USING RADON-222 AS A TRACER OF MIXING BETWEEN SURFACE AND GROUND WATER IN THE SANTA FE RIVER SINK/RISE SYSTEM

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
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Karst aquifers (which provide 25% of the world's population with potable water) are characterized by links between surface and ground water, making them susceptible to contamination. Linkage between groundwater and surface water occurs through the unconfined Floridan Aquifer in north-central Florida. An example of surface-groundwater linkage occurs when the Santa Fe River flows into a 32-m deep sinkhole, the River Sink, and resurges approximately 8 km down gradient at the River Rise. This system provides opportunities to observe mixing between surface and ground water within a karst aquifer. Mixing can be observed using natural chemical and isotopic tracers, one of which is the isotope ^{222}Rn (half-life = 3.82 days). Radon-222 is formed by the alpha decay of ^{226}Ra, an alkaline earth element common in carbonate and clay minerals. Surface waters have low ^{222}Rn activities (~20 dpm/L) due to atmospheric evasion and ground water have high ^{222}Rn activities (>200 dpm/L). The difference in

activities of these two end members should make ^{222}Rn a good tracer for surface-ground water mixing in karst areas.

Activities of ^{222}Rn were measured to depths of 8 and 10 m at two sinkholes (Vinzants Landing and River Rise) and indicated that ^{222}Rn is heterogeneous in the sinkholes. Water samples were collected from the River Sink, River Rise, and karst windows between the Sink and Rise from May 2002 to April 2003. These samples encompass drought, base flow, and flood stages. As the river stage rises to flood conditions (~11.51 masl) the excess ^{222}Rn activities decrease from approximately 100 dpm/L to less than 25 dpm/L, indicating that no matrix water enters the conduit; and that the conduit is filled with ^{222}Rn-poor surface water from the Santa Fe River. During low stage (9.25 masl), when past studies have found groundwater dominates the system, the water activities are also low ($\leq$ 25 dpm/L) possibly caused by evasion and radioactive decay of ^{222}Rn as the water slowly flows through the Sink/Rise System. At times of base flow conditions for the river (10.70 m stage), activities are ~100 dpm/L, indicating some ground water and surface water mixing. The fraction of surface and groundwater in the system could not be determined through a two end-member mixing model because evasion and radioactive decay complicate the simple mixing model. ^{222}Rn may be a good tracer of mixing between surface and ground water; however, further studies need to be conducted to fully understand the impacts of decay, evasion, and lithology over the ^{222}Rn activities in the Sink/Rise system.

CHAPTER 1
INTRODUCTION

Karst aquifers provide 25% of the world's population with potable water (Ford and Williams, 1989). These aquifers are typically characterized by direct links between the surface and ground water systems through sinkholes, swallets, and highly permeable rocks, which make karst groundwater resources susceptible to surface contamination (Ford and Williams, 1989). For example, tannins, pesticides, and nitrates from agricultural and animal byproducts have been shown to move rapidly into and through karst groundwater systems, contaminating water resources (Katz, 1992; Boyer and Pasquerell, 1996; Kincaid, 1998). The loss of undersaturated surface water with respect to calcite to the aquifer may also increase dissolution of carbonate rocks (Drever, 1988).

Tracking contaminants can be difficult because the heterogeneous permeability of karstic rocks complicates modeling of fluid flow and contaminant transport. Complications are due to the exchange of water among three types of porosity: intergranular matrix porosity, fracture porosity, and conduits (White, 1999). Many studies of karst aquifers have been conducted, but most focus on aspects of either conduit flow or matrix flow. Highly altered karst aquifers, like those found in Paleozoic mid-continent carbonates are dominated by conduit and fracture flow because recrystallization has led to dense, low permeability matrix rocks. Less altered karst aquifers may have matrix rocks with high permeability, creating flow characteristics that differ from karstic aquifers formed in dense and altered carbonates with low permeability.

An important example of a less altered karst system dominated by both conduit and matrix flow is the Floridan Aquifer system (Bush and Johnston, 1988), a regionally important aquifer because it is the main source of potable water in north central Florida. The Floridan Aquifer represents a class of karst aquifers with high intergranular porosity and permeability (Budd and Vacher, 2002), which may allow a significant fraction of the subsurface flow through matrix rocks (Martin and Screaton, 2001). Typical of all karstic aquifers, the Floridan Aquifer has direct links to surface water through sinkholes, swallets, and highly permeable rocks. Bush and Johnston (1988) suggested that on a regional scale, it could be assumed that the conduit and matrix systems in the Floridan Aquifer of the southeastern United States could be treated as homogenous or as an equivalent porous medium. At a local scale, even in porous karst aquifers such as the Floridan Aquifer, conduit flow predominates and the equivalent porous medium approach is invalid (Bush and Johnston, 1988; Padilla et al, 1994; Halihan et al, 1998). Prevention and remediation of contamination in these aquifers require an understanding of the mixing among surface and ground water and controls of flow paths in the subsurface.

Many techniques have been used for studies of flow paths, mixing, and flow velocities through karst aquifers. Common techniques include injection of artificial dyes (e.g., rhodamine and fluorescein), studies of physical characteristics of the water, and measurement of chemical and isotopic compositions of the water and dissolved constituents (e.g., Smart, 1988; Ryan and Meiman, 1996; Martin and Dean, 1999). One dissolved radioactive component with good potential for studying the mixing between ground and surface water is the isotope ^{222}Rn (half-life=3.82 days). Radon is a product of the natural radioactive decay series of ^{238}U and a direct product of alpha disintegration of

^{226}Ra (Bertin and Bourg, 1994). As an alkaline earth element, radium is found in carbonate and clay minerals; and thus large amounts of radon are generated in ground water. However, because of atmospheric evasion (loss of radon gas to the atmosphere), radon activity should be low in surface waters. In addition, radon is chemically conservative (i.e., no source other than ^{226}Ra and no sinks other than decay); and is easily measured at low activities (e.g., 0.02 pCi/L (0.044 dpm/L)) through alpha-counting techniques. Therefore, activities of ^{222}Rn in karst water should reflect the relative amounts of water from the surface with low ^{222}Rn activity and water that has been stored in matrix porosity and thus gained a high ^{222}Rn activity.

Rogers (1958) was the first to use ^{222}Rn to study ground water and surface water relationships. He demonstrated that ^{222}Rn activities in springs (ground water) were much higher than in surface water and that the springs were a source of ^{222}Rn in the streams surrounding his study area. A study by Ellins et al. (1990) of Puerto Rican streams in an upland karst region confirmed Rogers' (1958) work. Ellins et al. (1990) described low activities of ^{222}Rn in the streams (18 to 200 dpm/L) as a function of the atmospheric evasion and the high levels of ^{222}Rn (up to 693 dpm/L) in related springs due to the input of enriched groundwater. Bertin and Bourg (1994) were able to use the difference in ^{222}Rn activities in ground and surface water to trace the seeping of Lot River water in France into an alluvial aquifer. Though Bertin and Bourg (1994) did not work in a karstic terrain, their study suggests that ^{222}Rn can be used as a tracer of infiltrating river water and can be used in the presence of mixing within the aquifer.

