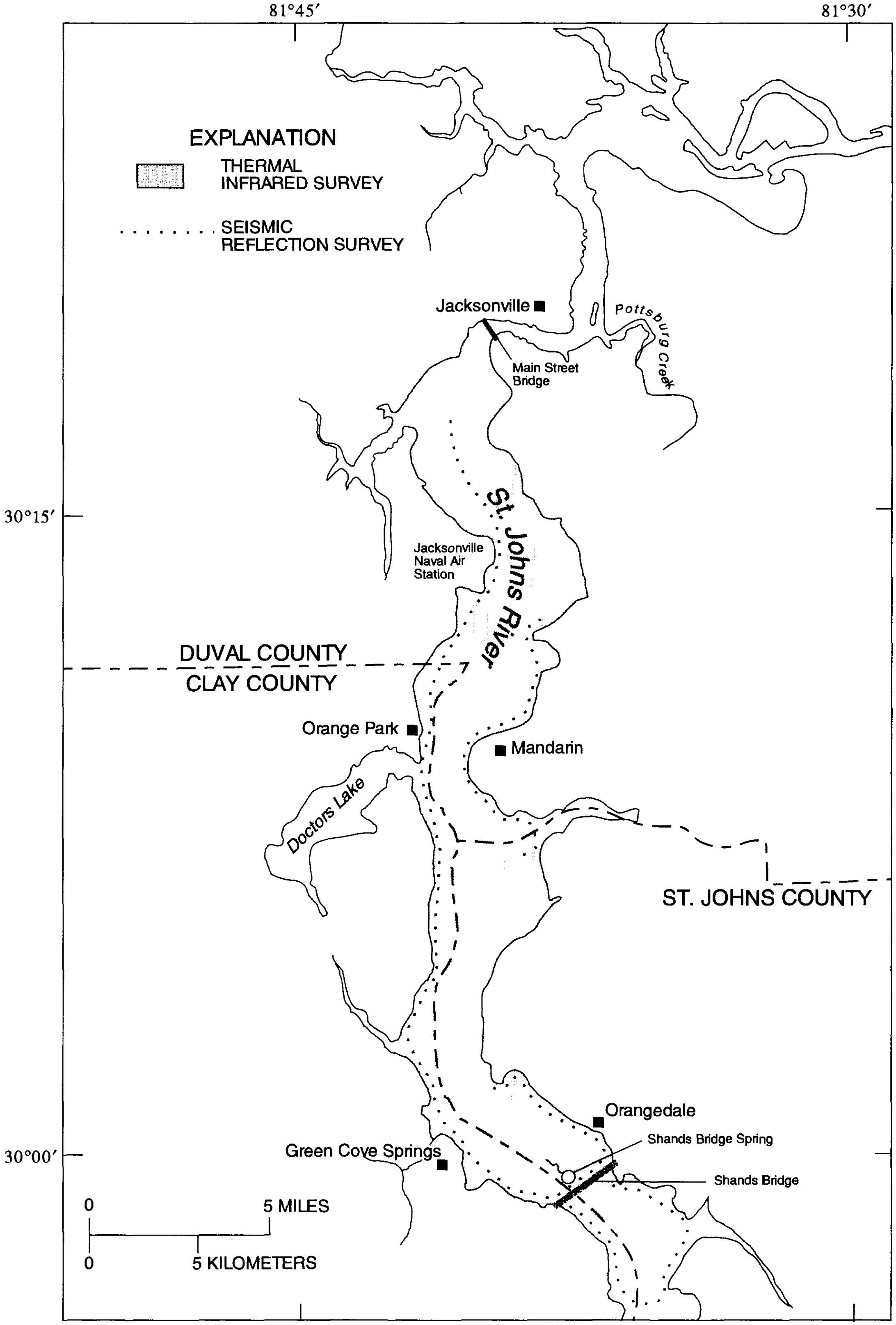

Figure 6. Location of thermal infrared imagery and seismic reflection surveys.

A Daedalus 1230 scanner was used for the survey. The infrared detector is sensitive to radiation emitted in the 8 to 14 μm range and has a temperature resolution of about 0.2 °C. All flights were carried out at an altitude of 2,000 ft above sea level. At this altitude, 23 flight lines with scan widths of about 3,200 ft were flown parallel to the river. The flight lines were planned to provide an overlap of coverage between adjacent swaths. Thermal infrared data were recorded on analog magnetic tape during the flight and later transferred to photographic film. Images produced are similar to black and white photographs. On these photographic prints, dark tones indicate relatively warm surfaces and light areas indicate cooler surfaces.

Continuous Seismic Reflection

A continuous seismic-reflection survey also was conducted on selected reaches of the St. Johns River from Jacksonville Naval Air Station to a few miles south of the Shands Bridge near Green Cove Springs (fig. 6). This study was done in cooperation with North Carolina State University to examine geologic structures beneath the river that might be related to spring discharge or upward diffuse leakage.

Seismic-reflection data were collected using a mix of components from the EG&G UNIBOOM and ORE GEOPULSE profiling systems. The frequency spectrum of these profiling systems ranges from 400 Hz to 14 kHz. All data are single-channel, analog profiles. Power levels on the seismic source varied, but generally ranged between 100 to 300 joules. The electromagnetic transducer was consistently fired every 0.4 seconds. The incoming signal was collected on a multi-element hydrophone and filtered between 500 Hz and 5 kHz. These data were graphically displayed using an EG&G 254 recorder. An 18-ft outboard-powered boat was used to convey the seismic-reflection system and the three-man field crew. The sound source and hydrophones were towed from opposite sides of the boat, about 10 to 20 ft apart. Both were towed about 50 to 75 ft behind the boat to minimize noise interference from the motor. Navigation was by LORAN C, with positions taken about every 2 minutes and features marked as necessary.

Areas of the St. Johns River where thick organic sediments are present were avoided when possible because the gas associated with them impeded the seismic signal and often did not produce an interpretable record. The most useful transects were focused near the shoreline where organic-rich sediments were thinner or nonexistent. The quality of the seismic profiles, depending primarily on the presence or absence of the organic sediments, varied from poor to very good.

Water Quality Sampling

Water samples were collected from five springs in the study area (fig. 1 and table 1). Samples were collected at the source of each spring. Where there was a spring pool, a weighted bottle was lowered into the spring vent and a water sample collected. Because one of the five springs sampled was located at the bottom of the St. Johns River, a method was devised to collect a water sample that would not be contaminated with river water.

Water samples originally were collected from the submerged spring by diving into the spring with water-filled plastic sample bottles. Each bottle was then emptied by inverting and filling it with air from a SCUBA regulator. A water sample was then collected at the spring orifice. However, because of the small amount of water discharging from the spring, the water samples showed evidence of mixing with river water. On a second dive made at a later date, a water sample was collected from the spring using a method designed to prevent mixing. A 2-in diameter, 5-ft PVC well point with the first 2 ft slotted, was driven into the orifice of the spring. Attached to the PVC well point were 60 ft of .25-in. diameter plastic tubing. An uncontaminated water sample was obtained by pumping the water from the spring vent to the surface using a small peristaltic pump.

Water samples were processed at the time of collection using standard USGS procedures (Brown and others, 1970). Samples collected to determine dissolved-constituent concentrations were filtered through a 0.45-micron membrane filter. All water samples were analyzed at a USGS laboratory using analytical procedures described by Fishman and Friedman (1985).

Table 1. Record of springs in the study area

[Spring locations shown in figure 1; ft^3/s, cubic feet per second]

Site identification number	Local name	Probable source of aquifer water	Altitude of land surface, in feet above or below (-) mean sea level	Range of discharge (ft^3/s)	Number of measurements
295916081372800	Shands Bridge Spring	Floridan aquifer system	−30	1.0 (estimated)	0
295936081404000	Green Cove Springs	Floridan aquifer system	10	1.15–5.40	9
300913081434500	Camp Echockotee Spring	Surficial aquifer system	15	0.139	1
300925081432000	Wadesboro Spring	Intermediate confining unit	5	0.71–1.41	4
301759081343800	Pottsburg Creek Spring	Surficial aquifer system/ Intermediate confining unit	−2	1.29 (discharge measurement possibly influenced by tide	1

DETECTION OF GROUND-WATER DISCHARGE

Possible areas of ground-water discharge were determined from interviews, field reconnaissance, examination of thermal infrared images, and by continuous seismic-reflection surveys. Although most of the interviews with local residents did not lead to the detection of submarine springs in the lower St. Johns River between Jacksonville and Green Cove Springs, at least one spring was found through these interviews. Before more sophisticated methods were attempted, suspected locations of ground-water discharge were investigated through field reconnaissance. Thermal infrared imagery and seismic-reflection surveys were used to further investigate suspected discharge locations following initial field reconnaissance.

