River Water Intrusion to the Unconfined Floridan Aquifer

TODD R. KINCAID

Department of Geology & Geophysics, University of Wyoming, P. O. Box 3006, Laramie, WY 82071

Key Terms: *Aquifers, Ground-Water Discharge, River Water, Hydrogeology*

ABSTRACT

Rapid infiltration of river water into unconfined parts of the Floridan aquifer represents a significant component of subsequent ground-water discharge in regions where the aquifer is dissected by surface streams. A two-year investigation of the Devil's Ear cave system, an extensive saturated conduit network in the Floridan aquifer which underlies a 1.5-km reach of the Santa Fe River in north-central Florida, revealed that there is an appreciable and rapid exchange of water between the river and the underlying Floridan aquifer. Natural tracers Radon-222 (^{222}Rn) and δ^{18}O were used to quantify these exchanges. Cave diving was employed to collect 50 water samples which were analyzed for tracer content and to observe water clarity conditions within the saturated karst conduits as far as 1.2 km from the cave entrance.

^{222}Rn concentrations measured in the cave system revealed three distinct zones where river water is rapidly intruded into the Floridan aquifer. A two-component mixing model was used to quantify the intruded river water that was found to account for as much as 62 percent of the discharge at Devil's Ear spring. Observations of diminished water clarity in the cave system following large precipitation events in the highland provinces of the Santa Fe River basin indicate that river water intrusion to the aquifer can occur in as little as one or two days. The results of this investigation imply that, in regions such as the western Santa Fe River basin, there can be no clear distinction between ground and surface waters and intruded river water provides a significant vehicle for contamination of the unconfined Floridan aquifer.

PURPOSE

This paper presents and describes a geochemical data set that has been collected from within a phreatic cave system developed in the upper Florida aquifer beneath the Santa Fe River, Florida. The objectives of this paper are to demonstrate the potential magnitude and rate of direct river water intrusion to the Floridan aquifer in regions where the Floridan aquifer is unconfined and dissected by surface streams, and to offer a hypothesis which describes the mechanisms responsible for ground-water/surface-water exchange in this region. Finally, it is the intent of this paper to demonstrate that, in regions where an unconfined aquifer is dissected by surface streams, there can be no clear distinction between ground water and surface water.

Problem

Standard hydrogeological data such as potentiometric surface maps and discharge measurements from stream gauging stations are not capable of documenting surface-water/ground-water interactions taking place across short reaches of a river or stream. Researchers have long recognized the significance of these interactions and attempted several methods of quantification with various levels of success. Most of the research to date has focused on lake seepage. Local head and stage measurements have been employed either directly or coupled with finite difference and finite element models to predict exchange rates (Ackerer et al., 1990; Devito et al., 1996; and Lee, 1996). These attempts break down under anisotropic conditions found in karst aquifers like the upper Floridan aquifer. Seepage meters have been constructed and employed to make direct measurements (Shaw and Prepas, 1990) but are not suited for deployment in a swift river cutting through bedrock such as the western Santa Fe River. By comparison, isotopic studies provide a well tested and widely applicable means of distinguishing between ground and surface waters (Rogers, 1958; Ellins et al., 1990; Ellins, 1992; Herczeg et al., 1992; Kincaid, 1994; and Criss and Davisson, 1996). Although methods and applications differ, it seems generally accepted that surface-water/ground-water interactions must be studied at the local scale in order to adequately estimate the flux of water and thus the potential for contaminant migration from one system to another.

In this investigation, I have adapted the geochemical technique originally described by Rogers (1958) to quantify river water intrusion to an extensive network of phreatic conduits developed in the Floridan aquifer. The impetus for this research grew from observations reported by cave divers of significant seasonal water clarity reductions that occur in most if not all of Florida's saturated cave systems. For years, divers have attributed increased turbidity to river water intrusion that introduces dark tannin-stained water into the otherwise crystal clear ground water. To investigate these observations that have rarely been noted by the hydrologic and regulatory communities, this investigation capitalized on cave diving techniques to collect water samples from large saturated karst conduits beneath the Santa Fe River. The water samples were subsequently measured for geochemical tracers to identify and quantify river water intrusion to the aquifer. Figure 1 shows the mixing of ground water and river water in the Santa Fe River above Devil's Ear spring.

Study Area

The field area lies in the western Santa Fe River basin of north-central Florida along a 1.5 km reach of the Santa Fe River between Rum Island and July springs. The investigation focused on the exchange of water between the Santa Fe River and the underwater conduits that comprise the Devil's Ear cave system underlying this reach of the river. Figure 2 is a reduced section of the U. S. Geological Survey High Springs SW topographic quadrangle showing the location of the field area and the position of the Devil's Ear cave system relative to the Santa Fe River.

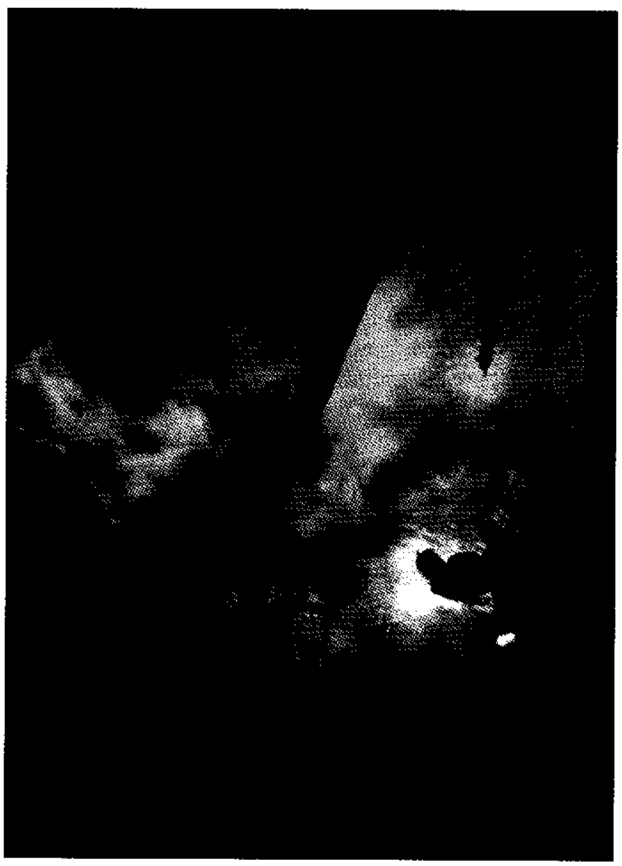

Figure 1. Ground water and surface water mixing at the entrance to the Devil's Ear cave system. View is looking up at the surface of the Santa Fe River. The tannin-stained surface water appears in shades of gray whereas the ground water is clear. Photo by Wes Skiles of Karst Productions, High Springs, Florida.

Significance

Ground water is a vital natural resource in Florida providing 87 percent of the public water supply and 94 percent of the dispersed private supply (Fernald and Patton, 1984). Florida has promulgated environmental regulations with the specific intent of protecting the present and future beneficial uses of ground water to insure continued availability and utility (Florida Environmental Health and Safety Regulations, 62-520, 1994a). The regulations continue to specifically outline the permissible levels of known contaminants for aquifers and surface waters. Under the regulations, aquifers are classified as class-1, -2, and -3 where class-1 is the most protected. Surface waters typically have the least stringent regulations and narrative rather than numerical criteria which are often used to set water quality standards. Definitions at the beginning of Chapters 62-520 and 62-520.200 of the Florida Environmental Health and Safety Regulations (1994a, b) specifically outline the criteria for classifying a body of water as ground water or surface water.

> "Ground Water means water beneath the surface of the ground within the zone of saturation, whether or not flowing through known or definite channels... Surface Water means water upon the surface of the earth, whether contained in bounds created naturally or artificially or diffused. Water from natural springs shall be classified as surface water when it exits from the spring onto the earth's surface."

Much of the land in north Florida, and particularly in the western Santa Fe River basin, is used for agriculture and industrial dairy farms. Pesticides, fertilizers, and high-nitrate sewage effluent associated with these land uses either infiltrate directly to underlying aquifers or discharge to rivers and streams via overland runoff. The continued growth of the dairy industry has caused increased public concern for the protection of water quality in local springs, rivers, and the Floridan aquifer from organic pollution. Andrews (1992) showed that ground water and surface water in the vicinity of dairies commonly contains large quantities of nitrate, ammonia, and soluble organic nitrogen species. Water quality data compiled from nine dairy farms in north Florida demonstrated that, where unconfined, the Floridan aquifer is vulnerable to contamination from wastes applied to the land surface and that nearby surface waters receive large quantities of nutrient-rich runoff (Andrews, 1992).