This study has two principle objectives:

- To evaluate the potential for using ^{222}Rn in a karst environment for tracing groundwater and surface water interactions

- To define the interaction between surface water and ground water in a karst system with high matrix permeability using ^{222}Rn.

To satisfy these objectives, several questions concerning ^{222}Rn activities in a karstic terrain were addressed:

- Does ^{222}Rn trace surface water and ground water mixing in a karst region?
- Will ^{222}Rn trace mixing of the water from the matrix and conduit?
- How can the interactions between surface and ground water be quantified?
- Will lithology prove to be a main control over ^{222}Rn activities?

Study Area

Location and Climate

The Santa Fe River Basin (Figure 1-1) covers an area of 3584.5 km^2 and is a tributary basin of the Suwannee River (Hunn & Slack, 1983). The Santa Fe River originates in Altho and Santa Fe lakes in north-central Florida (Hunn & Slack, 1983) and flows westward approximately 50 km until it reaches a 32 m deep sinkhole at O'Leno State Park. River water that enters the sinkhole mixes with groundwater from the Floridan Aquifer and travels through areas of mapped and unmapped conduits. This water resurfaces at the River Rise (~8 km down gradient of the Sink) and continues as the lower Santa Fe River (Hisert, 1994; Dean, 1999) (Figure 1-2).

Located in a semi-tropical climate, average air temperature in the Santa Fe River Basin is 20°C and average groundwater temperature is around 22°C (Hisert, 1994; Florida Geological Survey, 1992). Precipitation averages 123 cm/yr with most occurring between June and September. Most summer rainfall occurs during local thunderstorms and seasonal tropical storms. As a result, precipitation can be heterogeneous over small areas. Winter rainfall is from extratropical storms, which causes most flooding.

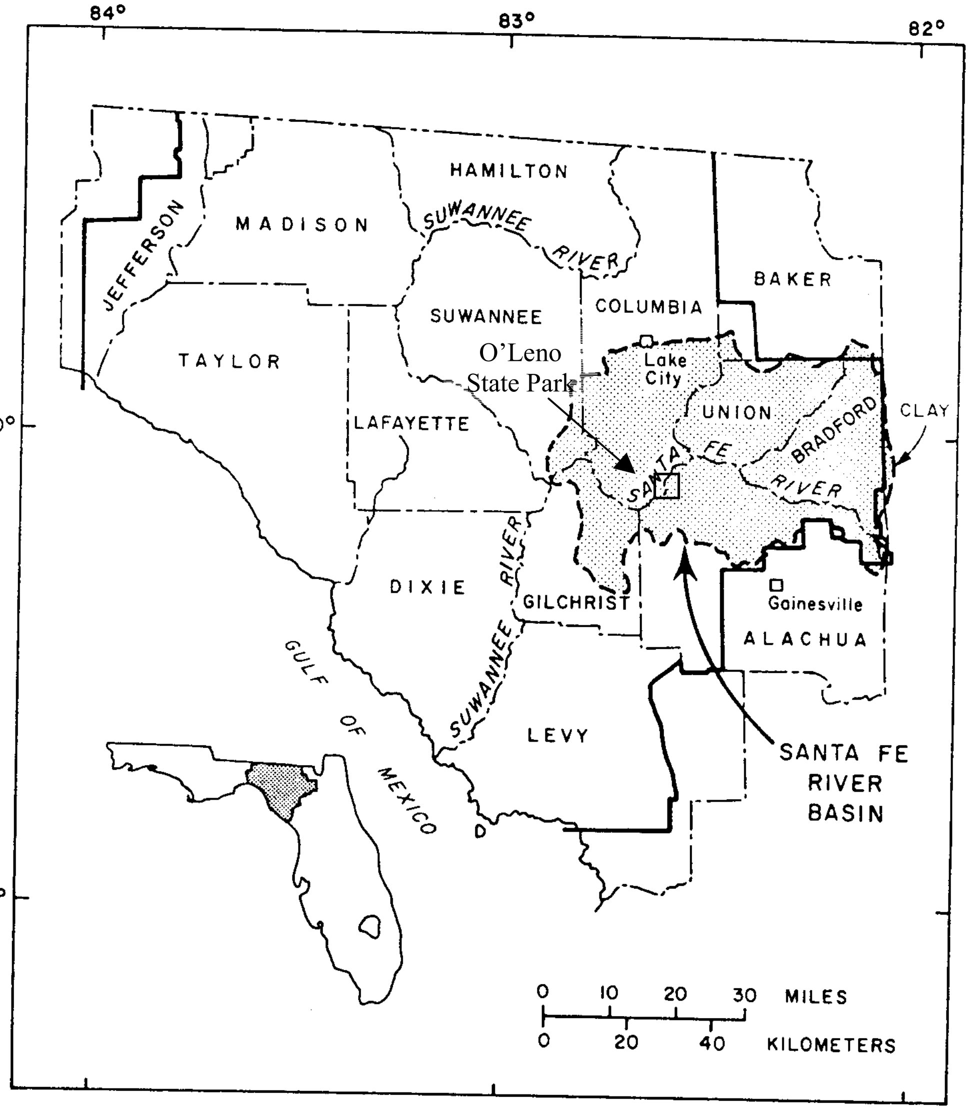


Figure 1-1. Map of the Santa Fe River basin, shown in shaded area. The location of O'Leno State Park is shown by the square and is seen in detail in Figure 1-2. Modified from Hunn, J. D., Slack, L. J., 1983. Water resources of the Santa Fe River Basin, Florida. U. S. Geological Survey.

Physiography

Three dominant physiographic divisions in the region include the Northern or Proximal zone, the Central or Mid-peninsular zone and the Southern or Distal zone (White, 1970). O'Leno State Park is located on the border between the Northern and Central physiographic zones within the Western Valley, a 140 mile long lowland, and the High Springs Gap, an opening within the Western Valley. This portion of Florida is a well-drained area of high recharge, and variably developed karst. The High Springs Gap includes the Cody Scarp, which represents the erosional edge of the Hawthorn Group. This scarp is the most prominent topographic feature in peninsular Florida, yet it is a subtle feature (with ~25m per 10km) (Puri and Vernon, 1964; White, 1970). The Hawthorn Group is the confining unit for the Floridan Aquifer, and thus karst features are common where the Hawthorn Group is absent. Most streams, including the Santa Fe River, either disappear or become losing streams to the aquifer systems below as they cross the scarp.

Geology and Hydrostratigraphy

Three aquifer systems comprise the hydrostratigraphy of the study area and include the Surficial Aquifer system, Intermediate Aquifer system, and the Floridan Aquifer system. The connection between the stratigraphy and hydrostratigraphy is shown in Table 1-1. The Surficial Aquifer system provides small-yield domestic and agricultural water supplies (Scott, 1992) and is composed of undifferentiated Plio-Pleistocene sediments containing sinkhole fill, fine to medium sands, and layers of clay and silt (Hunn and Slack, 1983; Scott, 1992). In O'Leno State Park, the Surficial Aquifer system is less than 2 meters thick to absent (Hunn and Slack, 1983).