The thermal infrared imagery obtained from the survey was carefully examined to identify thermal anomalies on the river. The initial interpretation consisted of simply recognizing a "hot" spot and plotting its location on a nautical chart. During the summer and winter months following the infrared imagery (the period when the ground-water/surface-water temperature differences were at their maximums), numerous field trips were made to the St. Johns River.

Some of the warmer temperature anomalies determined from the thermal infrared imagery were found to be associated with some shallow areas of the river. As previously mentioned, the weather preceding the survey was unusually warm. Some of the very shallow areas in the river are covered primarily with *Vallisneria americana*, a brackish-water grass (B. Brody, St. Johns River Water Management District, oral commun., 1994). The grass is green to light brown and tends to absorb solar radiation during the day, causing the temperature of the water to rise above that of the adjacent riverwater. The presence of these grasses also reduced the circulation in these shallower areas, partially isolating the water from the areas of higher velocities. The heat, which was retained in the shallow areas during the evening thermal-imagery flight, not only produced several areas of significant thermal contrast, but sometimes produced small, isolated, dark areas that sometimes appeared to be areas of ground-water discharge.

The application of thermal infrared imagery in locating spring discharge into the St. Johns River was somewhat successful in identifying natural discharges to the river. At least one temperature anomaly identified in the St. Johns River was associated with spring discharge from the Floridan aquifer system. The exact location of this spring was later confirmed by P. Noles, U.S. Army Corps of Engineers. The spring is referred to in this report as the Shands Bridge Spring. Figure 7 shows a thermal plume located about 1,850 ft north of the Shands Bridge and just west of Orangedale. The plume, approximately 700 ft in length, trails in a southeasterly direction toward the Shands Bridge.

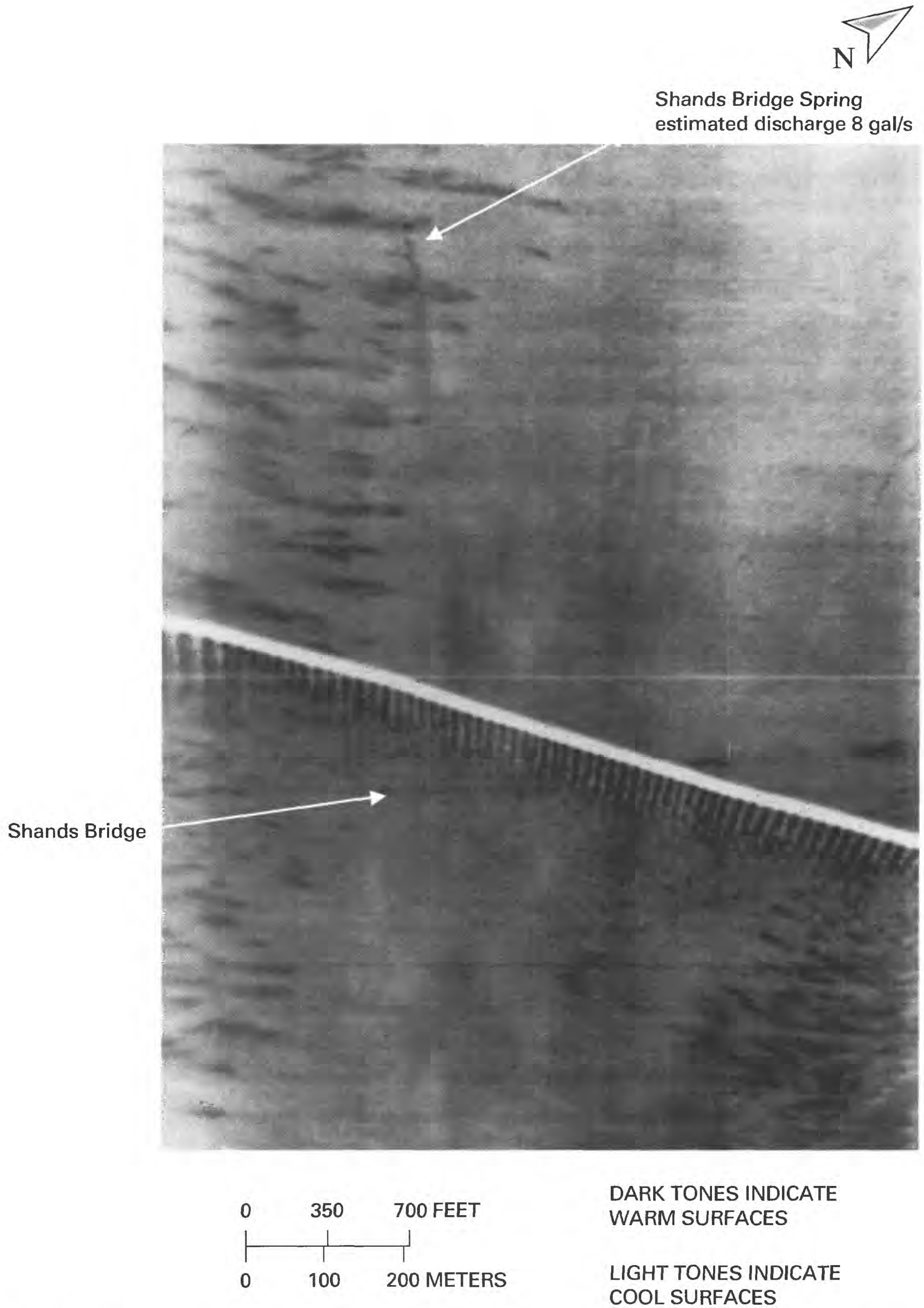

Figure 7. Thermal infrared imagery showing discharge of water from a submerged spring in the St. Johns River (location shown in figure 1).

Fathometer readings around the spring indicate a depression in the river bottom. The depth of the depression at its deepest point is 30 ft. Discharge from the spring was estimated at 1 ft^3/s (about 8 gal/s) by direct observation from divers using SCUBA. Temperature of the springwater was measured at 25.1 °C. The morphology and water chemistry of the Shands Bridge Spring will be discussed in more detail in later sections.

The thermal infrared imagery also identified six artificial discharges to the river. At the time of the survey, 10 municipal or industrial facilities were discharging treated wastewater into the St. Johns River (fig. 8) in amounts ranging from about 0.3 to 63 gal/s (table 2). The thermal plumes from the effluent from four submerged outfalls are visible in figure 9.

The largest plume observed is produced by wastewater effluent discharged from the city of Jacksonville's Southwest District municipal wastewater treatment plant (fig. 9A). Approximate discharge to the river was 63 gal/s. Although the temperature of the discharged effluent is not known, it was estimated at 19–20 °C based on temperature measurements of effluent from other wastewater-treatment facilities. The depth of the discharge pipe is about 10 ft below the surface of the water. The effluent is warmer than the receiving waters of the St. Johns River, as indicated by the darker shades of gray.

Thermal plume from wastewater treatment facilities that discharge smaller amounts of treated wastewater also were clearly visible in the St. Johns River. At the Orange Park facility, discharge was estimated at 10 gal/s (fig. 9B). Estimated temperature of the effluent was 19–20 °C. Depth of the discharge pipe is about 9 ft below the surface of the water. Thermal plumes also were visible at the Jacksonville Naval Air Station and Kingsley Service-Miller Street facility (fig. 9A and B). Discharges at the two sites were about 17 and 48 gal/s, respectively, and approximate temperatures of the discharged effluent were 19.5 °C and 19.0 °C, respectively. Depths of the discharge pipes were about 4 and 7 ft, respectively.