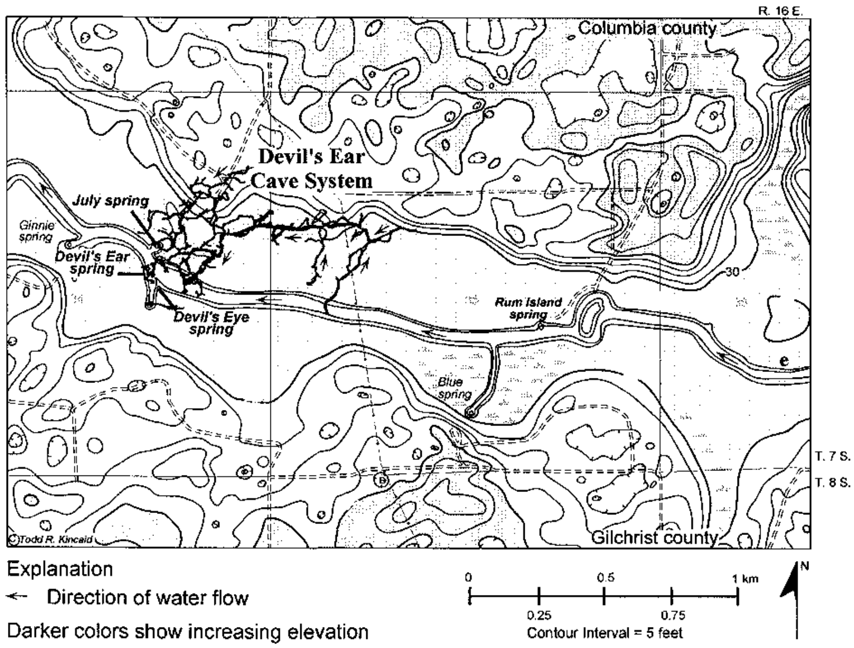

Figure 2. Topographic map showing the position of the Devil's Ear cave system relative to the Santa Fe River, north-central Florida. Topography from the U. S. Geological Survey High Springs SW 7.5 Minute Topographic Quadrangle.

Forty-four percent of all the ground water consumed in Florida and 100 percent of the water used for private consumption in this study area comes from the Floridan aquifer which is designated as a class-1 aquifer (Fernald and Patton, 1984). In the western Santa Fe River basin, many wells used for private water consumption are located within tens of meters of the Santa Fe River. Here and in other similar regions, pollutants carried to the river by overland runoff from area farms and dairies can enter the Floridan aquifer via river water intrusion and pose a significant threat to water quality in the aquifer.

HYDROGEOLOGIC SETTING

The Floridan Aquifer

The Floridan aquifer is areally extensive underlying all of peninsular Florida, nearly half of Georgia and South Carolina, and part of Alabama. It is regarded as one of the most productive aquifers in the United States (Spangler, 1981). The Floridan aquifer consists vertically of several hundred meters of limestone and dolomite but only the upper 100–250 m of the Floridan aquifer yields potable water (Hunn and Slack, 1983). The stratigraphic units constituting the aquifer are, from oldest to youngest: the Ocala Limestone, formerly the Ocala Group (Scott, 1992) of Eocene age; the Suwannee Limestone of Oligocene age; and the limestones at the base of the Hawthorn Formation of Miocene age (Hunn and Slack, 1983). The productivity of the Floridan aquifer is evidenced by more than 300 springs that discharge an average of 360 m^3/sec to Florida's major rivers (Fernald and Patton, 1984). Of the 78 largest springs on the North American continent, 27 discharge more than 272 m^3/sec from the Floridan aquifer (Lane, 1986). Aside from the large magnitude springs, pumping tests carried out in this study area reveal transmissivity values that range from 3,000–50,000 m^2/day which permit well yields of between 0.1–0.3 m^3/sec (Hunn and Slack, 1983).

Karstification is ubiquitous in the limestones and dolomites that comprise the Floridan aquifer. Sinkholes such as the famous Winter Park sinkhole in central Florida are the most common surface expressions of the karstification. Many of these sinkholes have at least partially filled with water and constitute most of the over 7,700 freshwater lakes in Florida that are larger than 40,000 m^2 (Spangler, 1981). Dry caves such as those found in Florida Caverns State Park in Marianna, Florida, are exposed in regions where the limestones and dolomites are unsaturated.

Much more common are the regionally extensive cave systems that occur in the limestones beneath the water table. These saturated cave systems are of particular hydrogeologic interest because they transmit large quantities of upland recharge to springs in Florida's major rivers such as the Suwannee, St. Johns, Santa Fe, Oklawaha, and Withlacoochee. In fact, all of the 27 first magnitude springs (discharge ≥ 2.8 m^3/sec) in Florida discharge from phreatic cave systems. The ground-water discharge from these springs is, in each case, between one and three orders of magnitude greater than the largest well yields. The distribution and magnitude of these spring discharges demonstrate that phreatic karst conduits provide the major ground-water flow pathways in the Floridan aquifer. A more thorough discourse on the springs in Florida is provided by Rosenau and others (1977).

The Santa Fe River Basin

The Santa Fe River basin comprises over 3,500 km^2 of land in north central Florida and is a major tributary to the Suwannee river. The region is characterized as semi-tropical with mean annual precipitation of 135 cm, 52 percent of which falls between the months of June and September. The large seasonal variation in precipitation renders the Santa Fe River basin very susceptible to flooding.

The Ocala Limestone, Hawthorn Formation, and Alachua Formation are the three geologic units present in all or part of the Santa Fe River basin that are significant to this investigation. The Ocala Limestone, a thick sequence of highly permeable Eocene limestone beds, is the predominant geologic formation comprising the Floridan aquifer in this region. Extensive karstification in the Ocala Limestone has created anisotropic conditions where permeability has increased by many orders of magnitude in dissolved conduits. The Hawthorn Formation is a 25 to 30-m thick Miocene sequence of phosphatic clays and dolomitic limestones that overlies the Ocala Limestone in the eastern Santa Fe River basin. Where present, the Hawthorn Formation effectively confines the Floridan aquifer. The Alachua Formation is a thin sequence of phosphatic sand and clay deposits thought to be erosional remnants of the Hawthorn Formation. Outcrops exist as outlying hills and ridges in the western part of the Santa Fe River basin covering the Ocala Limestone (Williams et al., 1977). The Alachua Formation is ineffective at confining the Floridan aquifer (Hunn and Slack, 1983).

The Santa Fe River basin is commonly subdivided into eastern and western halves with the Floridan aquifer being confined in the east and unconfined in the west. The Santa Fe River flows from east to west. Figure 3 adapted from White (1970) shows the course of the river and its main tributaries across the three physiographic provinces that merge within the basin: the Northern Highlands, Central Highlands, and Gulf Coastal Lowlands.

The Santa Fe River originates in the eastern half of the basin on a high flat plateau known as the Northern Highlands physiographic province. Elevations in these highlands range between 50 and 60 m. The Floridan aquifer is effectively confined by the Hawthorn Formation in this province and precipitation drains directly, via overland flow, to the Santa Fe River and its tributaries (Hunn and Slack, 1983). As the Santa Fe River reaches the western edge of the Northern Highlands it crosses the Cody Scarp, which marks the western erosional boundary of the Hawthorn Formation. The Cody Scarp is characterized by intense karstification of the Ocala Limestone and marks the transition from confined to unconfined conditions in the Floridan aquifer (Scott, 1991). Several of Florida's rivers and streams including the Santa Fe River disappear into underlying conduit systems as they cross this transition zone resurfacing at the western margin of the Cody Scarp.

When the Santa Fe River reaches the Cody Scarp, it is diverted underground at O'leno sink and resurfaces 5 km down-gradient at the River Rise. Hisert (1994) conducted tracing experiments in O'leno State Park demonstrating that the water travels between the sink and resurgence with a velocity of over five km/day. Hisert also recorded the ground-water tracer at eight intermediate sinkholes that are now known to be karst windows that intersect the underground flow path of the river. Furthermore, he found that over 40 percent of the resurgence is ground water that has augmented the river flow.