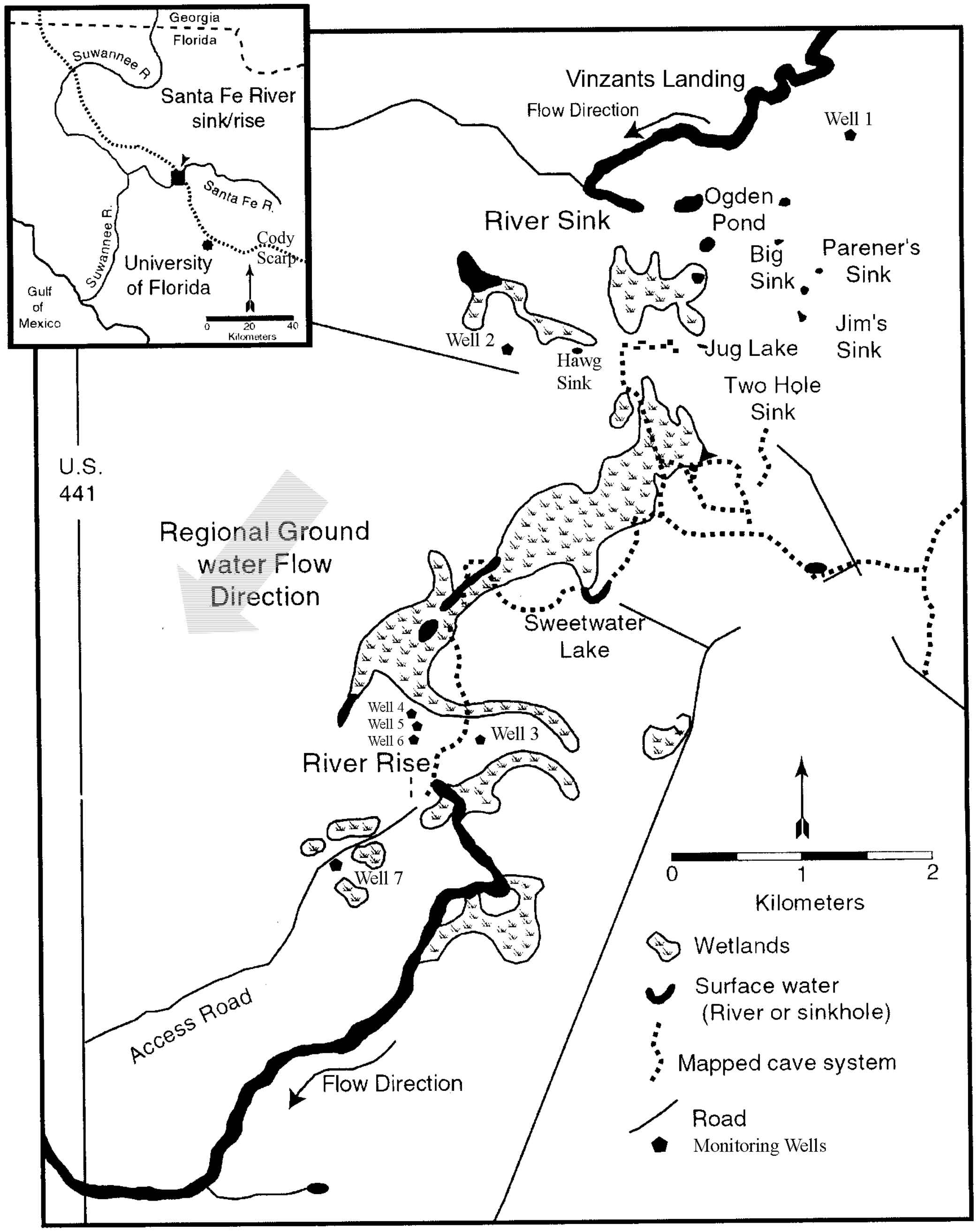


Figure 1-2. Site map of the Santa Fe River Sink/Rise system in O'Leno State Park. The dashed line represents locations of caves mapped by cave divers (Old Bellamy Exploration Team, unpublished report). The solid line represents roads and the pentagons represent wells drilled in 2003. Modified from Hisert (1994); Dean (1999).

The Intermediate Aquifer is contained within the Hawthorn Group (Bush and Johnston, 1988). The Hawthorn Group in Northern Florida consists of interbedded phosphatic carbonates and siliciclastics with a trend of increasing siliciclastics in the younger sediments. These sediments have low permeability and form an effective aquiclude, the intermediate confining unit, which confines the Floridan Aquifer where present (Bush and Johnston, 1988). In areas where the intermediate confining unit is absent such as the western portion of the Santa Fe River Basin, the Surficial Aquifer directly overlies carbonates of the Floridan Aquifer (Scott, 1992). The lack of the confining unit limits lakes and wetlands in the surface (Scott, 1992). Karst features, such as sinkholes are common through both the Surficial and Intermediate Aquifer systems and provide direct recharge to the Floridan Aquifer System.

The Floridan Aquifer System is composed of several hundreds of meters of limestone and dolostone and is the main source of water in northern Florida and parts of Georgia, South Carolina and Alabama (Hunn and Slack, 1983; Stingfield and LeGrand, 1966). The stratigraphic units comprising the Floridan Aquifer system from late- Eocene to Oligocene include the Oldsmar Limestone, Avon Park Limestone, Ocala Limestone, and Suwannee Limestone. The Ocala Limestone is the uppermost stratigraphic unit in O'Leno State Park (Hisert, 1994).

Background ^{222}Rn Studies

Two surface and groundwater mixing studies using ^{222}Rn were conducted previously in portions of the Santa Fe River Basin. Ellins et al. (1992) used background ^{222}Rn activities of the Santa Fe River (~10 dpm/L) and spring ^{222}Rn activities in the lower Santa Fe River Basin (~1000 dpm/L) to observe a ratio of ground to river water ^{222}Rn activities of 100:1. Hisert (1994) sampled ^{222}Rn in the Santa Fe River along

Hollingsworth Bluff, located southwest of O'Leno State Park. In samples collected at the riverbed, the depth halfway between the riverbed and surface, and the surface of the river, Hisert (1994) found that ^{222}Rn activities decreased with depth and were dependent on groundwater influxes.

Hisert (1994) also measured ^{222}Rn activities within the O'Leno State Park. At an average discharge of 42 m^3/s, ^{222}Rn activities in water from selected karst windows in the northern section of the park (River Sink and Jim Sink) are identical to atmospheric background levels (< 50 dpm/L) (Hisert, 1994). At these discharges, activities in water from the karst windows in the southern section of the park (Two Hole, Sweetwater Lake, and River Rise) were close to ground water levels (~450 dpm/L). Hisert interpreted this increase in activity to result from an influx of groundwater into the southern karst windows.

It is unclear as to whether the Hawthorn Group or the carbonates in the Floridan Aquifer is the major source of the ^{222}Rn in the study. Smoak et al. (2000) found well water from the Floridan Aquifer near Tampa, FL to have ^{226}Ra activities for the Floridan Aquifer to range from 5.8 to 6.6 dpm/L. These ^{226}Ra activities are similar to those seen at wells in this study, which correspond to ^{222}Rn activities of approximately 1000 dpm/L. Wherett (1992) found average soil gas ^{222}Rn activities of the Hawthorn Group to be approximately 2000 dpm/L. Although it is unclear how average soil gas converts to the liquid gas used in this study, it can be assumed that the numbers are within the same order of magnitude.