An approximation of the effectiveness of thermal infrared imagery for detecting natural ground-water discharge to the St. Johns River was determined using municipal and industrial outflows as controls in areas where approximate discharges and temperatures of the wastewater effluent and river depth were known. At several sites, the thermal plumes from the industrial and domestic outflows were clearly visible; whereas at other sites, the thermal plumes were barely visible or not visible at all. Whether a temperature anomaly is observed depends not only on the temperature of the effluent and the quantity of water being discharged, but also on the depth of the discharged water and the streamflow velocity.

Water depths in the St. Johns River in the reach from Jacksonville to Green Cove Springs generally are less than 25 ft, and in many stretches of the river, depths do not exceed 10 ft. Maximum velocities range from about 6 ft/s in the channel at the Main Street Bridge to less than 2 ft/s at the Shands Bridge (John Sloat, U.S. Geological Survey, oral comm., 1994). A spring beneath the surface of the river can be detected only if the spring water reaches the surface of the river and the temperature difference is within the resolution limits of the detector. That is, if a high-flow point-source discharge of high temperature contrast emanates into a low-flow or shallow water body, then the thermal anomaly after mixing should be readily detected. If, on the other hand, a low-flow spring emanates into a high-flow or deep water body, then rapid mixing will take place and the thermal anomaly at the water surface may be too small to be detected.

Seismic profiles collected from the St. Johns River in the study area revealed some solution collapse and other karst features similar to those described in the preceding paragraph and by other investigators. Figure 10A shows a small collapse feature located near Orangedale in St. Johns County. The seismic record shows a collapse feature in which the reflectors have been deformed by the collapse. The collapse of the overlying strata is estimated to have resulted in about 30 ft of subsidence. Width of the collapse feature is estimated to be 400 to 500 ft.

A smaller solution collapse feature or pipe (fig. 10B) is marked by the abrupt lateral termination of continuous Miocene and Eocene reflectors. Subbottom strata gaps exist where the Miocene and Eocene sections have apparently disappeared, possibly indicating collapse into an underlying cavern. The feature appears to be filled with sediment, some of which is gas charged as demonstrated by the attenuation of the seismic signal. Termination of the subbottom flexures in the underlying strata in the collapse features shown in figure 10 could not be observed due to the penetration limits of the seismic equipment used.

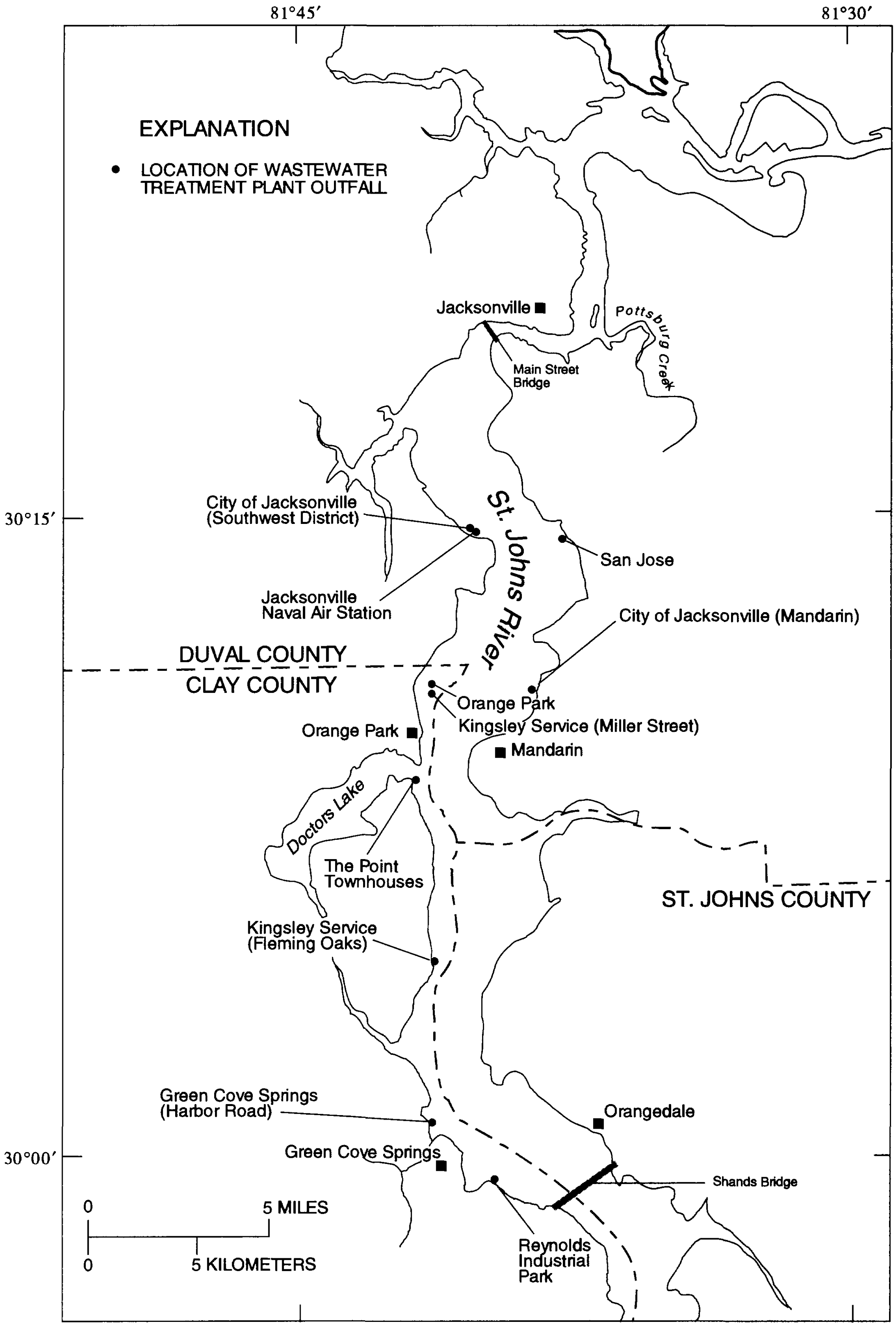

Figure 8. Location of wastewater treatment plant outfalls to the St. Johns River.

Table 2. Domestic and industrial wastewater treatment facilities that discharge directly into the St. Johns River (data from the files of the Department of Environmental Protection and individual plant operators)

[Locations shown in figure 8; gal/s, gallons per second; °C, degrees Celsius; <, less than]

Wastewater treatment plant	Estimated discharge at the time of survey (gal/s)	Resolution	Reported temperature of effluent (°C)	Approximate depth of discharge pipe (feet)
City of Jacksonville (Southwest District)	63	excellent	unknown	10
City of Jacksonville (Mandarin)	49	good	unknown	8
Green Cove Springs (Harbor Road)	< 4	not observed	unknown	3
Kinsley Service (Fleming Oaks)	3	not observed	20	5
Kinsley Service (Miller Street)	48	excellent	19	7
Jacksonville Naval Air Station	17	excellent	19.5	4
Orange Park	10	excellent	unknown	9
Reynolds Industrial Park	< 0.5	not observed	unknown	2
San Jose	24	fair	unknown	7
The Point Townhouses	< 0.05	not observed	18	6

Several seismic transits also were collected around the spring that was discovered north of the Shands Bridge. It was hoped that the seismic reflection profiles could prove the association of this spring with collapse features. However, organic flocculent surrounding the spring vent tended to attenuate the seismic signal, therefore little about the subsurface geology or structure underlying the spring could be determined from the seismic record.

Results of seismic reflection surveys show a variety of different solution collapse features underlying the St. Johns River. Some of these collapse features can be hundreds to thousands of feet in diameter (solution valleys). Others are only tens of feet in diameter (solution pipes). Although some of the solution collapse features may form in the carbonate units within the Hawthorn Formation, many appear to originate in the Eocene carbonate rocks of the Floridan aquifer system. Where caverns develop and collapse occurs in the Floridan aquifer system, the overlying Miocene confining unit can be deformed. The deformation or destruction of these confining beds create zones of relatively high vertical leakance, which would provide a potential pathway for connections between the Upper Floridan aquifer and the St. Johns River.