After its resurgence, the Santa Fe River flows onto the lowland limestone plains of the Central Highlands and Gulf Coastal Lowlands. The Hawthorn Formation has been eroded leaving the Floridan aquifer unconfined. Most precipitation falling on the limestone plains infiltrates directly into the aquifer (Hunn and Slack, 1983). In this region, the Santa Fe River is both a gaining and loosing stream. Several major springs augment the river flow as well as countless seeps that can be found along the riverbed. Mixed in between the springs and seeps, however, are several siphons that divert part of the flow underground for unknown distances (Ellins et al., 1991; Kincaid, 1994). Unpublished tracing experiments conducted by local residents have demonstrated that one "spring" marked on the USGS High Springs SW topographic quadrangle is actually a resurgence for river water that was diverted underground from an upstream siphon.

Several phreatic cave systems have developed in the Santa Fe River basin. All of the known springs discharge through conduits forming "spring" caves. Conduits forming "river" caves have developed beneath the river stemming from siphons.

The Devil's Ear Cave System

The Devil's Ear cave system has developed in the High Springs Gap sub-province of the Central Highlands and is the largest and most extensive cave system in the Santa Fe River basin. The cave system is an anastomosing network of underwater conduits in the Ocala Limestone. The main conduit in the cave system trends east for over 1,500 m upstream from the entrance at Devil's Ear spring. The depth of the conduits is relatively consistent at 33

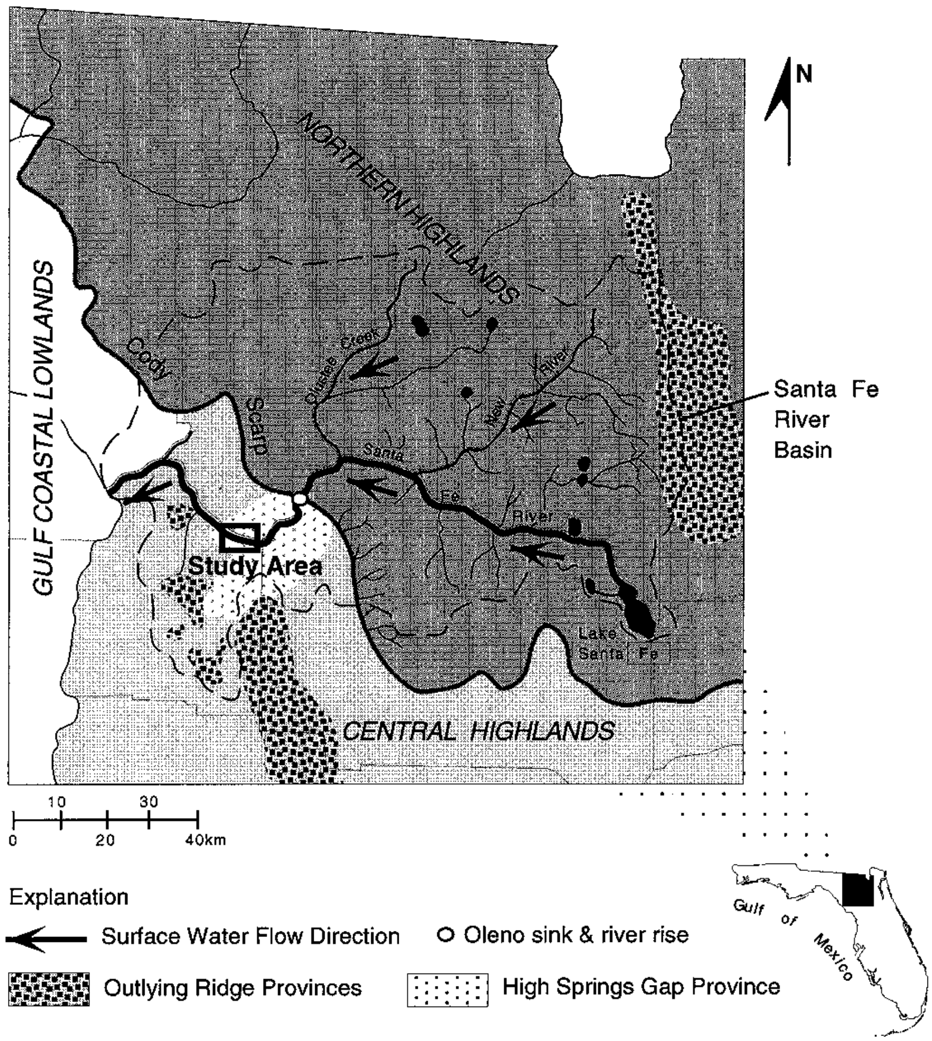

Figure 3. Location of the Devil's Ear cave system and course of the Santa Fe River from the Northern Highlands across the Cody Scarp onto the limestone plains of the Central Highlands and Gulf Coastal Lowlands physiographic provinces in north-central Florida. Adapted from White (1970).

m below the water surface in the river except where they rise to meet the Santa Fe River at the principal springs. Conduit diameters range from 2 to 20 m. Figure 4 shows a diver swimming through one of the larger sections of the main conduit.

Figure 5 is a map of the Devil's Ear cave system showing its position relative to the overlying Santa Fe River and the direction of ground-water flow through the conduits. Three springs (July, Devil's Eye, and Devil's Ear) discharge most of the water from the cave to the river. The combined discharge from these springs averages 8.5 m^3/sec (Wilson and Skiles, 1988). Most of the ground-water discharge from the Devil's Ear cave system infiltrates through the limestone plains on the north side of the Santa Fe River (Kincaid et al., 1992). Some of the discharge at Devil's Ear spring originates on the south side of the river and is delivered through the Little Devil's cave system labeled on Figure 5 (Kincaid et al., 1992).

Compared to other saturated caves in Florida, the Devil's Ear cave system is only slightly larger than average. Every known spring along the western part of the Santa Fe River discharges from cave systems that have been mapped by cave divers. The Devil's Ear cave system has particular hydrogeologic importance because of its proximity and relationship to the Santa Fe River. As shown on Figure 5, several conduits extend from the recharge area on the north side of the river to a larger conduit that parallels and, in places, directly underlies the river. Three regions of the cave system marked by sample location numbers 9, 17, and 21 on Figure 5 are closest to the Santa Fe River. In these regions, dissolved joints in the limestone that are passable by divers proceed up to a depth of less than 3 m below the river providing probable avenues for river water intrusion to the aquifer.

Water clarity in the conduits is typically clear but becomes turbid during higher stages of the river or after

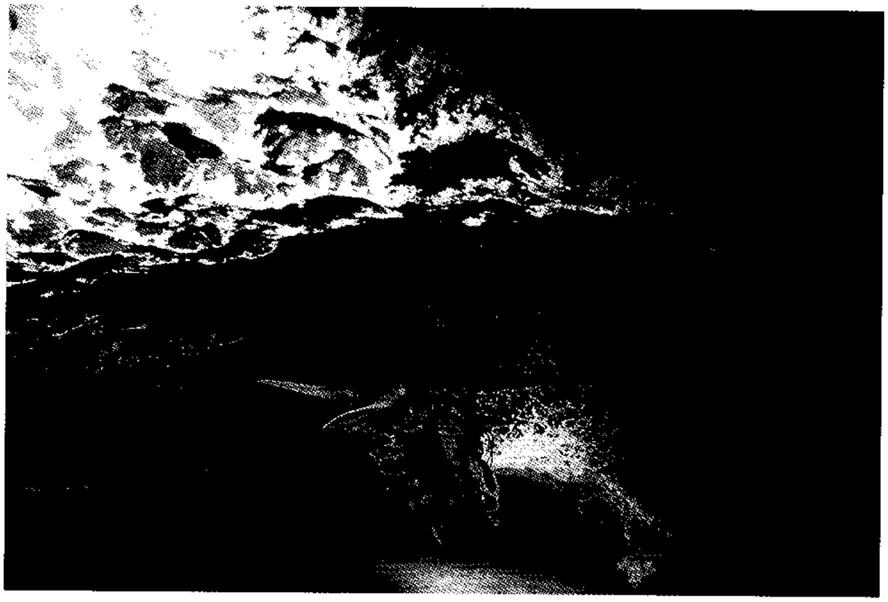

Figure 4. A cave-diver in the main passage of the Devil's Ear cave system. View is northeast in the upstream direction. Photo by Wes Skiles of Karst Productions, High Springs, Florida.

flood events. During periods of turbid water discharge at the three springs, cave divers report that clear water enters the main passage from the northern conduits and mixes with turbid water from the southern conduits producing the turbid water discharge visible at the surface. Reverse flow, a common situation at many springs in Florida where spring discharge is reversed and river water flows into a cave system through the spring opening, has never been reported at the Devil's Ear cave system. The absence of reverse flow during high river stages reflects the unconfined condition of the Floridan aquifer and reveals that the aquifer is receiving direct recharge from the river.