Background O'Leno Studies

Skirvin (1962) conducted the first study of water flow through the Sink/Rise system of the Santa Fe River. Based on the tannic acid content of the water, Skirvin

Table 1-1. Geologic and hydrogeologic units found in the Santa Fe River Basin. Modified from Hunn and Slack (1983), Scott (1992), Hisert (1994), and Dean (1999).

Series	Stratigraphic Unit	Hydrogeologic Unit	Lithologic Description	Thickness (m)
Holocene Pleistocene	Undifferentiated Sediments	Surficial Aquifer	Sinkhole fill, fluvial terraces, and thin surficial sand	0-25
Pleistocene to Miocene	Alachua Formation	Intermediate aquifer/ Upper confining unit	Reddish-white sands, with clays, sandy clays, and phosphate pebbles	0-30
Middle to Lower Miocene	Hawthorn Group		Phosphatic clayey sand-sandy clay with varying amounts of Fullers Earth and carbonate	
Oligocene	Suwannee Limestone	Floridan Aquifer	Very pale yellow, moderately indurated, porous, fossil-rich calcarenite	0-100
Eocene	Ocala Limestone Avon Park Limestone Oldsmar Limestone		Very permeable limestone, dolomitic limestone, and dolomite	275-300
Paleocene	Cedar Keys Formation	Sub- Floridan confining unit	Limestone, some evaporites and clay	?

(1962) suggested that most water entering the River Sink discharged at the River Rise. Skirvin (1962) also observed that water discharged from the Rise and intermediate karst windows when water was blocked from the River Sink by a temporary dam. Skirvin found that more water discharged from the Rise than flowed into the Sink in May and November 1961. The overall discharge gain in May and November were 5.30 m^3/s and 5.08 m^3/s, respectively. These observations indicate that the system gains water from sources other than the River Sink.

Hunn and Slack (1983) suggested that the water quality of the basin at this time was more influenced by natural factors, such as limestone dissolution, than by anthropogenic factors. Hunn and Slack (1983) describe the sinking eastern rivers as having lower concentrations of iron, calcium, magnesium, and bicarbonate than the water within the Floridan Aquifer. The rising western rivers have concentrations of iron, calcium, magnesium, and bicarbonate similar to the Floridan Aquifer. These chemical compositions indicate that the rivers contain water from the Floridan Aquifer, which is similar to the results reported by Skirvin (1962).

Hisert (1994) provided the first in-depth look into the complex underground system of O'Leno State Park by using sulfur hexafluoride (SF_6), temperature, and $\delta^{18}O$ to trace groundwater flow from the River Sink to the River Rise. The SF_6 tracer experiment, conducted in July 1991, required two injections to link flow from the Sink to the Rise. The first injection, performed at a discharge of 31.3 m^3/s, connected the River Sink to Sweetwater Lake through multiple karst windows, but SF_6 from this injection was not recovered at the River Rise. A second injection into Sweetwater Lake was detected at the River Rise (Fig. 1-2). The discharge rate during this second injection was not reported, but a third injection was made at Jim Sink when River discharge was 5.8 m^3/s into the River Sink, which connected Jim Sink to the River Rise via Sweetwater Lake. Even though a direct connection was never made between the River Sink and Rise, Hisert concluded that the karst windows in the Santa Fe River Sink/Rise system are hydraulically connected.

Hisert was also able to use background temperatures of the river (15°C) and groundwater (22°C) to conclude that the 2.5°C increase in temperature found within some of the windows, including the Rise, indicated a 37.5% influx of groundwater. This conclusion was supported by variations in oxygen ratios of the water samples. The karst windows have a slightly enriched $\delta^{18}O$ signature compared to the River Rise reflecting an influx of $\delta^{18}O$-enriched groundwater.

Dean (1999) used water chemistry to determine the extent of mixing between the river and ground water, and he used temperature as a tracer of flow rate from the River Sink to the River Rise. Using natural variations in temperature, Dean (1999) found that subsurface travel time of the water from the River Sink to the River Rise varies from approximately 12 hours to nearly 8 days, depending on river stage. By using temperature as a tracer and discharge measurements, Ginn (2002) and Screaton et al. (2004) found a subsurface conduit flow at rates of 3.11 km/day, which are similar to the subsurface flow rate found in Hisert's thesis. Both Ginn (2002) and Dean (1999) agree with Hisert's conclusion that the sinks in O'Leno State Park are all hydraulically well connected.

Chloride (Cl^-) concentrations from Dean (1999) increased between the River Sink and Sweetwater Lake by an average of 35.8% during low flow conditions. This increase suggests an addition of Cl^- rich water, probably groundwater. During high flow conditions the Cl^- concentrations between the Sink and Sweetwater Lake change by an average of 4.3%, which suggests very little addition of ground water.

CHAPTER 2
METHODS

The objectives of this project were met through a series of physical and chemical measurements including daily precipitation, river stage records, and measurements of isotopic compositions in water samples collected from various sites in the region of the Santa Fe River Sink/Rise system. Park staff collected daily precipitation and river stage measurements for the O'Leno State Park station on the Santa Fe River. New chemical analyses used in this thesis include measurement of ^{222}Rn activities in all collected water samples and measurement of absorbance in selected samples.

Field Methods

Sample Bottle Construction

Sample bottles were constructed from emptied, cleaned 2.5 L glass acid bottles, which were wrapped in duct tape to prevent breakage (Figure 2-1). A two-holed rubber stopper along with two lengths of 1/40-inch diameter copper pipes, one 2-inch long piece and the other 12-inches long were placed in the mouth of each bottle. The base of the 12-inch pipe was attached to an Aqua-Tech air diffuser. The rubber stopper was secured with thin wire and attached to the bottle with silicon to make a gas tight seal. Rubber tubing with male/female connectors was attached to the ends of the two copper pipes that extend from the rubber stopper. Clamps were attached to each rubber tube to control airflow. Each bottle was evacuated in the lab for approximately 5 min. before water sampling. The vacuum allows the water samples to be sucked into the bottle and prevents atmospheric contamination of the sample.

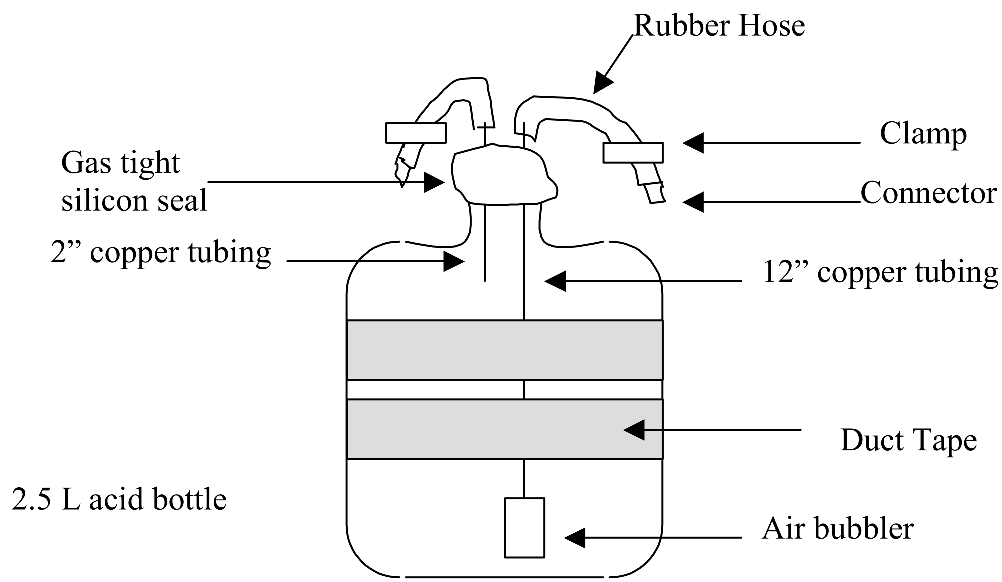


Figure 2-1. Schematic of the sample bottles used for collection of water for ^{222}Rn analysis.