FIELD VERIFICATION OF SUSPECTED GROUND-WATER DISCHARGE

Suspected ground-water discharge locations were further investigated following analysis of thermal infrared imagery and seismic-reflection surveys. At each suspected area, the site was examined for signs of spring discharge, such as boils, surface slicks, or a hydrogen sulfide odor. A probe was then lowered to the river bottom, where measurements of temperature and specific conductivity were recorded as the boat drifted over the site.

Spring vents in the river were difficult to locate because of the depth of the water, relatively fast tidal-induced currents, and the probable small volume being discharged from these springs. Temperature probes lowered into the river were unable to detect temperature anomalies at the surface or in the upper part of the water column near the vent of the Shands Bridge Spring. The spring discharge was identified only when the temperature probe was lowered near the bottom and passed directly over the spring vent. Because of the small volume discharging through the vent (estimated at 1 ft^3/s), the thermal anomaly was quickly dissipated by the mixing of the spring water with the tidally affected riverwater.

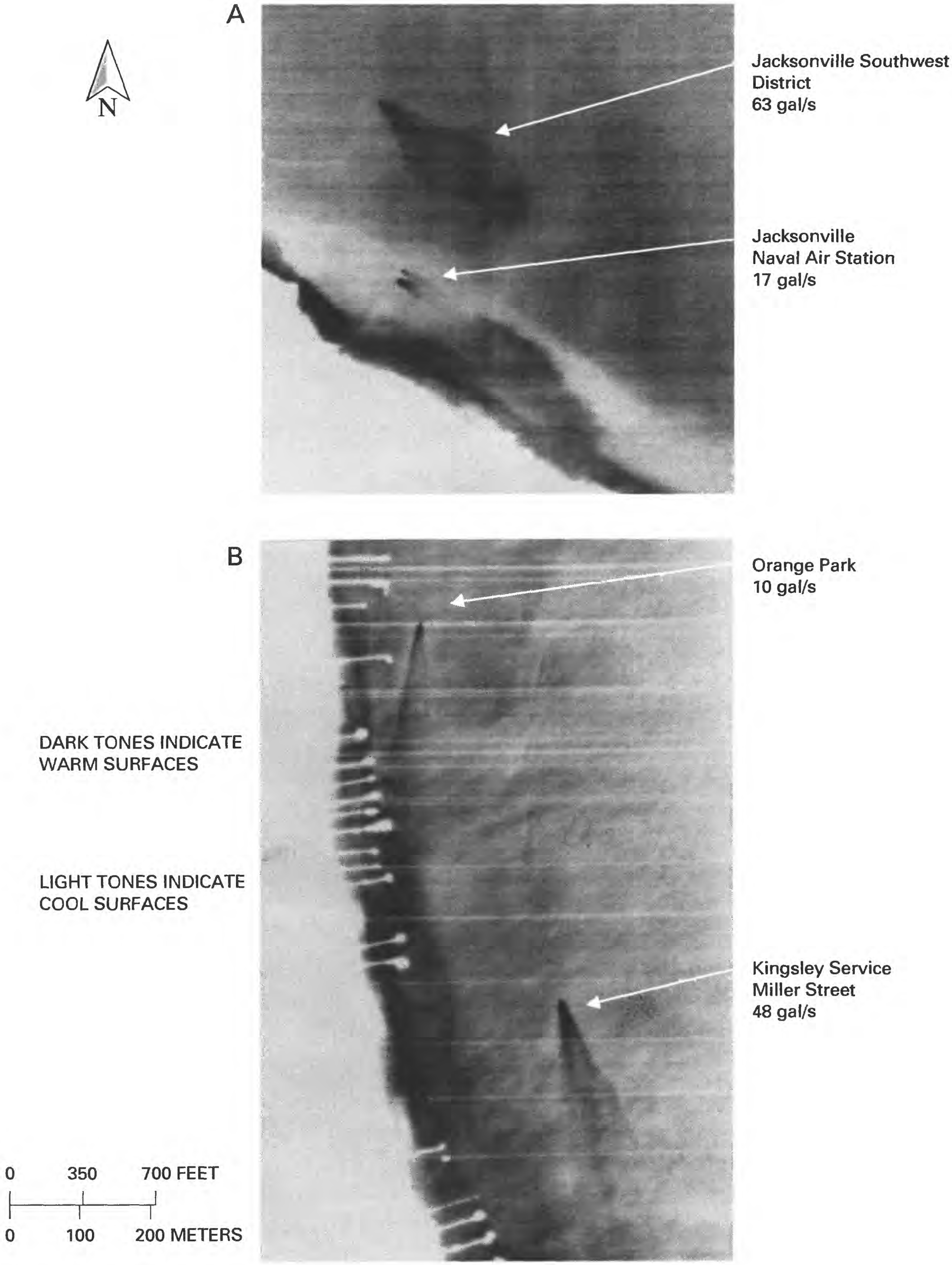

Figure 9. Thermal infrared imagery showing discharge of treated wastewater effluent into the St. Johns River (location shown in figure 10).

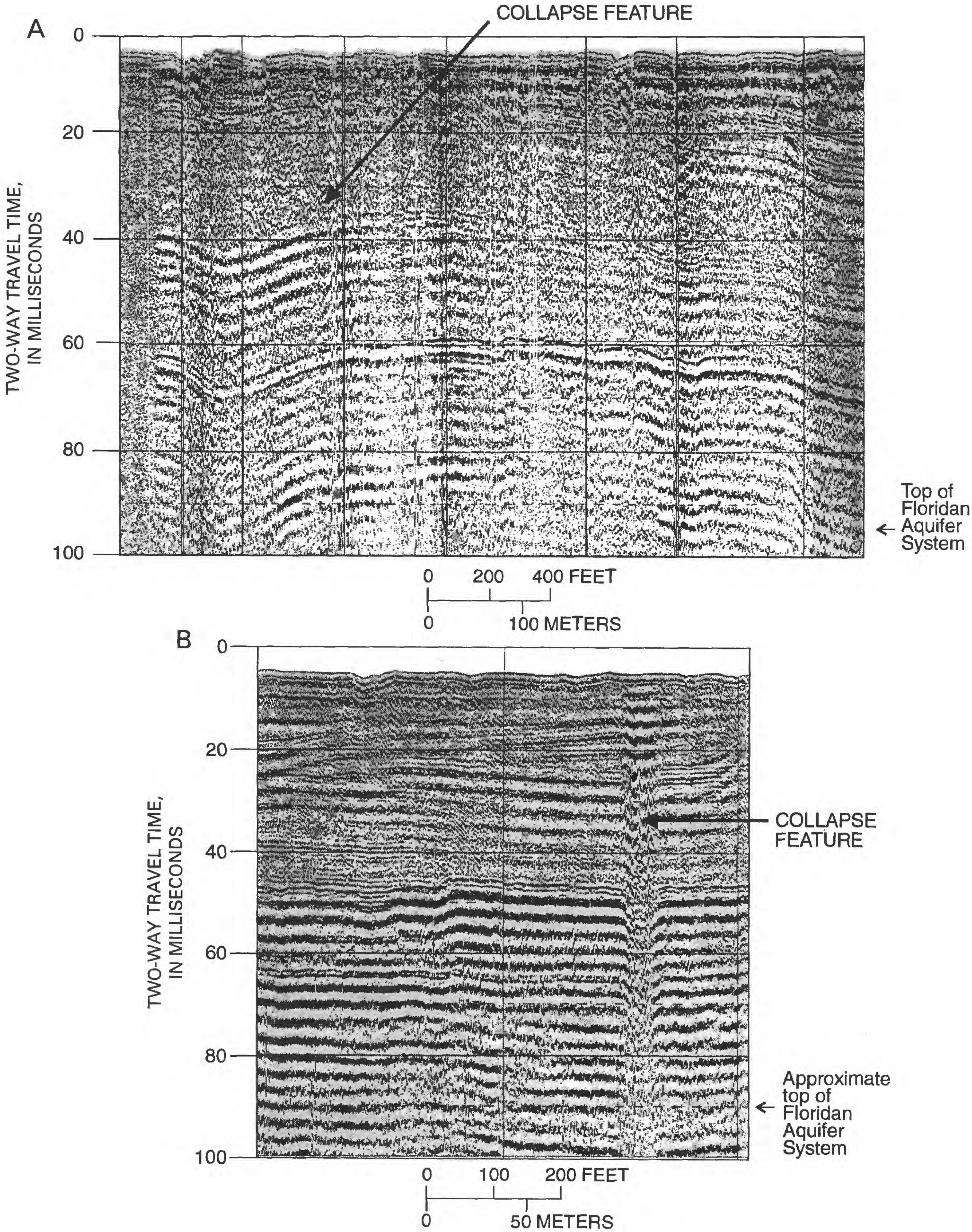

Figure 10. Seismic record showing collapse features along the St. Johns River near Orangedale, St. Johns County (location of collapse features shown in figure 1).