The River-Aquifer System

For the purpose of this discussion, the river-aquifer system is divided into three parts: the Santa Fe River, the conduits in the aquifer, and the saturated Ocala Limestone in between. The 30-m thick section of saturated

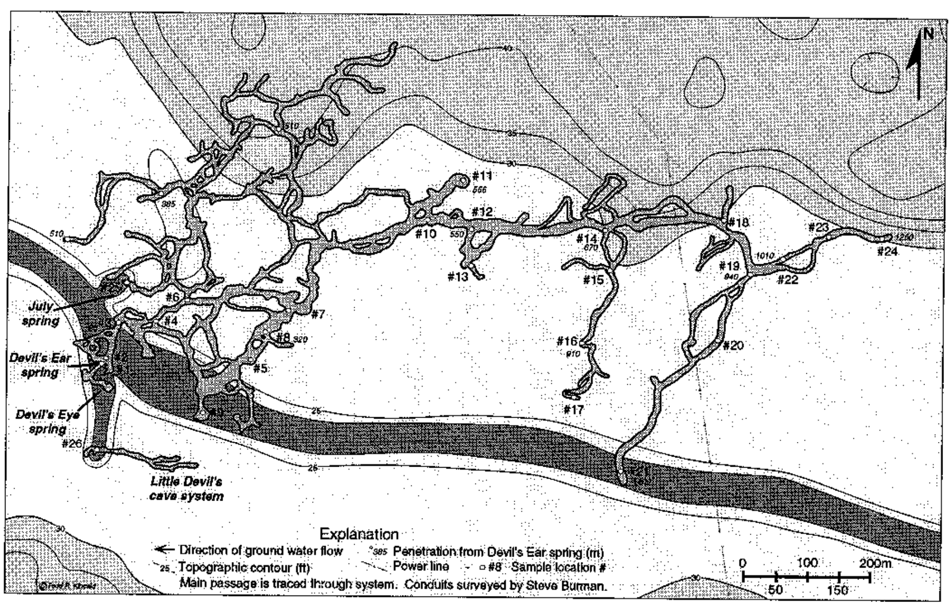

Figure 5. Map of the Devil's Ear cave system underlying the 1.5 km reach of the Santa Fe River upstream of July spring in north-central Florida, showing the course of the Santa Fe River relative to the conduits, direction of ground-water flow in the conduits, and the location of the three principal discharge points.

Ocala Limestone above the cave system is a leaky confining layer separating the extremely permeable conduits from the overlying river. The confining layer allows a hydraulic gradient to develop between the river and the cave, and contains water in storage that is displaced when either a downward or upward hydraulic gradient develops. The rate at which water moves through this layer is dependent on the magnitude and duration of the hydraulic gradient and the vertical hydraulic conductivity.

METHODOLOGY

Radon-222

Radon-222 (^{222}Rn) provided an ideal natural tracer for this investigation because concentrations in ground water are typically an order of magnitude or more greater than in surface water. ^{222}Rn is the radioactive decay product of Radium-226 (^{226}Ra: half-life = 1.6 x 10^3 years) which is ubiquitous in the phosphatic sediments composing all or part of the Alachua Formation, present in outlying hills, and the Hawthorn Formation, present in the Northern Highlands (Kaufmann and Bliss, 1978). ^{222}Rn is a volatile gas with a half-life of 3.8 days and is highly soluble in water. ^{222}Rn concentrations are measured in alpha-scintillation counters and reported in Becquerels per liter (Bq/L) which equate to the number of alpha particle disintegrations per second per liter.

^{222}Rn is released to ground water by the radioactive decay of ^{226}Ra on or near the grain boundaries of aquifer material (Asikainen, 1981; Krishnaswami et al., 1982) and, to a lesser extent, the dissolution of aquifer material that supplies soluble ^{226}Ra which subsequently decays to ^{222}Rn (Ellins et al., 1990). A strong gradient exists between atmospheric and ground-water ^{222}Rn concentrations. Gessel (1983) reports ^{222}Rn concentrations in continental air that range between 8.3 x 10^{-3} (New Jersey) and 2.83 x 10^{-2} (Colorado). Reported concentrations of ^{222}Rn in ground-water range between 2.0 x 10^2 and 6.6 x 10^4 (Davis and DeWiest, 1966). Because of its high volatility, ^{222}Rn gas quickly dissipates when exposed to the atmosphere creating a significant disequilibria between concentrations in ground water and surface water (Rogers, 1958). Specific concentration gradients between ground water and surface water are dependent on ^{226}Ra content in local rocks.

Rogers (1958) demonstrated that elevated ^{222}Rn concentrations measured in streams and rivers are indicative of ground-water inputs. Furthermore, Ellins and others (1990, 1991) showed that by accounting for gas exchange across the air-water boundary, the measurement of ^{222}Rn in a stream or river can be used to quantify ground-water influx with a two-component mixing model. The same principles were applied in this investigation but in reverse. When sampling the Floridan aquifer from inside the Devil's Ear cave system, low ^{222}Rn concentrations indicated river water intrusion. The difference between the ^{222}Rn concentration in a sample and that of a pure aquifer standard was used as the basis for quantifying river water intrusion.

Mixing Model

The quantity of intruded river water in the samples taken from the Devil's Ear cave system was determined using the following equation:

$$Rs = Riv*X + Raq*(1 - X)$$

where:

Rs = the ^{222}Rn concentration in the sample,
$Rriv$ = the background ^{222}Rn concentration in the river,
X = the decimal fraction of river water in the sample,
Raq = the background ^{222}Rn concentration in the aquifer.

Solving the equation for the percentage of river water in a given sample produces:

$$\%X = \left(\frac{Rs - Raq}{Rriv - Raq}\right) * 100$$

Background ^{222}Rn concentrations in the aquifer were measured by sampling three wells near the field. Wells 1 and 2 are located 1 and 1.5 km southwest of Devil's Ear spring respectively. Well 3 is located approximately 3 km northwest of Devil's Ear spring. The discharge from Blue spring, shown on Figure 2, and Ginnie spring, located approximately 500 m west of Devil's Ear spring, is consistently clear and both springs are subject to reversals during periods of high stage in the Santa Fe River. These hydrologic conditions are very different from those associated with the Devil's Ear cave system leading to the conclusion that they have little or no hydrologic connection with the river and discharge water indicative of the local Floridan aquifer. ^{222}Rn measurements collected from these locations are provided in Table 1. *Raq* was determined to be 13.0 Bq/L in February 1992 and 14.2 Bq/L in June 1993 by averaging the values obtained from the three wells and two springs.

Measuring *Rriv* in the field area revealed values ranging between 4.2 and 9.0 Bq/L. These values were not considered accurate estimations of the background ^{222}Rn concentration in the river because of large ground-water inputs from several springs. Instead, *Rriv* was determined by averaging several measurements collected by Ellins and others (1991) and Hisert (1994) that were taken just upstream of the field area where there is less ground-water input. Their work showed that ^{222}Rn input to the river remains relatively constant over time in regions with limited ground-water influx. Averaging these reported ^{222}Rn concentrations produced a value for *Rriv*

Table 1. *^{222}Rn concentrations and $\delta^{18}O$ values and the calculated percentage of river water for each sample collected from listed sample locations in the Devil's Ear cave system, north central Florida. Sample location numbers refer to those shown on Figure 5.*