Water Sampling

Water was sampled at 11 sites along the river (Vinzants Landing, River Sink, Ogden Pond, Big Sink, Parener’s Sink, Jim Sink, Jug Lake, Hawg, Two Hole, Sweetwater Lake, and the River Rise) and at 5 wells (Wells 1, 2, 3, 4, 6, and 7) located within the park (Figure 1-2). Samples were collected between May 2002 and May 2003 at stages ranging from 9.78 to >11.51 masl (Table 2-1).

One objective of this study was to develop simple and robust techniques for sampling and observing ^{222}Rn activities in karst systems. Consequently, sampling techniques evolved as the study proceeded. Two types of samples were collected initially and include grab samples and vertical profile samples. Grab samples were taken approximately one foot from shore of the various sinks by submerging the tube with the male connector and loosening the clamp. Vertical profile samples were taken at the River

Table 2-1. Dates, river stages, and sample sites of each sample event.

Sample Periods	Sampling Dates	River Stage (m)	Grab or Peristaltic Samples	Sample sites
I	5/8/02	9.78	Grab Samples	All 11 sites
	6/6/02	9.61	Grab Samples	Vertical profile of River Rise (1, 2, 4, 6, 8, 10 m depths)
	7/3/02	9.56	Grab Samples	Vertical profile of River Rise (0.3, 1, 2, 4, 6, 10 m)
				Vertical profile of Vinzants Landing (0.3, 1, 2, 4, 6, 8 m)
	8/29/02	10.12	Grab Samples	Vertical profile of Vinzants Landing (0.3, 1, 2, 4, 6, 8 m)
II	9/13/02	10.16	Grab Samples	All 11 sites
III	1/31/03	10.53	Peristaltic Samples	All 11 sites
IV	2/19/03	11.49	Peristaltic Samples	River Sink, Ogden, Jim, Hawg, Sweetwater, River Rise
V	2/27/03	11.51	Peristaltic Samples	River Sink, Ogden, Hawg, Sweetwater, River Rise
VI	3/5/03	>11.51	Peristaltic Samples	River Sink, Ogden, Jim, Hawg, Sweetwater, River Rise
	4/30/03	10.56	Peristaltic Samples	Wells
	5/7/03	10.47	Peristaltic Samples	Vertical profile of River Rise (0.3, 1, 2, 4, 6, 10 m)
				Vertical profile of Vinzants Landing (0.3, 1, 2, 4, 6, 8 m)

Rise and Vinzants Landing to depths of 10 and 8 meters, respectively. These samples were collected using a rubber raft and a rope to secure the raft position. Once in position, a tube was lowered to various depths, and water was siphoned to the tip of the tube. After the tube was filled with water, it was attached to the evacuated bottle, which was allowed to fill with sample water.

Subsequent samples were collected from shore using a peristaltic pump (Geotech Geopump 2). This sample system included a tube that was extended up to 20 meters from shore. One end was connected to the pump and the other was weighted and screened with a woven mesh of polypropylene with a mesh size of 210 μm. The tube was set to a 2-meter depth and attached to a long PVC pipe with floats on either side and pushed from shore. The tubing was purged with 2 liters of water before being connected to the sample bottle. The peristaltic pump was also used for the vertical profiles. A weighted rubber tube was lowered from the side of the boat at various depths (0.3, 1, 2, 4, 6, 8, and 10 m) and then connected to the pump, which like the other samples, was allowed to purge for two minutes before each sample was taken.

Ground Water Sampling

Ground water samples were taken from 6 wells (Well 1, 2, 3, 4, 6, and 7) that are located within the Park. Completed depth, screened interval, and depth to bedrock are given in Table 2-2.

Table 2-2. Drilling records of six wells drilled during 2003.

Wells	Completed Depth (ft)	Screened Interval (ft)	Depth to Bedrock (ft)
1	75	75-55	56
2	100	100-80	20
3	93	93-73	10
4	97	97-77	15
6	102	102-82	16
7	98	98-78	18

At each well a Redi-flow 2" variable performance submersible pump was used to pump water directly into the base of an 8.4-liter bucket, which was allowed to overflow ensuring no atmospheric interference. The wells were purged with at least three well volumes before ^{222}Rn samples were collected. The samples were collected by submerging the tubing to the base of the bucket and allowing the vacuum to fill the bottle.

Lab Methods

Radon was extracted from the water samples within 24 hours from sample time to insure a minimal loss of ^{222}Rn to decay. Bottles were attached to the extraction line (Figure 2-2), clamps were loosened, and ultra pure (99.999992 %) helium was allowed to bubble into the sample through the l2-inch copper pipe (Figure 2-1). The helium sparged gases from the water, and all gases flowed from the bottle through the shorter copper pipe. Gases flowed to a U-shaped collection tube, which is filled with copper filings and submerged in liquid nitrogen (Figure 2-2). Prior to entering the U tube, water and carbon dioxide are removed from the carrier gas by Hammond drierite and Thomas ascarite. As the gases flow through the U tube, the ^{222}Rn freezes to the surfaces of the copper filings and other remaining gases (e.g. He and O_2) escape. After one hour, the liquid nitrogen is removed, the bottles are disconnected, and the U tube is warmed. Counting cells (Lucas cells) are attached to the extraction line and helium pushes the trapped ^{222}Rn into the cells (Figure 2-2). The cells are then allowed to sit for a minimum of three hours for the alpha particle from the ^{222}Rn decay to allow an ingrowth of daughters (Operations Manual, 1985) (Figure 2-3) and then are placed on the alpha counter. After ^{222}Rn has been extracted from a sample, it is allowed to sit for a minimum of 7 days to allow regrowth of