Once the spring was located, it was explored and water samples were collected by divers using SCUBA. Two dives were made at the Shands Bridge Spring. The greatest problem associated with diving at the spring site was extremely poor visibility (less than 1 ft). Underwater lights were ineffective because of the backscatter from suspended matter and the dark brown color of the water caused by tannic acid. Within the depression, the river bottom was covered with fine sediment and organic material that easily moved into suspension, further reducing the visibility of the water. At a depth of about 20 ft, sunlight was completely filtered out, making visual observation virtually impossible.

The water is about 17 to 20 ft deep in the vicinity of the Shands Bridge Spring. The water becomes deeper near the spring vent, and a nearly circular depression (recorded by a fathometer) was observed in the bottom of the river. Ground-water discharges from a vent at the deepest point in the spring (30 ft).

A large amount of debris in and around the spring vent made exploration and data collection difficult. Several crab traps were lying on the river bottom adjacent to the spring and an unknown number were lodged in the spring vent. A log and other unidentified debris also were scattered about the depression.

Of particular interest is the fact that such a low-flow discharge point could produce a thermal signature at the surface of the river that could be observed on a thermal infrared image. Each time the Shands Bridge Spring was visited, the thermal plume was always evident near the bottom of the river but was never observed at or near the surface. Although spring discharge appears to be small, it is possible that at the time of the investigation, current velocities were favorable, allowing the warmer water to reach the surface. However, two other scenarios could explain the observed thermal infrared plume. From the time the thermal infrared survey was performed to the time the spring was discovered, approximately 1 year had passed. It is possible that some of the debris found within the spring vent could have been deposited during that period, considerably reducing the amount of ground water being discharged. Therefore, during the initial thermal infrared survey, ground-water discharge could have been considerably greater. Another explanation could be the presence of another unidentified spring in the immediate area. Although the thermal plume observed from the infrared images matches the general area of the identified submerged spring, another spring of much greater discharge could be nearby.

Attempts to match geologic features obtained from the seismic reflection with spring discharge were inconclusive. Temperature and specific conductance profiles taken in the vicinity of several probable collapse features did not identify spring discharge to the St. Johns River. However, if the spring discharge from a vent was small, the detection of ground-water discharge could have been missed by the temperature probe. Also, subsidence features may be areas of diffuse upward leakage and probably would show no observable thermal anomalies near the bottom.

The lack of discovery of additional Floridan aquifer system springs, if they are present, can be explained in part by the presence of relatively fast water currents and depths of as much as 25 ft, factors which make the detection of springs with low discharge rates difficult. Additionally, the thermal infrared imagery data collected in some of the areas surveyed were of poor quality due to instrument problems. Another factor, which can explain the difficulty in locating spring discharge from the Floridan aquifer system, is the gradual decline in the potentiometric surface of the Upper Floridan aquifer over the years. Long-term declines in the Upper Floridan aquifer have been averaging about 1/3 to 1/2 ft/yr in much of the study area. This decline in head over the study area could, in effect, reduce the flow of springs discharging into the St. Johns River. This reduction in flow would in turn decrease the chances of detecting spring flow by locating boils, or surface slicks, or by thermal infrared imagery.

WATER QUALITY OF SPRINGS

The source of ground-water discharge to the St. Johns River was verified by determining the quality of water at the suspected discharge site and comparing it to the quality of water from the Upper Floridan aquifer in the area. Many factors affect the chemical characteristics of ground water in the study area including the initial chemical character of the water recharging the aquifer, the composition and solubility of rocks with which the water comes in contact, and the length of time the water has been in circulation. The mixing of freshwater with relict and connate seawater also affects the quality of water in the Upper Floridan aquifer within the study area.

The water quality within the Floridan aquifer system varies vertically and areally in the study area. The areal distribution of specific conductance in water collected from the Upper Floridan aquifer ranges from about 150 to 1,310 µS/cm (Spechler, 1994; unpublished data in files of the U.S. Geological Survey, Altamonte Springs, Fla.) and generally increases toward the east. Lowest specific conductance values are in northeastern Clay County where specific conductance values of less than 300 µS/cm are common. Highest specific conductance values in the study area mostly occur in northwestern St. Johns County.

Sulfate concentrations range from about 1 to 640 mg/L (Spechler, 1994; unpublished data in files of the U.S. Geological Survey, Altamonte Springs, Fla.) and generally increase toward the east. Lowest sulfate concentrations in the study area are in northeastern Clay County, where concentrations of dissolved sulfate generally are less than 10 mg/L. Highest sulfate concentrations are in northwestern St. Johns County. Chloride concentrations in water from the Upper Floridan aquifer in the study area range from about 4 to 250 mg/L, but in most locations, concentrations are less than 30 mg/L (Spechler, 1994; unpublished data in files of the U.S. Geological Survey, Altamonte Springs, Fla.). Lowest concentrations are present in northern Clay County where concentrations generally are less than 5 mg/L. Chloride concentrations increase toward the east, but generally do not exceed 20 mg/L.

Chemical analyses of water from two of the five springs sampled—the Shands Bridge Spring and Green Cove Springs—indicate that the probable origin of the water is the Floridan aquifer system. Water from three other springs—Pottsburg Creek, Camp Echockotee, and Wadesboro Springs—probably originates from the surficial aquifer system or the carbonate units within the Hawthorn Formation (intermediate confining unit). These springs, though not located in the St. Johns River, are discussed briefly because of their proximity to the river and because little or no geochemical data have been reported. The springs at Pottsburg Creek and at Camp Echockotee have not previously been documented.

Results of the chemical and physical analyses of water from the five springs are listed in table 3. Samples were analyzed for major cations, anions, trace elements (iron and strontium), and $^{87}Sr/^{86}Sr$. Field specific conductance, temperature, and pH also were measured in the field at the time of sample collection.

The quality of water sampled from Green Cove Springs and the Shands Bridge Spring is consistent with published maps showing water-quality of the Upper Floridan aquifer. At Green Cove Springs, chloride and sulfate concentrations were 6.4 and 56 mg/L, respectively; specific conductance was 292 µS/cm. The concentration of chloride in water collected from the Shands Bridge Spring, located about 3 mi east of Green Cove Springs, was 12 mg/L. Sulfate concentrations and specific conductance values were 340 mg/L and 826 µS/cm, respectively. The high strontium and sulfate concentrations in the spring water also indicate that the probable source of the water is from the Floridan aquifer system.

Water-quality analyses of spring water from Green Cove Springs and the Shands Bridge Spring show differences in the dissolved ionic composition. These water types are illustrated in the plot of major cations and anions equivalent concentration percentages on the trilinear diagram shown in figure 11. Water from the Shands Bridge Spring is typical of a calcium magnesium sulfate water commonly present in the Upper Floridan aquifer in northern St. Johns County. This water type contains low concentrations of sodium and chloride and the dominant ion is sulfate. Water from Green Cove Springs represents a transitional water type whose chemical quality is intermediate between a calcium bicarbonate and a calcium magnesium sulfate type. Calcium, magnesium, bicarbonate, and sulfate are the major cations and anions. Individual cation or anion species generally did not exceed 55 percent of the total milliequivalents per liter in this water type.

Water samples also were collected from Camp Echockotee, Pottsburg Creek, and Wadesboro Springs (fig. 1 and table 3). The probable origin of the water from Camp Echockotee Spring is from the surficial aquifer system (Pleistocene or Pliocene sediments) based primarily on the low strontium and high iron concentrations. Water from the Upper Floridan aquifer in the study area generally has considerably higher strontium and lower iron concentrations than water from the surficial aquifer system. The relatively high calcium concentrations in the water from the spring also indicate probable contact with shallow carbonate deposits, most likely consisting of shell beds.