Location Number	Main Conduit Distance From Entrance	Distance From Main Conduit (m)	1992 ^{222}Rn (Bq/L)	River Water (%)	1993 ^{222}Rn (Bq/L)	River Water (%)	δ^{18}O (ppm)
1	0	0	5.6	62	7.7	49	–3.56
2	20	0	5.3	64	n/a		
3	80	0	5.7	61	8.0	47	
4	170	0		n/a	9.1	39	–3.52
5	170	120		n/a	6.7	57	–3.64
6	240	0	6.8	52		n/a	
7	340	0	6.4	55	5.8	64	–3.62
8	340	60	3.0	84		n/a	
9	170	150	12.3	6		n/a	
10	430	0	5.9	60	8.4	44	–3.66
11	430	–60	6.7	53	n/a		
12	520	0	5.7	61	6.4	59	–3.62
13	520	60	5.3	65	5.7	64	–3.48
14	670	0	6.0	59	6.3	60	–3.64
15	670	90	5.6	62		n/a	–3.65
16	670	240		n/a	5.4	66	–3.52
17	670	300		n/a		n/a	
18	880	0	10.5	21	6.9	56	–3.59
19	940	0	5.3	65	5.7	64	–3.62
20	940	150	5.0	67	3.7	79	–3.58
21	940	370	2.5	88		n/a	
22	1010	0	12.1	8	12.4	14	–3.66
23	1130	0		n/a	12.2	16	
24	1220	0		n/a	13.6	4	
25			12.8	2	10.9	25	–3.66
26			13.2	–1	14.2	0	
Rl spg.				n/a		n/a	–3.70
well-1			13.2		14.2		–3.97
well-2			13.2		14.3		
well-3			12.8		14.0		
Blue spg.			13.0		14.2		
Ginnie spg.			13.0		14.1		
Background aquifer conc.			13.0		14.2		
Background river conc.			1.0		1.0		

'–' sign indicates north of the main conduit
n/a indicates no calculation because no sample was taken

of 1.0 Bq/L. The model only assumes fixed end-member concentrations for the mixing waters. Note that a greater value for *Rriv* would result in an increased value for *%X*.

Delta Oxygen-18 (δ^{18}O) Confirmation

Variations in δ^{18}O provided a qualitative check on the ^{222}Rn mixing results. Oxygen isotope ratios are expressed in parts per mil (‰). Variations in δ^{18}O in natural waters result from isotopic fractionation driven by evaporation and condensation. Preferential evaporation of ^{16}O causes a relative ^{18}O enrichment in surface waters producing more positive values of δ^{18}O. Ground water does not evaporate so ground-water samples are characterized by more negative δ^{18}O (Ellins, 1992). Thus, fractionation permits the discrimination between ground water and surface water based on the δ^{18}O signatures. Water samples, collected in the 1993 sampling period, were analyzed for δ^{18}O to qualitatively check the results obtained from the ^{222}Rn mixing model. Greater δ^{18}O values were expected to correspond to sampling locations with small ^{222}Rn concentrations and thus confirm regions of river water intrusion to the cave system. δ^{18}O was not directly measured in the river, however, lakes and ponds near the study area yielded a consistent δ^{18}O of –1.5‰, whereas ground-water values approached –4.0 ‰ (Hisert, 1994).

Sampling the Devil's Ear Cave System

The Devil's Ear cave system was sampled twice: in February 1992 and in June 1993. In both cases, a team of two cave divers made 10 dives into the system over a one-week period and collected 25 water samples. Additional dives were conducted throughout the two-year period to observe water clarity fluctuations associated with precipitation events. Water clarity was estimated by judging the approximate maximum horizontal distance from which objects could be visually recognized at various points in the cave system. The two sampling periods corresponding to high and low stages of the Santa Fe River respectively and were chosen to investigate the effect of river stage on river water intrusion.

^{222}Rn sampling was conducted following the fundamental methodology described by Key (1981) and the modifications described by Ellins and others (1990). Water samples for ^{222}Rn measurements were collected in evacuated 250 ml plastic bottles. The bottles were filled with approximately 150 ml of aquifer water leaving 100 ml of head space to collect the ^{222}Rn gas that would be volatilized from the water sample. After surfacing, the samples were transported to a laboratory where the gasses in the head space were extracted from the sample bottles into Lucas-type counting cells. After sufficient time to allow the ^{222}Rn to equilibrate with it's daughter products, the cells were placed into alpha-scintillation counters where light photons emitted by alpha particle disintegrations were counted and recorded as Becquerels per second per liter of sample. Key (1981) reports that the error associated with this method does not exceed 14 percent.

$\delta^{18}O$ samples were collected in 50 ml glass vials, precleaned with nitric acid and filled with distilled water prior to the dive. The vials were flushed with air from the scuba cylinders at the underwater sampling locations then rinsed and refilled with aquifer water.

A more detailed accounting of the methodology used to collect samples for ^{222}Rn and $\delta^{18}O$ as well as a description of the error involved with the data collection is provided in Kincaid (1994).

RESULTS: RIVER WATER INTRUSION TO THE DEVIL'S EAR CAVE SYSTEM

Table 1 presents the ^{222}Rn and $\delta^{18}O$ data collected from the Devil's Ear cave system during both sampling periods. ^{222}Rn concentrations, converted to the corresponding percent river water in the sample, have been contoured on top of the cave map and are presented on Figure 6. The contour maps from both sampling periods delineate distinct zones of river water intrusion to the Devil's Ear cave system. The maps clearly show that intruded river water enters the cave system from the conduits nearer to the river and that the conduits emanating from the recharge areas north and south of the river consistently provide the sources of background aquifer water.

Low ^{222}Rn concentrations ranging between 2.5 and 5.8 Bq/L measured in sections A, B, C and D clearly demonstrate that the conduits in these sections provide direct pathways for river water to intrude into the Floridan aquifer. As shown on Figure 6, these conduits trend south of the main cave toward and, in the case of those in sections A and B, beneath the Santa Fe River. During both sampling periods, turbid water was observed entering the main conduit from these three regions. It also emanated from fractures in the limestone on the south side of the main conduit. More turbid water was observed during the 1992 sampling period. During both sampling periods, the water clarity in the main conduit improved upstream of the section A junction and clear water was always observed in sections E, F, and G. Overall, water clarity decreased in the system immediately following major precipitation events particularly those localized over the Northern Highlands physiographic province.

High ^{222}Rn concentrations ranging between 11.7 and 14.2 Bq/L indicate that the three most prominent sources of background aquifer water in the cave system are found in sections E, F, and G. Water clarity consistently improved and the ^{222}Rn concentration dramatically increased upstream of section A shown on Figure 6. These conditions indicate that section A is the upstream extent of river water intrusion to the main conduit of the cave system.

Figure 7 plots ^{222}Rn concentrations and the corresponding river water percentages in samples collected along the main conduit of the cave system. Variations in the ^{222}Rn concentration shown on Figure 7 reflect junctions where waters of different sources enter the main conduit. The percentage of background aquifer water in the main conduit decreases as the water moves toward Devil's Ear and Devil's Eye springs. The mixing model demonstrates that 62 percent of the discharge at Devil's Ear spring was recently intruded river water during the February 1992 sampling period. The magnitude of river water intrusion dropped to 49 percent of the spring discharge during the June 1993 sampling period.

As shown on Figure 8, the variations in $\delta^{18}O$ in the cave system during the June 1993 sampling period qualitatively support the ^{222}Rn data. More positive $\delta^{18}O$ values, between −3.55 and −3.45, were recorded in sections B and C of the cave system which were identified by the ^{222}Rn mixing model as regions of high river water intrusion. More negative $\delta^{18}O$ values ranging from −3.65 to −3.75 were recorded in section E that corresponds to one of the principal sources of background aquifer water identified by the ^{222}Rn mixing model. The mixing model was not applied to the $\delta^{18}O$ values because the $\delta^{18}O$ signature of the river was not determined.