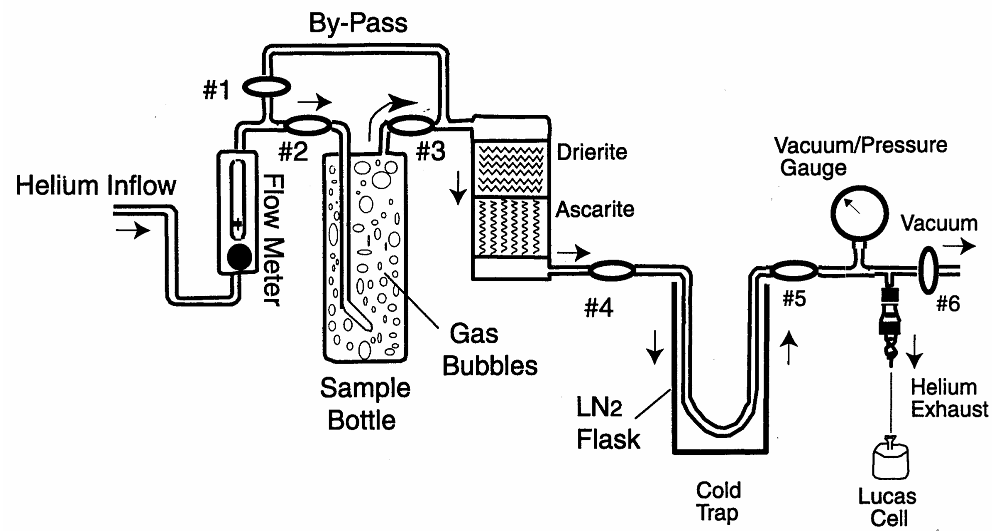


Figure 2-2. A simplified schematic of the Radon Extraction Line. Each number below corresponds with the number in the diagram. (J. Cable, 2003 personal communication)

1. By-pass valve purges line between samples or will be used when evacuating Lucas cells.
2. Valve controls flow into the sample bottle. Flow is regulated by the Flow meter (400 ml/min is recommended).
3. Valve controls flow out of sample bottle. Gas from bottle headspace is forced out of bottle and carried through the line. Flow passes through Drierite to remove water vapor and Ascarite to remove carbon dioxide. These gases must be removed to eliminate their freezing inside the LN_2 trap and taking up surface area reserved for radon molecules.
4. Valve controls flow into LN_2 cold trap. This valve is open during the sample processing and is closed after the collection period (about 60 minutes) is complete. Time series experiments using standards have shown that after 50 minutes 90% of radon in water is collected on the trap. After 60 min, 99% of radon is collected.
5. Valve controls flow into the Lucas cell. During sample processing, Lucas cell is left off of the line and helium is allowed to exit the cell port. Valve 5 is open. Radon and helium are forced into the cell after the trap has been heated and the cell is evacuated.
6. Valve controls flow to vacuum pump. Left closed during sample processing. It is opened only when the trap is closed (4 & 5 valves) so that you can evacuate the Lucas cell.

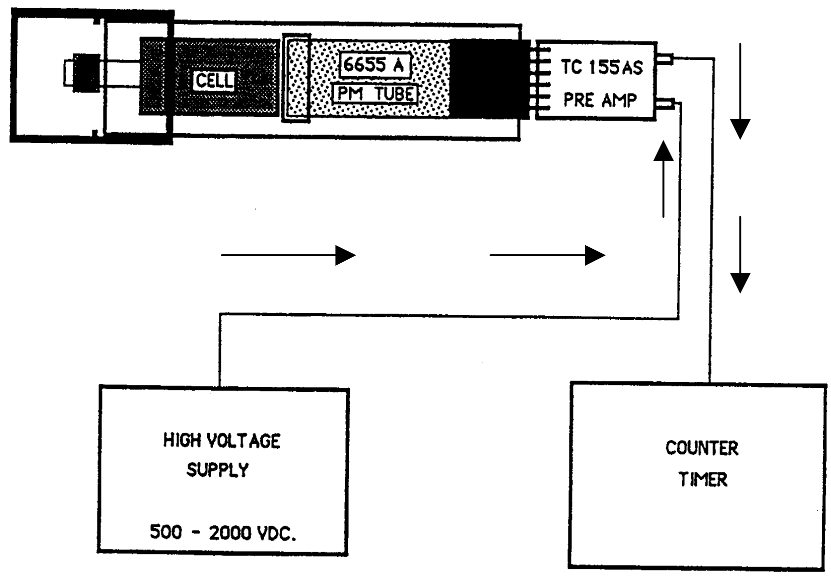


Figure 2-3. A simplified schematic of the radon counting system modified from Operations Manual 1012899A. The voltage travels to the PM tube and gives off pulses of light with each detected α - particle. The pulse of light is then sent to the counter.

^{222}Rn from the ^{226}Ra dissolved in the water. The ingrown ^{222}Rn is then extracted and measured following the techniques for initial ^{222}Rn analysis, which provides a measurement of ^{222}Rn activity in the sample. Once all samples have been run, the bottles are emptied to determine water volume.

The error associated with radon analysis are those associated with sample counting, cell background counting, volume, line efficiency, and operator error. Efficiency of the extraction line and counter were calculated by running ^{222}Rn standards. The primary standard used was NIST 268.2 Bq/g (16,092 dpm/g). The standard was diluted into 8 standards in bottles identical to those used for the measured ^{222}Rn samples and were extracted for ^{222}Rn using the same process as with the measured samples. Each Lucas cell was used three times. Table 2-3 shows that the average percent efficiency of the

Table 2-3. Average percent efficiency and standard deviation for each Lucas cell.

Counter	Red			Green			Blue			Yellow		
Cells	I	II	III	I	II	III	I	II	III	I	II	III
Average % efficiency	45	41	39	56	44	48	72	70	53	65	80	57
Standard Deviation	0.08	0.29	0.12	0.2	0.01	0.11	0.04	0.16	0.25	0.39	0.03	0.54

extraction line, lucas cells, and alpha counter range from 41 – 80 % and standard deviation ranges from 0.01 to 0.54. The precision of the procedure was determined by running duplicates. Duplicates were taken at Vinzants Landing at a depth of one and six meters, at the River Rise at a depth of one and six meters, and at Well 2. The percent difference of the duplicates taken at Vinzants Landing (1m) is 11% and is 64% at Vinzants Landing (6 m). The percent difference of the duplicates taken at the River Rise 1 m and 6 m are 73% and 18%, respectively. The percent difference of the duplicates of Well 2 is 29%.

Absorbance

A spectrophotometer measures the color absorbance quantitatively within the visible spectrum (360-375 nanometers). The instrument used in this study was the Milton Roy Spectronic 401 spectrophotometer. To get an absorbance value a wavelength was set on the spectrophotometer that will be maximally absorbed by river water. In this case the wavelength is 375 nanometers. Water with a higher amount of color due to tannins; such as river water, will have a higher absorbance value than water with little color (groundwater). It would be expected that the samples composed of groundwater will have a higher ^{222}Rn activity and should have the lowest absorbance. Therefore, absorbency should be a good check for the ^{222}Rn activities of this study.

CHAPTER 3
RESULTS

Precipitation and River Stage

The precipitation and river stage records for the study period are shown in Figures 3-1 and 3-2. A total of 120.45 cm of rainfall fell at the O'Leno station during the study period (April 1, 2002 – May 7, 2003) with 57% of the total (120.45 cm) occurring between September 2002 and April 2003, or 62% of the study interval.