Table 3. Chemical and physical analyses of water from springs in the study area

[°C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 °C; µg/L, micrograms per liter]

Local name	Date	Water temperature (°C)	pH (standard units)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Iron, dissolved (µg/L as Fe)	Strontium dissolved (µg/L as Sr)	[a]Strontium87/Strontium86	Chloride dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Floride, dissolved (mg/L as F)	Alkalinity (mg/L as $CaCO_3$)	Specific conductance (µS/cm)	Silica, dissolved (mg/L as SiO_2)
Camp Echockotee Spring	12–17–93	21.7	7.18	45	4.9	11	0.8	2,400	78	0.70929	24	14	0.1	111	325	5.3
Green Cove Springs	12–17–93	24.8	7.11	29	15	4.7	1.5	7	1,200	0.70790	6.4	56	.2	82	292	13
Pottsburg Creek Spring	01–22–94	22.1	7.38	54	26	12	1.2	12	190	0.70911	18	17	.1	150	380	15
Shands Bridge Spring	03–04–94	25.1	7.58	98	45	9.3	2.7	4	4,600	0.70783	12	340	.5	92	826	16
Wadesboro Spring	01–15–93	22.3	7.08	42	8.1	9.1	1.0	280	230	0.70846	17	20	.2	117	328	8.0

[a]All numbers are precise to better than 0.00002 at the 95 percent confidence level. All data have been normalized to $^{86}Sr/^{88}Sr$=0.1194. NBS 987 is measured as 0.71024.

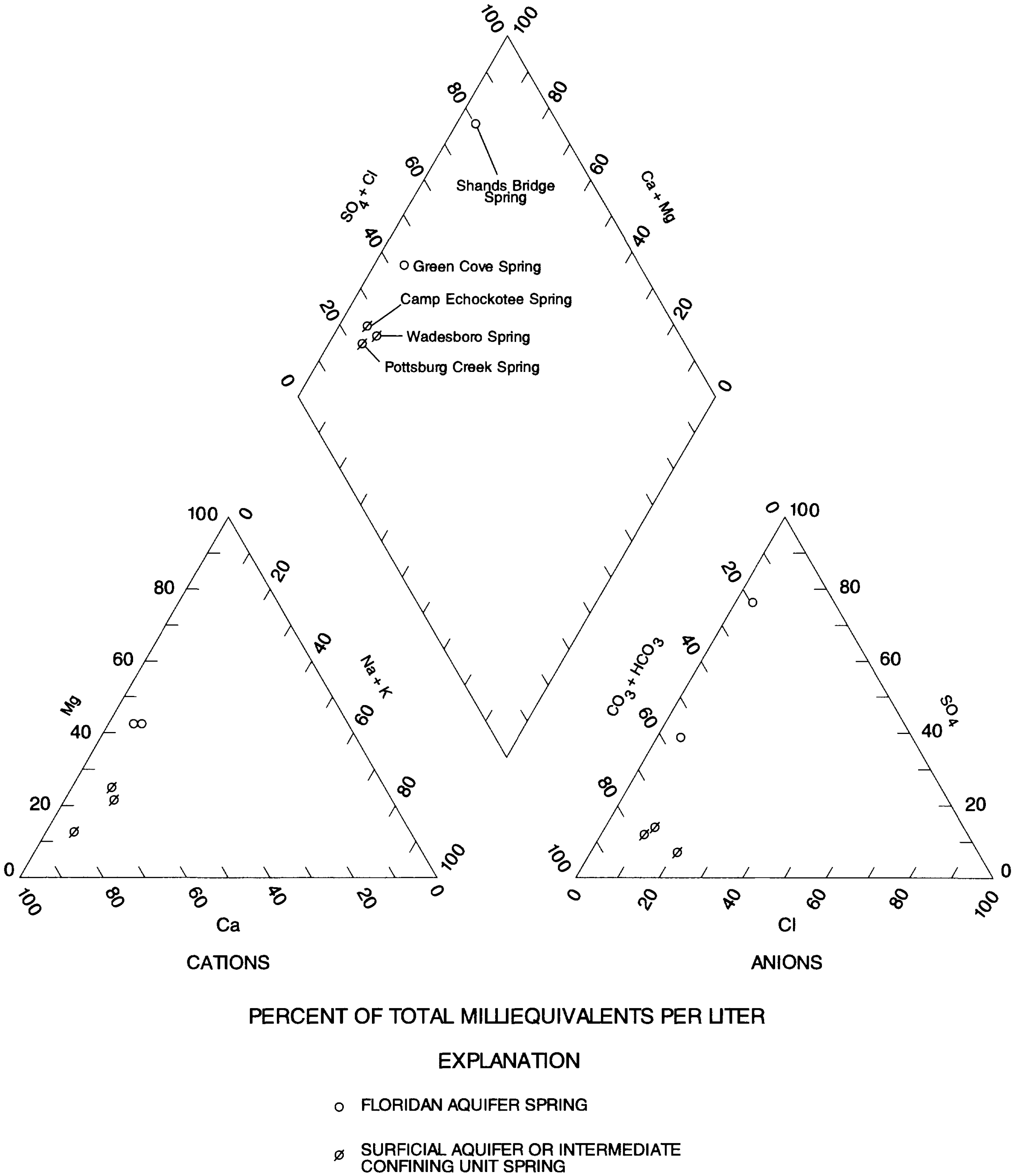

Figure 11. Major dissolved-constituent ratio in water from springs.

Relatively low specific conductance values, sulfate, and strontium concentrations in the water samples collected from Pottsburg Creek Spring indicate that the water does not originate from the Upper Floridan aquifer. Calcium and magnesium concentrations indicate discharge from underlying carbonate units that generally are present near the top of the Hawthorn Formation. A carbonate unit consisting of limestone and dolomite underlies much of Duval County and at this location is estimated to be 10 to 15 ft below land surface. Higher iron and lower strontium concentrations in water from Wadesboro Spring also indicate that the source of the spring water is not the Upper Floridan aquifer. The chemical analyses of the water indicate contact with carbonate units, probably also within the Hawthorn Formation.

Trilinear diagrams indicate that water from all the surficial or intermediate confining unit springs are a calcium bicarbonate type (fig. 11). They contain low concentrations of sodium, chloride, and sulfate. The dominate anion is bicarbonate, which is characteristic of a carbonate aquifer.

In an effort to further confirm the aquifer source of the spring water, isotopic compositions of strontium were determined from water samples collected at each spring. Results of the $^{87}Sr/^{86}Sr$ isotopic ratios are presented in table 3.

$^{87}Sr/^{86}Sr$ ratio is a technique that has successfully been used for stratigraphic correlation and absolute dating of marine sediments (Burke and others, 1982; DePaolo and Ingram, 1985; DePaolo, 1986; Elderfield, 1986a; Hess and others, 1986; Hodell and others, 1990; and Miller and others, 1988). Strontium isotopic ratios also can be used to identify the source of the rock materials that are in contact with the ground water (T.D. Bullen, U.S. Geological Survey, oral commun, 1994). Water that reacts with marine carbonates and/or evaporites will carry the $^{87}Sr/^{86}Sr$ ratio of those rocks. Using this ratio, it may be possible to tell with which rock units it has reacted. Certain conditions, however, can affect the accuracy of the strontium isotopes when used for identifying a ground-water aquifer source. Because pore waters are open systems, the ground water could exchange strontium from overlying clays as the water is discharged upward through the overlying Hawthorn Formation. Strontium ratios of ground water also could be affected by diagenesis of the carbonate rocks. Carbonate rocks that undergo diagenesis have strontium isotope ratios that usually are different from the ranges observed for unaltered carbonates. Input from these sediments may cause the strontium isotope ratio of pore water to differ from that of coexisting sediments.