During both sampling periods, the discharge of the Santa Fe River was measured at several points along the 1.5 km transect between Rum Island and July springs shown on Figure 2. Figure 9 compares the discharge transects with the percentage of river water measured in

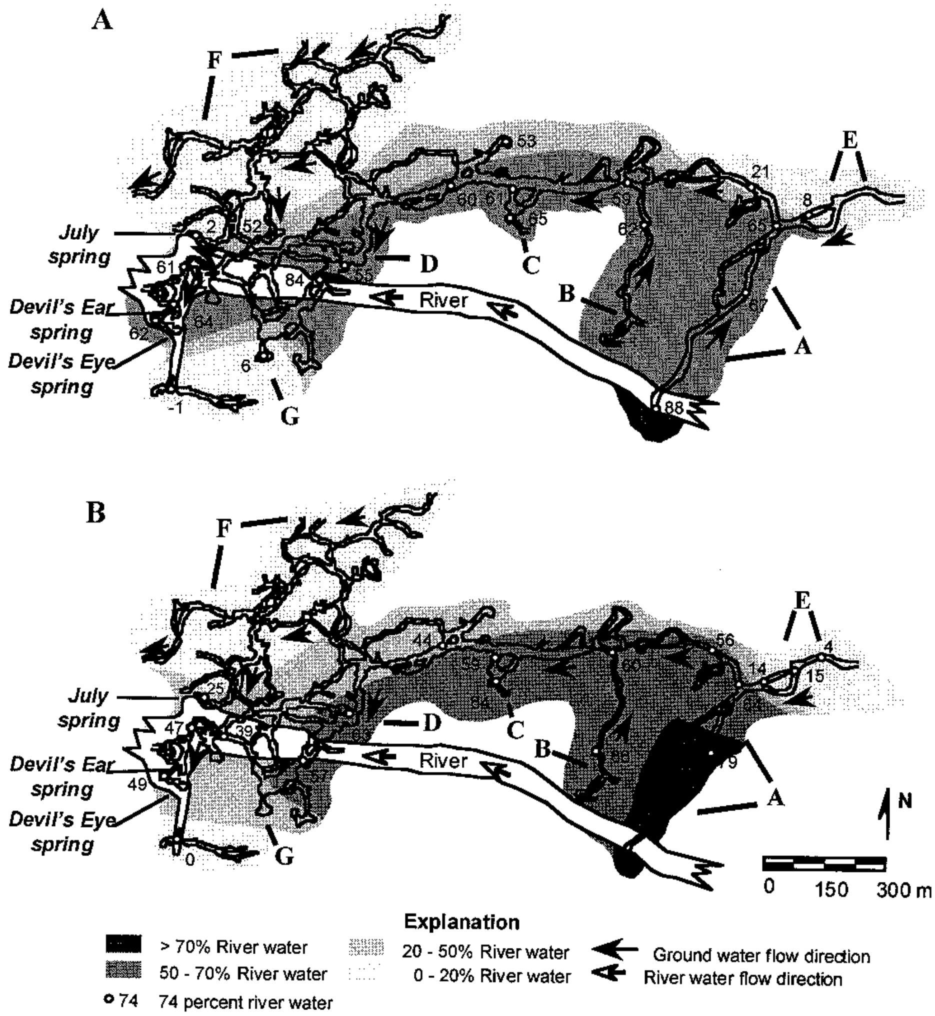

Figure 6. The extent of river water intrusion to the Devil's Ear cave system during (A) the February 1992 sampling period and (B) the June 1993 sampling period, north central Florida. The degree of shading is proportional to the percentage of intruded river water. Notice that sections A, B, and C show the regions with the greatest amount of intruded river water while sections E, F, and G show the regions of purest aquifer water.

the spring discharge from Devil's Ear spring. The overall river discharge increased between the two sampling periods from 23 m^3/s during the February 1992 experiment to 26.2 m^3/s during the June 1993 experiment reflecting different river stage conditions. Both transects demonstrate a downstream increase in river discharge due to ground water influx. However, the measurements collected during the 1993 sampling period reflect a substantial loss in stream flow immediately downstream of Rum Island. Unfortunately, the same number of measurements were not collected during the 1992 sampling period and the stream flow loss measured in 1993 was not documented with that broader sampling interval. Notice that the percentage of recently intruded river water discharging from the Floridan aquifer at Devil's Ear spring decreased during the period of higher stage in the Santa Fe River.

DISCUSSION: GROUND-WATER CIRCULATION BETWEEN THE DEVIL'S EAR CAVE SYSTEM AND THE SANTA FE RIVER

The fact that the cave system experienced more river intrusion during a period of lower recorded river stage indicates that ground-water/surface-water exchange is not a simple direct function of the stage of the Santa Fe River. Rainfall and ground-water level data collected from the field area and the Northern Highlands (Suwannee River and St. Johns River Water Management districts) during this investigation provide the clues necessary to explain this complication. Ground-water levels were measured in a Department of Transportation (DOT) well located approximately 2 km west of the field area. Those data are shown graphically on Figure 10. There was significantly more rainfall in the highlands

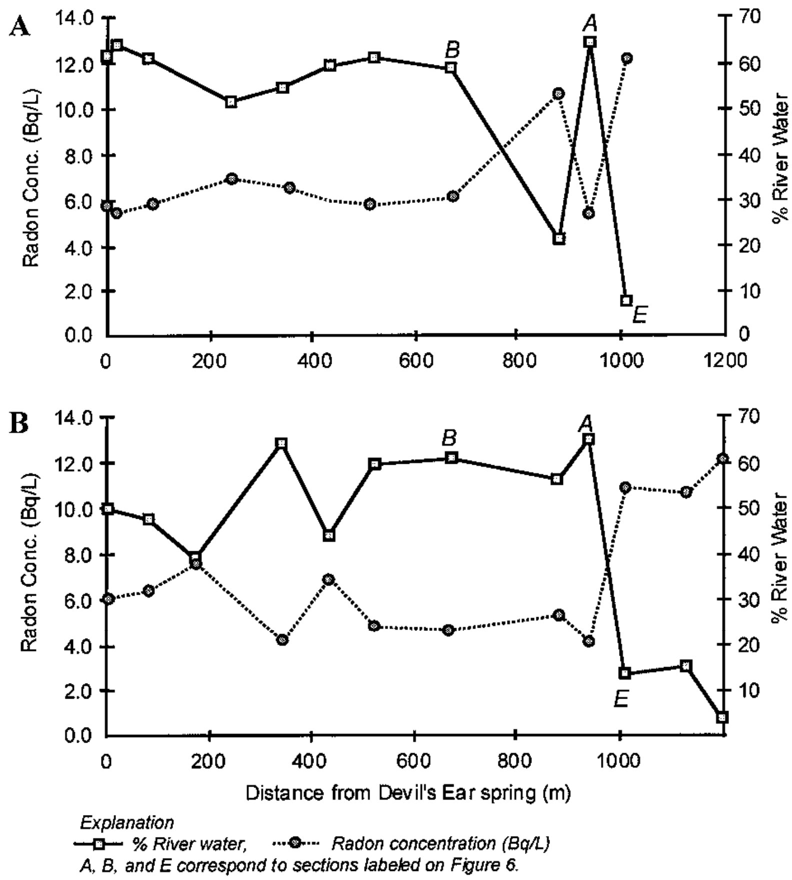

Figure 7. Graphs show the variation in the ^{222}Rn concentration and the corresponding percent of intruded river water along the main conduit in the Devil's Ear cave system during the (A) February 1992 and (B) June 1993 sampling periods, north-central Florida. Peaks in the solid lines indicate junctions with connecting conduits that introduce intruded river water to the cave system whereas troughs show the sources of background aquifer water.

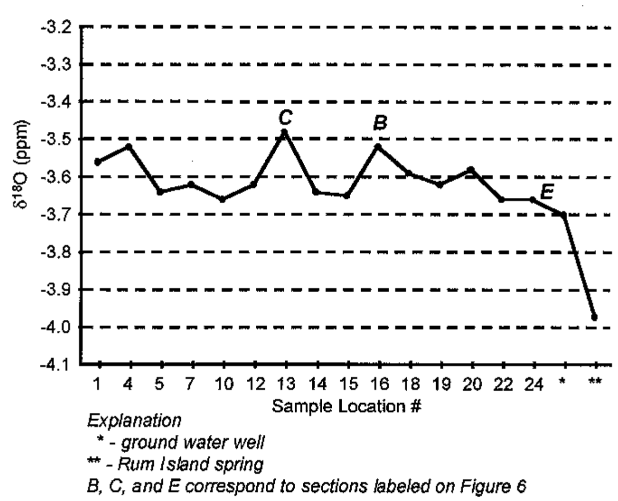

Figure 8. Variations in $\delta^{18}O$ measured in the Devil's Ear cave system during the June 1993 sampling period, north-central Florida. The graph supports the radon data showing that sections B and C are regions of greater intruded river water while section E is a region of pure aquifer water. Sample location numbers reference those provided on Figure 5. Section labels refer to those shown on Figure 6.

than in the lowlands during the February 1992 sampling period when the greatest amount of intruded river water was measured in the cave system. On the contrary, there was more rainfall in the lowlands than in the highlands during the June 1993 sampling period when the least amount of intruded river water was recorded. The water level in the Floridan aquifer was higher during the June 1993 sampling period when there was more rainfall over the lowlands and less river water intrusion to the cave system.