River stage is controlled by precipitation and evapotranspiration, but river stage varies seasonally primarily due to evapotranspiration, which ranges from approximately 5 cm/month during the winter to approximately 14 cm/month during the summer (Gordon, 1998). The river stage between April 1, 2002 and May 7, 2003 ranged from a minimum of 9.48 masl on August 1, 2002 to a maximum of 14.43 masl on March 13, 2003 (Figure 3-2). Between the stages of 9.48 and approximately 10.50 masl, the river is completely captured by Vinzants Landing, a swallet upstream of the River Sink. Once stage reaches approximately 12 masl, the river overflows its banks at the south/southwestern portion of the Sink and continues overland flow in a south/southwestern direction within the Park. At stage of approximately 14.3 masl the river overflows its banks at the eastern portion of the Sink and begins to connect to all the other intermediate karst windows and the River Rise via overland flow (Dean, 1999).

Depth Profiles

Profiles of ^{222}Rn activity with depth were measured at Vinzants Landing and the River Rise. River Rise profiles are shown on Figure 3-3 A and B and Vinzants Landing profiles are shown on Figures 3-4 A and B. Figure 3-3 A has two profiles, one taken on June 5, 2002 and the other on July 2, 2002. On these dates all river water was captured by the sinkhole at Vinzants Landing. Both profiles have low ^{222}Rn activities, but show distinctly different trends. The July 2nd profile decreases with depth from a maximum of ~13 dpm/L to a minimum of ~2 dpm/L, whereas the June 5th profile is variable at the surface but increases slightly with depth below the sample taken at 4 m below the surface. Figure 3-4 B shows the first two profiles along with a third profile taken on May 7, 2003, when the river water was being captured by the River Sink at a stage of 10.43 masl. There is no pattern with depth; activities vary from a minimum of 25 dpm/L to a maximum of 186.7 dpm/L. This profile also shows no similarity with the first two profiles.

The first two Vinzants profiles were taken during the summer of 2002 (July 2, 2002 and August 29, 2002) when all river water was captured by the sinkhole at Vinzants Landing (Figure 3-4 A). The profile taken on July 2nd shows the highest activity (32.86 dpm/L) at a depth of 0.3 m with a minimum at a depth of 4.0 m. The August 29th profile has the highest activity (30.37 dpm/L) at a depth of 0.3 m, but the activity changes with depth less than on July 2nd. Figure 3-4 B. shows the first two profiles as well as a third profile taken on May 7, 2003. The May 7th profile has the highest activity (393 dpm/L) at depths of 0.3 meters and passes through a minimum between 2 and 6 meters below the water surface.

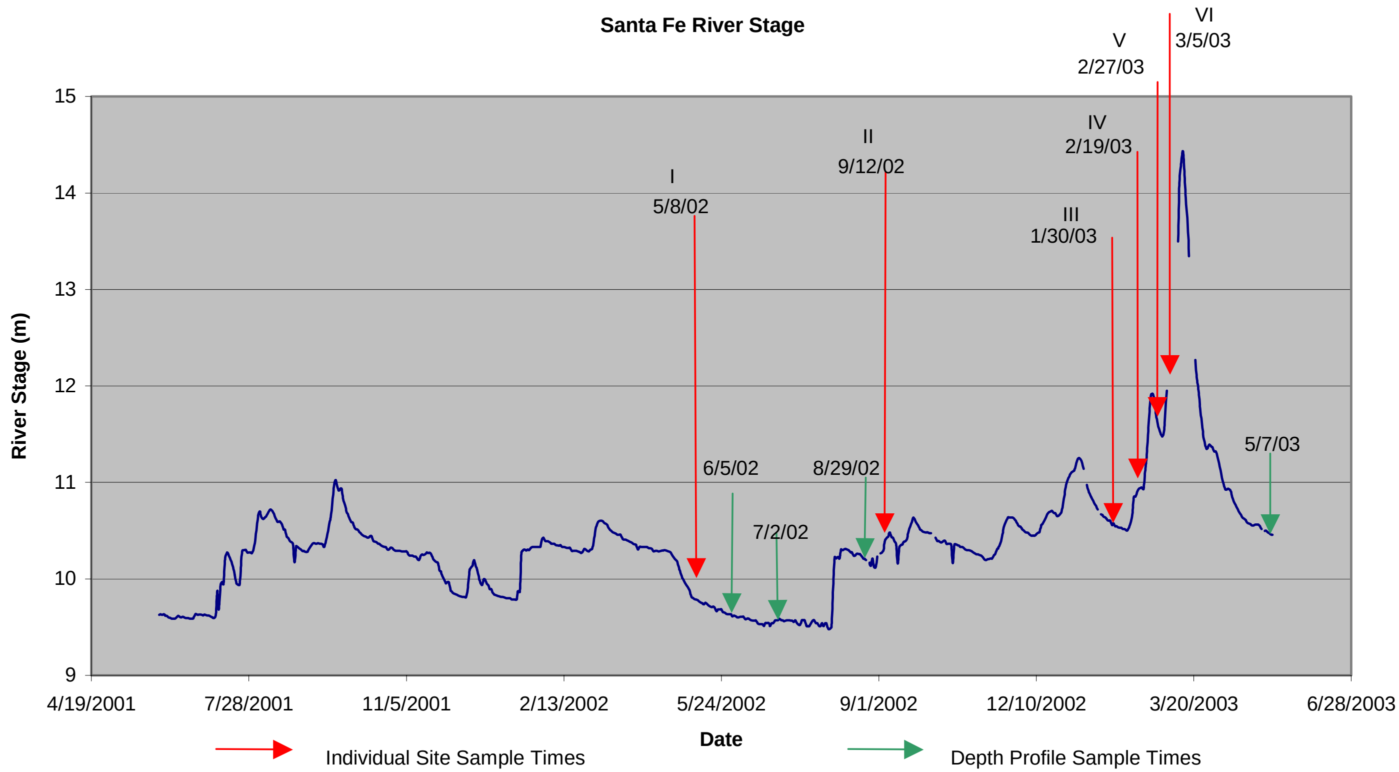


Figure 3-1. The precipitation record for O'Leno State Park from June 2001 to July 2003, which encompasses the entire study period. The red arrows indicate when individual sinks were sampled and the green arrows indicate when the depth profile sampling was performed. The roman numerals indicate the sample periods (Table 2-1).