If the ratios have not been altered significantly, the approximate age of the rock material in contact with ground water can be determined from the strontium isotopic ratios. Table 4 shows the range of seawater $^{87}Sr/^{86}Sr$ ratios from Eocene to Holocene. Physical constituents and major cations and anions determined from water samples collected from the Shands Bridge Spring and Green Cove Springs indicate that the probable source of the water is the Floridan aquifer system. The $^{87}Sr/^{86}Sr$ value of 0.70783 obtained from water from the Shands Bridge Spring (table 3) is within the range of middle Eocene strontium isotopic values, indicating that the Eocene-age host rock is the probable source of strontium. A $^{87}Sr/^{86}Sr$ isotopic ratio of 0.70790 obtained from the waters from Green Cove Springs indicates water of Late Eocene age.

Table 4. Seawater $^{87}Sr/^{86}Sr$ ratios and corresponding age (T.D. Bullen, U.S. Geological Survey, written commun., 1994)

Age	$^{87}Sr/^{86}Sr$ range
Eocene	0.70775–0.70790
Oligocene	0.70790–0.70830
Miocene	0.70830–0.70911
Pliocene	0.70911–0.70916
Pleistocene to Holocene	0.70916–0.70925

The $^{87}Sr/^{86}Sr$ isotopic ratio determined from water collected from Wadesboro Spring indicates the probable source of the water is from lower Miocene units. A $^{87}Sr/^{86}Sr$ ratio determined from water collected from the Pottsburg Creek Spring indicates that the water has been in contact with late Miocene or early Pliocene rocks. At the Camp Echockotee Spring, the strontium isotopic ratio is higher than the value indicated for recent seawater, indicating that some exchange with the clays within the aquifer may have taken place, possibly altering the $^{87}Sr/^{86}Sr$ ratios.

SUMMARY AND CONCLUSIONS

The study area includes an approximately 20 mile-long portion of the lower St. Johns River that extends from the Main Street Bridge in downtown Jacksonville in Duval County southward to the Shands Bridge near Green Cove Springs. The river tends to be wide and relatively shallow and the flow is strongly affected by ocean tides and, to a lesser extent, by wind, precipitation, surface-water runoff, and evapotranspiration. Periods of reverse flow occur daily along the entire reach.

Because of the tidal nature of the river, the chemical quality of the riverwater is highly variable. Saltwater from the Atlantic Ocean advances up the St. Johns River during each incoming tide and recedes during each outgoing tide. The advancing ocean water mixes with the existing fresh riverwater, thereby increasing the salinity of the water.

Three hydrogeologic units are present in the study area: the surficial aquifer system, the intermediate confining unit, and the Floridan aquifer system. The surficial aquifer system is the uppermost water-bearing unit in the study area and contains deposits of sand, clay, shell, dolomite, and limestone. The intermediate confining unit underlies the surficial aquifer and varies in thickness from more than 500 feet in the central part of Duval County to about 200 feet near the Shands Bridge. Throughout most of the area, the clays and silts in the intermediate confining unit serve as an effective confining layer that retards the vertical movement of water between the surficial aquifer system and the underlying Floridan aquifer system. However, permeable sediments and breaches in the intermediate confining unit can locally increase the vertical permeability of the unit, resulting in a more direct hydraulic connection between the Floridan aquifer system and the river. It is in these areas where springflow is most likely to occur.

The Floridan aquifer system primarily consists of limestone and dolomite of Eocene age. The top of the aquifer ranges from about 250 feet below sea level near the Jacksonville Naval Air Station and the Shands Bridge area to about 600 feet below sea level in parts of central Duval County.

The potentiometric surface of the Upper Floridan aquifer ranged from about 60 ft above sea level in the southeastern part of the study area to about 25 ft above sea level near Green Cove Springs in September 1992. The direction of lateral ground-water movement in the Upper Floridan aquifer is toward the St. Johns River. The September 1992 potentiometric surface map indicates the presence of two depressions along parts of the St. Johns River from Jacksonville to Green Cove Springs. One depression in the potentiometric surface from the city of Jacksonville south toward Mandarin probably is caused, in part, by withdrawals from industrial and public-supply wells, diffuse upward leakage, and possibly springflow. In the Mandarin/Jacksonville Naval Air Station area, springs discharging into the river are thought to exist; however, to date, none have been located. In the Green Cove Springs area, the depression in the potentiometric surface is, in part, the result of withdrawals from domestic and public-supply wells and pumping for irrigation immediately south of the area. Discharge of water by diffuse upward leakage and from springs in the St. Johns River also contributes substantially to this depression.

Provided that the temperature differences between the surface water and the ground water are sufficient to create a recognizable thermal anomaly, ground-water discharge to the St. Johns River can be detected by thermal infrared imagery. Other factors which determine whether ground-water discharge can be identified using thermal infrared imagery are the amount of water being discharged, the depth of the river, and the velocity of the river.

The application of thermal infrared imagery in locating spring discharge into the St. Johns River was somewhat successful in identifying natural discharges to the river. At least one temperature anomaly identified in the St. Johns River was associated with spring discharge from the Floridan aquifer system. The spring, located at a depth of 30 ft, produced a thermal plume that was about 700 ft in length. Estimated discharge was 1 cubic foot per second (about 8 gallons per second). Thermal infrared imagery also identified six artificial discharges to the river. Eleven municipal or industrial facilities were discharging wastewater into the St. Johns River at the time of the survey in amounts ranging from about 0.3 to 63 gallons per second.

Seismic reflection survey results show the presence of collapse and other karst features underlying the St. Johns River. The presence of collapse features indicates that the overlying Hawthorn Formation and surficial deposits below the river probably do not consist of coherent, continuous beds. Rather, beds are disrupted because of subsidence activity and the associated infilling of solution voids in the limestone. The collapse or deformation of the Hawthorn Formation could create zones of relatively high vertical leakance which could result in a more direct hydraulic connection between the Upper Floridan aquifer and the river.

Water samples collected from the only submerged spring discovered in the St. Johns River within the Jacksonville-Green Cove Springs reach indicate that the source of the water is the Floridan aquifer system. Chloride and sulfate concentrations were 12 and 340 milligrams per liter, respectively. Specific conductance was 826 microsiemens per centimeter and temperature of the water discharging from the spring was 25.1 degrees Celsius. The $^{87}Sr/^{86}Sr$ ratios also indicate that the springwater has been in contact with Eocene age rock materials, indicating that the springwater is derived from the Floridan aquifer system.

SELECTED REFERENCES

Anderson, W., and Goolsby, D.A., 1973, Flow and chemical characteristics of the St. Johns River at Jacksonville, Florida: Florida Geological Survey Information Circular 82, 57 p.

Bentley, C.B., 1977, Surface-water and ground-water features, Clay County, Florida: U.S. Geological Survey Water-Resources Investigations 77–87, 59 p.

Bermes, B.J., Leve, G.W., and Tarver, G.R., 1963, Geology and ground-water resources of Flagler, Putnam, and St. Johns Counties, Florida: Florida Geological Survey Report of Investigations 32, 97 p.

Boniol, D., Williams, M., and Munch, D., 1993, Mapping recharge to the Floridan aquifer using a geographic information system: St. Johns River Water Management District, Technical Publication SJ 93–5, 41 p., 1 pl.

Brereton, N.R., 1984, Groundwater discharge mapping by thermal infra-red imagery: Seminar on the site investigation techniques and assessment methods for underground disposal of radioactive wastes: Sofia, Bulgaria, February 1984, 13 p.

Brown, Eugene, Skougstad, N.W., and Fishman, M.J., 1970, Methods for collection and analyses of water samples for dissolved minerals and gases: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 170 p.

Brown, D.P., Johnson, R.A., and Baker, J.S., 1984, Hydrogeologic data from a test well at Kathryn Abbey Hanna Park, city of Jacksonville, Florida: U.S. Geological Survey Open-File Report 84–143, 41 p.

Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnik, R.B., Nelson, H.F., and Otto, J.B., 1982, Variation of seawater $^{87}Sr/^{86}Sr$ throughout Phanerozoic time: Geology, v. 10, no. 10, p. 516–519.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–C, 80 p., 17 pls.

Causey, L.V., and Phelps, G.G., 1978, Availability and quality of water from shallow aquifers in Duval County, Florida: U.S. Geological Survey Water-Resources Investigations 78–92, 36 p.