The hydraulic data and the results of this investigation reveal that the ground-water/river-water exchange process is dictated by the net head difference between the aquifer and the river. Figure 11 is a conceptual model of the mechanisms controlling ground-water circulation between the Devil's Ear cave system and the Santa Fe River.

The river receives water from both runoff in the highlands and spring discharge in the lowlands. Therefore, head in the river is dependent on both the quantity of aquifer discharge to the river and the quantity of surface

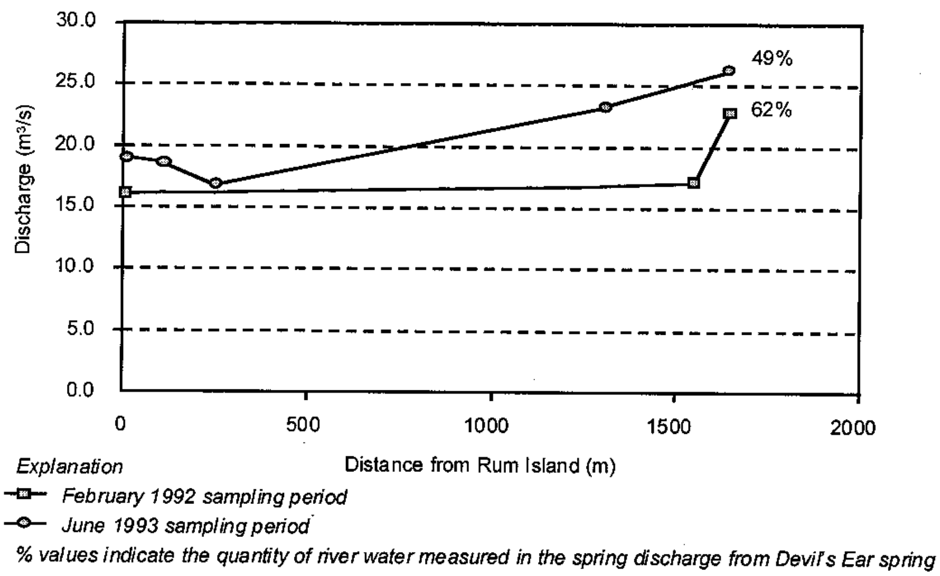

Figure 9. Comparison of Santa Fe River discharge measured between Rum Island and July springs (Figure 2), north-central Florida during the February 1992 and June 1993 sampling periods. Notice that there was more intruded river water measured in the discharge from Devil's Ear spring during the period of lower river stage.

runoff received by the river and its tributaries. By contrast, head in the cave is primarily dependent on the quantity of recharge. Thus, surface runoff, which is greater in regions where the aquifer is confined, is the independent variable that causes the head difference. The magnitude and direction of the hydraulic gradient between the river and the cave is, therefore, a direct function of the distribution of major regional precipitation events.

Figure 10. Comparison of water levels in the Floridan aquifer near the Devil's Ear cave system and rainfall measured in the Northern Highlands and lowland provinces, north-central Florida. Notice that there was more rainfall in the highlands than in the lowlands during the February 1992 sampling period when more river water intrusion was measured in the Devil's Ear cave system. There was more rainfall in the lowlands and the water table in the Floridan aquifer was higher during the June 1993 sampling period when less river water intrusion was measured in the Devil's Ear cave system. Data are from the Suwannee River and St. John's River water management districts.

When precipitation is concentrated on the Northern Highlands where the Santa Fe River is not in hydraulic connection with the Floridan aquifer, the water accumulates in the river as overland flow and the flood pulse moves downstream onto the unconfined part of the aquifer. The subsequent increase in river stage produces a downward hydraulic gradient causing large amounts of river water to invade the cave through the leaky confining layer (Figure 11A). Observations of water clarity reductions in the cave, by the author as well as other cave divers, after large flood events originating in the highlands of the upper Santa Fe River reveal that river water intrusion to the aquifer can occur in as little as one or two days.

Conversely, when precipitation is concentrated on the lowland regions where the Floridan aquifer is unconfined, recharge to the aquifer results from direct infiltration with no resulting flood wave in the river. The hydraulic head in the cave rises above that of the river where a rising river stage is caused only by increased spring discharge. The resulting upward hydraulic gradient results in flow from the cave to the river (Figure 11B). The water in the cave will clear as the tannin surface water from the Santa Fe River is flushed up and out through the confining layer.

CONCLUSIONS

The findings of this study demonstrate the vulnerability of the unconfined sections of the Floridan aquifer to rapid contamination from surface streams. The ^{222}Rn and $\delta^{18}O$ data and water clarity observations presented in this paper clearly demonstrate the occurrence of rapid river water intrusion to the unconfined Floridan aquifer. The

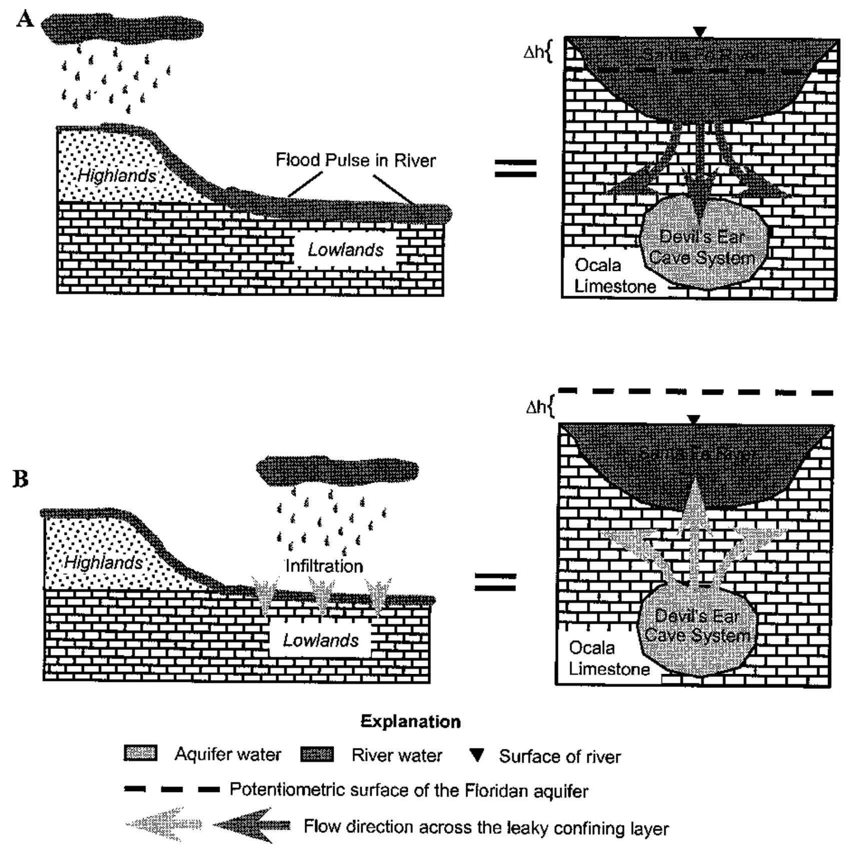

Figure 11. Ground-water/river-water exchange between the Santa Fe River and the extremely permeable caves in the Floridan aquifer across a 30-m thick section of Ocala Limestone which is a leaky confining layer. A) Rainfall in the highlands creates a flood pulse in the river that raises the stage of the river above the potentiometric surface of the aquifer creating a downward gradient. B) Rainfall in the lowlands infiltrates directly to the aquifer raising the potentiometric surface above the stage of the river creating an upward gradient.

two component mixing model used in this investigation revealed that as much as 62 percent of the discharge at Devil's Ear spring can be river water that has recently intruded into the Devil's Ear cave system. Observations of water clarity reductions in the cave system reveal that pervasive river water invasion to the major karstic conduits underlying the Santa Fe River can occur immediately after flood events originating in the Northern Highlands physiographic province.

Given the prevalence of karst conditions in Florida, the hydrologic character of the part of the western Santa Fe River basin investigated in this study can be considered typical of other regions in Florida where rivers or streams dissect the unconfined Floridan aquifer. The results of this investigation demonstrate that there can be no clear distinction between ground and surface waters in these regions. Instead, water is actively exchanged between the aquifer and rivers and streams at scales that cannot be measured by standard hydraulic analyses. Environmental regulations that segregate ground water from surface water in these regions will permit contaminants that enter the river to be carried into the aquifer by the exchange process and potentially degrade water quality.