Chen, C.S., 1965, The regional lithostratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geological Survey Bulletin 45, 105 p.

Clark, W.E., Musgrove, R.H., Menke, C.G., and Cagle, J.W., 1964, Water resources of Alachua, Bradford, Clay, and Union Counties, Florida: Florida Geological Survey Report of Investigations 35, 170 p.

DePaolo, D.J., 1986, Detailed record of the Neogene Sr isotopic evolution of seawater from DSDP site 590B: Geology, v. 14, no. 2, p. 103–106.

DePaolo, D.J., and Ingram, B.L., 1985, High-resolution stratigraphy with strontium isotopes: Science, v. 227, p. 938–941.

Elderfield, H., 1986a, Strontium isotope stratigraphy: Paleogeography, Paleoclimatology, Paleoecology, v. 57, no. 1, p. 71–90.

____1986b, Seawater $^{87}Sr/^{86}Sr$ evolution from Cretaceous to present: Science, v. 231, no. 4741, p. 979-984.

Fairchild, R.W., 1977, Availability of water in the Floridan aquifer in southern Duval and northern Clay and St. Johns Counties, Florida: U.S. Geological Survey Water-Resources Investigations 76–98, 53 p.

Fischer, W.A., Davis, D.A., and Sousa, T.A., 1966, Freshwater springs of Hawaii from infrared images: U.S. Geological Survey Hydrologic Investigations Atlas, HA–218, 1 sheet.

Fishman, M.J., and Friedman, L.C., eds., 1985, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, Open-File Report 85–495, 709 p.

Florence, B.L., 1990, Annual water use survey: 1988: Palatka, Fla., St. Johns River Water Management District Technical Publication SJ 90–12, 128 p.

Hess, J., Bender, M.L., and Schilling, J.G., 1986, Seawater $^{87}Sr/^{86}Sr$ evolution from Cretaceous to present: Science, v. 231, no. 4741, p. 979–984.

Hodell, D.A., Mead, G.A., and Mueller, P.A., 1990, Variation in the strontium isotopic composition of seawater (8 Ma to present): Implications for chemical weathering rates and dissolved fluxes to the ocean: Chemical Geology, v. 80, p. 291–307.

Johnston, R.H., and Bush, P.W., 1988, Summary of the hydrology of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–A, 24 p., 4 pl.

Kohout, F.A., Munson, R.C., Turner, R.M., and Royal, W.R., 1979, Satellite observations of a geothermal submarine spring off Florida west coast: American Water Resources Association (Satellite Hydrology), p. 570–578.

Kohout, F.A., Wiesnet, D.R., Deutsch, Morris, Shanton, J.A., and Kolipinski, M.C., 1979, Applications of aerospace data for detection of submarine springs in Jamaica: American Water Resources Association (Satellite Hydrology), p. 437–445.

Krause, R.E., and Randolph, R.B., 1989, Hydrology of the Floridan aquifer system in southeast Georgia and adjacent parts of Florida and South Carolina: U.S. Geological Survey Professional Paper 1403–D, 65 p., 18 pls.

Lawrence, G.R., White, D., and Deslauriers, I., 1980, The detection of groundwater discharges (springs) using aerial thermography: Proceedings of 6th Canadian Symposium on Remote Sensing, Halifax, Nova Scotia., May 21–23, 1980, p. 483–491.

Lee, Keenan, 1970, Infrared exploration for shoreline springs at Mono Lake, California, test site: Proceedings 6th international Symposium on Remote Sensing of Environment, Michigan University, Ann Arbor, October 13–16, 1969, v. 26, p. 1075–1100.

Leve, G.W., 1966, Ground water in Duval and Nassau Counties, Florida: Florida Geological Survey Report of Investigations 43, 91 p.

____1978, Altitude and configuration of the top of the Floridan aquifer, Duval County, Florida: U.S. Geological Survey Water-Resources Investigations 77–114, 1 sheet.

Locker, S.D., Brooks, G.R., and Doyle, L.J., 1988, Results of a seismic reflection investigation and hydrogeologic implications for Lake Apopka, Florida; St. Johns River Water Management District Special Publication SJ 88–SP5, 39 p.

Marella, R.L., 1992, Water withdrawals, use, and trends in Florida, 1990: U.S. Geological Survey Water-Resources Investigations Report 92–4140, 38 p.

Meisburger, E.P., and Field, M.E., 1976, Neogene sediments of Atlantic inner continental shelf off northern Florida: American Association of Petroleum Geologists, v. 60, no. 11, p. 2019–2037.

Miller, J.A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p., 28 pls.

Miller, K.G., Feigenson, M.D., Kent, D.V., and Olsson, R.K., 1988, Upper Eocene to Oligocene isotope ($^{87}Sr/^{86}Sr$, $\delta^{13}O$, $\delta^{13}C$) standard section, DSDP 522: Paleoceanography, v. 3, no. 2, p. 223–233.

Murray, L.C., Spechler, R.M., Phelps, G.G., and Bradner, L.A., 1993, Potentiometric surface of the Upper Floridan aquifer in the St. Johns River Water Management District and vicinity, September 1992: U.S. Geological Survey Open-File Report 93–50, 1 sheet.

Paulson, R.W., 1968, Preliminary remote sensing of the Delaware estuary: Prepared by the U.S. Geological Survey for NASA, Interagency Report NASA–128, 23 p.

Popenoe, Peter, Kohout, F.A., and Manheim, F.T., 1984, Seismic-reflection studies of sinkholes and limestone dissolution features on the northeastern Florida shelf, *in* Proceedings of First Multidisciplinary Conference on Sinkholes: Orlando, Fla., October 15–17, 1984, p. 43–57.

Puri, H.S., 1957, Stratigraphy and zonation of the Ocala Group: Florida Geological Survey Bulletin 38, 258 p.

Puri, H.S., and Vernon, R.O., 1964, Summary of the geology of Florida and a guidebook of the classic exposures: Florida Geological Survey Special Publication 5, 312 p.

Robinove, C.J., and Anderson, D.G., 1969, Some guidelines for remote sensing in hydrology: Water Resources Bulletin, v. 5, no. 2, p. 10–19.

Rosenau, J.C., Faulkner, G.L., Hendry, C.W., Jr., and Hull, R.W., 1977, Springs of Florida (revised): Florida Bureau of Geology Bulletin 31, 461 p.

Roxburgh, I.S., 1985, Thermal infrared detection of submarine springs associated with the Plymouth Limestone: Hydrological Sciences Journal, v. 30, no. 2, p. 185–196.

Rye, R.O., Back, W., Hanshaw, B.B., Rightmire, C.T., and Pearson, F.J., 1981, The origin and isotopic composition of dissolved sulfide in ground water from carbonate aquifers in Florida and Texas: Geochimica et Cosmochimica Acta, v. 45, no. 10, p. 1941–1950.

Snyder, S.W., Evans, M.E., Hine, A.C., and Compton, J.S., 1989, Seismic expression of solution collapse features from the Florida Platform: Third Multidisciplinary Conference on Sinkholes, St. Petersburg Beach, Florida, p. 281–297.

Spechler, R.M., 1994, Saltwater intrusion and the quality of water in the Floridan aquifer system, northeastern Florida: U.S. Geological Survey Water-Resources Investigations Report 92–4174, 76 p.

Spechler, R.M., and Hampson, P.S., 1984, Ground-water resources of St. Johns County, Florida: U.S. Geological Survey Water-Resources Investigations Report 83–4187, 49 p.

Sprinkle, C.L., 1989, Geochemistry of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403–I, 105 p.

Stringfield, V.T., 1966, Artesian water in Tertiary limestone in the Southeastern States: U.S. Geological Survey Professional Paper 517, 226 p.

Tibbals, C.H., 1990, Hydrology of the Floridan aquifer system in east-central Florida: U.S. Geological Survey Professional Paper 1403–E, 98 p.

U.S. Geological Survey, 1992, Water Resources Data for Florida, Water Year 1991: U.S. Geological Survey Water Data Report FL–91–1A, 430 p.

Vernon, R.O., 1951, Geology of Citrus and Levy Counties, Florida: Florida Geological Survey Bulletin 33, 256 p.