ACKNOWLEDGMENTS

Katherine Ellins provided significant insight and guidance with the geochemical interpretations. Peter W. Huntoon, University of Wyoming College of Arts and Sciences, reviewed this manuscript before submission. Jarrod Jablonski, Rich Hisert, and several other volunteers provided invaluable assistance with the data collection. Reviewer comments were constructive and greatly appreciated. This project was partially funded by the Department of Sponsored Research at the University of Florida.

REFERENCES

Ackerer, P. H.; Esteves, M.; and Kohane, R., 1990, Modeling interactions between groundwater and surface water: a case study. In Gambolati, G.; Rinaldo, A.; Brebbia, C.A.; and Gray, W.G. (Editors), *Computational Methods in Subsurface Hydrology*, Proceedings of the Eighth International Conference on Computational Methods in Water Resources, Venice, Italy: Computational Mechanics Publications, Boston MA.

Andrews, W. J., 1992, *Reconnaissance of Water Quality at Nine Dairy Farms in North Florida, 1990–1991*, Water Resources

Investigations Report 92-4058: U. S. Geological Survey, Denver, CO.

Asikainen, M., 1981, State of disequilibrium between ^{238}U, ^{234}U, ^{226}Ra, and ^{222}Rn in groundwater from bedrock: *Geochimica et Cosmochimica Acta,* Vol. 45, pp. 201–206.

Criss, R. E. and Davisson, M. L., 1996, Isotopic imaging of surface water/groundwater interactions, Sacramento Valley, California: *Journal of Hydrology*, Vol. 178, pp. 205–222.

Davis, S. N. and DeWiest, R. J. M., 1966, *Hydrogeology:* Wiley, New York.

Devito, K. J.; Hill, A. R.; and Roulet, N., 1996, Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield: *Journal of Hydrology,* Vol. 181, pp. 127–147.

Ellins, K. K., 1992, Stable isotopic study of the groundwater of the Martha Brae River Basin, Jamaica: *Water Resources Research,* Vol. 28, No. 6, pp. 1597–1604.

Ellins, K. K.; Roman-Mas, A.; and Lee, R., 1990, Using ^{222}Rn to examine groundwater/surface discharge interaction in the Rio Grande De Manati, Puerto Rico: *Journal of Hydrology*, Vol. 115, pp. 319–341.

Ellins, K. K.; Kincaid, T. R.; Hisert, R. A.; Johnson, N. A.; Davison, C. A.; and Wanninkohf, R. H., 1991, Using ^{222}Rn and SF6 to determine groundwater gains and stream flow losses in the Santa Fe River, in *Hydrogeology of the Western Santa Fe River Basin, Field Trip Guidebook No. 32:* Southeastern Geological Society, Tallahassee, FL.

Fernald, E. A. and Patton, D. J., 1984, *Water Resources Atlas of Florida,* Library of Congress Catalog No. 84-081758: Institute of Science and Public Affairs, Tallahassee, FL.

Florida Environmental Health and Safety Regulations, 1994a, *Ground Water Classes, Standards, and Exemptions*, Specific Authority: 403.061, Title 62; Chapter 62-520, F.S. New 9-8-92, Amended 4-14-94, Formerly 17-520.100: Florida Environmental, Health and Safety Regulations, Tallahassee, FL.

Florida Environmental Health and Safety Regulations, 1994b, *Definitions for Ground Water,* Specific Authority: 403.061, Title 62; Chapter 62-520.200, F.S. New 9-8-92, Amended 4-14-94, Formerly 17-520.100: Florida Environmental, Health and Safety Regulations, Tallahassee, FL.

Gessel, T. F., 1983, Background atmospheric ^{222}Rn concentrations outdoors and indoors, a review: *Health Physics*, Vol. 45, No. 2, pp. 289–302.

Herczeg, A. L.; Barnes, C. J.; Macumber, P. G.; and Olley, J. M., 1992, A stable isotope investigation of groundwater-surface water interactions at Lake Tyrrell, Victoria, Australia: *Chemical Geology,* Vol. 96, pp. 19–32.

Hisert, R. A., 1994, *A Multiple Tracer Approach to Determine the Ground Water and Surface Water Relationships in the Western Santa Fe River, Columbia County, Florida:* Unpublished Ph.D. Dissertation, Department of Geology, University of Florida, Gainesville, FL.

Hunn, J. D. and Slack, L. J., 1983, *Water Resources of the Santa Fe River Basin, Florida*, U. S. Geological Survey Water-Resources Investigations Report 83-4075: U. S. Geological Survey, Denver, CO.

Kaufmann, R. F. and Bliss, J. D., 1978, Radium-226 in ground water of west- central Florida: *Water Resources Bulletin,* Vol. 14, No. 6.

Key, R. M., 1981, *Examination of Abyssal Sea Floor and Near-Bottom Water Mixing Processes Using Radium-226 and Radon-222:* Unpublished Ph.D. Dissertation, Texas A&M University, College Station, TX.

Kincaid, T. R., 1994, *Groundwater and Surface Water Interactions in the Western Santa Fe River Basin near High Springs, Florida:* Unpublished Masters Thesis, Department of Geology, University of Florida, Gainesville, FL.

Kincaid, T. R.; Denizman, C.; and Ellins, K. K., 1992, *Abstract,* Using SF6 to establish the general recharge area for Three Springs in the Santa Fe River, Florida, in *Annual Meeting of the Geological Society of America, Cincinnati, Ohio, Abstracts with Programs:* Geological Society of America, Boulder, CO, p. A300.

Krishnaswami, S.; Graustein, W.S.; Turekian, K. K.; and Dowd, J. F., 1982, Radium, thorium, and radioactive lead isotopes in groundwaters: application to the *in situ* determination of adsorbtion-desorbtion rate constants and retardation factors: *Water Resources Research*, Vol. 18, No. 6, pp. 1633–1675.

Lane, E. 1986, *Karst in Florida,* Special Publication No. 29: Florida Geological Survey, Tallahassee, FL.

Lee, T. M., 1996, Hydrogeologic controls on the groundwater interactions with an acidic lake in karst terrain, Lake Barco, Florida: *Water Resources Research,* Vol. 32, No. 4, pp. 831–844.

Rogers, A. S., 1958, *Physical Behavior and Geologic Control of Radon in Mountain Streams,* Geological Bulletin No. 1052-E: U. S. Geological Survey, Denver, CO.

Rosenau, J. C.; Faulkner, G. L.; Hendry, C. W. Jr.; and Hull, R. W., 1977, *Springs of Florida*, Bulletin No. 31: U. S. Geological Survey, Denver, CO.

Scott, T. M., 1991, The geology of the Santa Fe River basin, central-northern Peninsular Florida, in *Hydrogeology of the Western Santa Fe River Basin,* Field Trip Guidebook No. 32: Southeastern Geological Society, Tallahassee, FL.

Scott, T. M., 1992, *A Geological Overview of Florida*, Open File Report No. 50: Florida Geological Survey, Tallahassee, FL.

Shaw, R. D. and Prepas, E. E., 1990, Groundwater-lake interactions: I. accuracy of seepage meter estimates of lake seepage: *Journal of Hydrology,* Vol. 119, pp. 105–120.

Spangler, D. P., 1981, Florida's water resources with particular emphasis on ground water, in *Proceedings of the First Annual Symposium on Florida Hydrogeology:* Northwest Florida Water Management District, Havana, FL.

St. Johns River Water Management District, 1992, 1993, unpublished rainfall and ground-water level data: St. Johns River Water Management District, Palatka, FL.

Suwannee River Water Management District, 1992, 1993, unpublished rainfall and ground-water level data: Suwannee River Water Management District, Live Oak, FL.

White, W. A., 1970, *The Geomorphology of the Florida Peninsula,* Geological Bulletin No. 51: Florida Geological Survey, Tallahassee, FL.

Williams, K. E.; Nicol, D.; and Randazzo, A. F., 1977, *The Geology of the Western Part of Alachua County, Florida,* Report of Investigations No. 85: Florida Geological Survey, Tallahassee, FL.

Wilson, W. L. and Skiles, W. C., 1988, Aquifer characterization by quantitative dye tracing at Ginnie Spring, northern Florida, in *Proceedings of the Second Conference on Environmental Problems in Karst Terranes and Their Solutions:* The Association of Groundwater Scientists and Engineers, Nashville, TN.