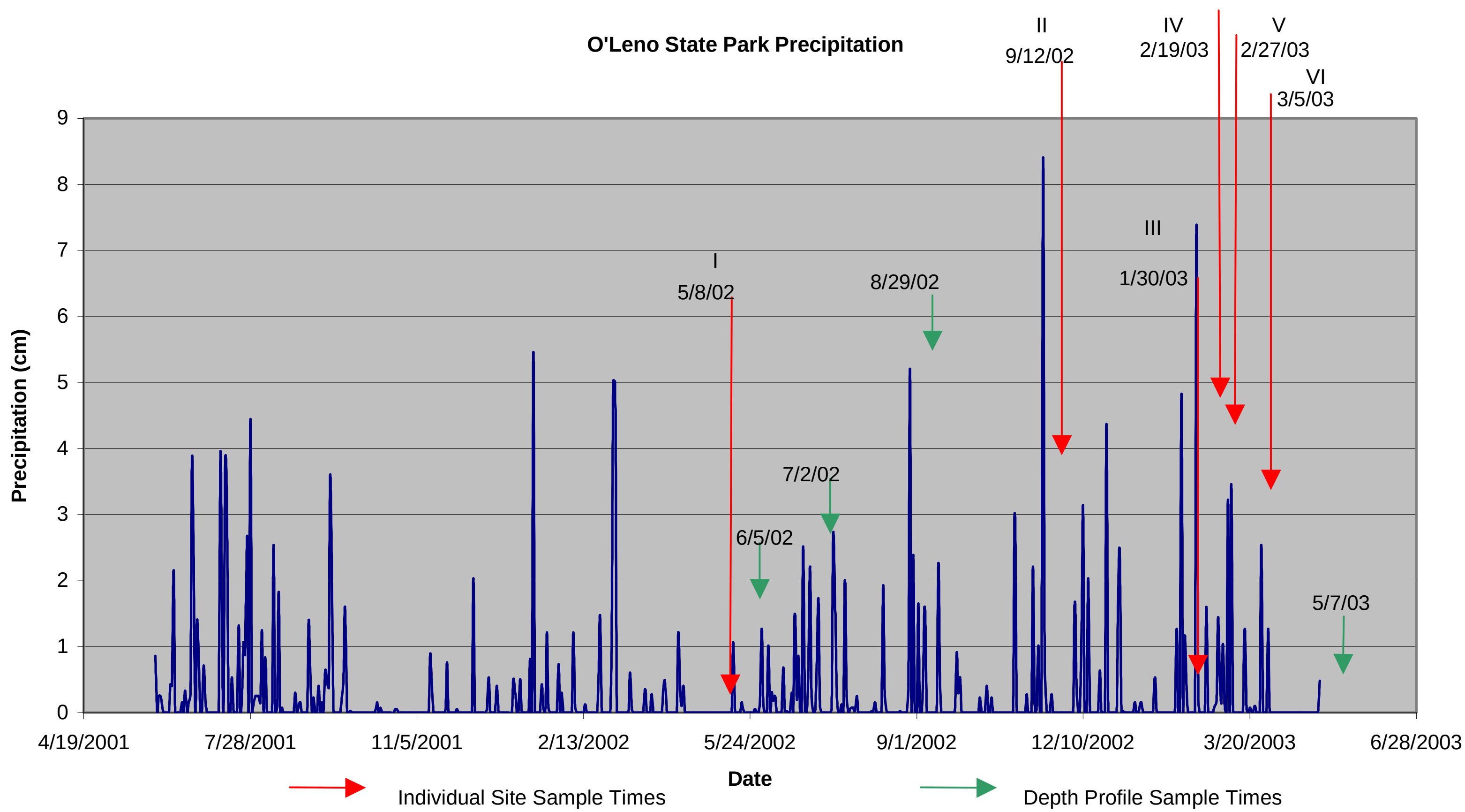


Figure 3-2. The Santa Fe River Stage recorded from O'Leno State Park from mid April 2001 till the end of June 2003. The red arrows indicate when individual sites were sampled and the green arrows indicate when the depth profile samples were performed. The roman numerals indicate the sample periods (Table 2-1).

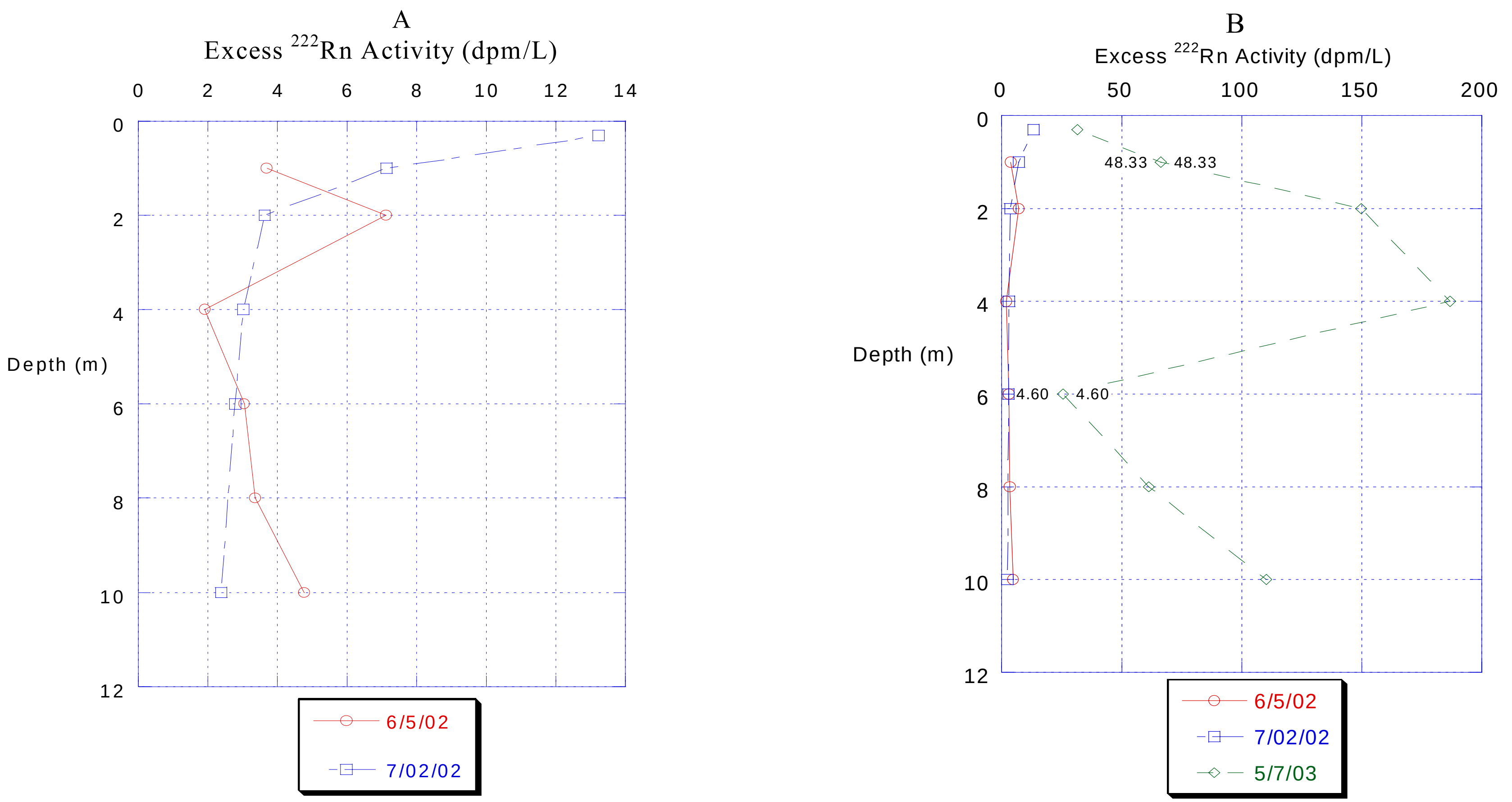


Figure 3-3. Vertical depth profiles at the River Rise. A. Depth profiles of the River Rise taken when the river was captured by the sinkhole at Vinzants Landing. B. The first two profiles as seen in graph A and the profile taken in May 2003 when the river was flowing to the River Sink. The values at 1 m and 6 m depths are averages of duplicate samples. Note the scale change between profile A and B.

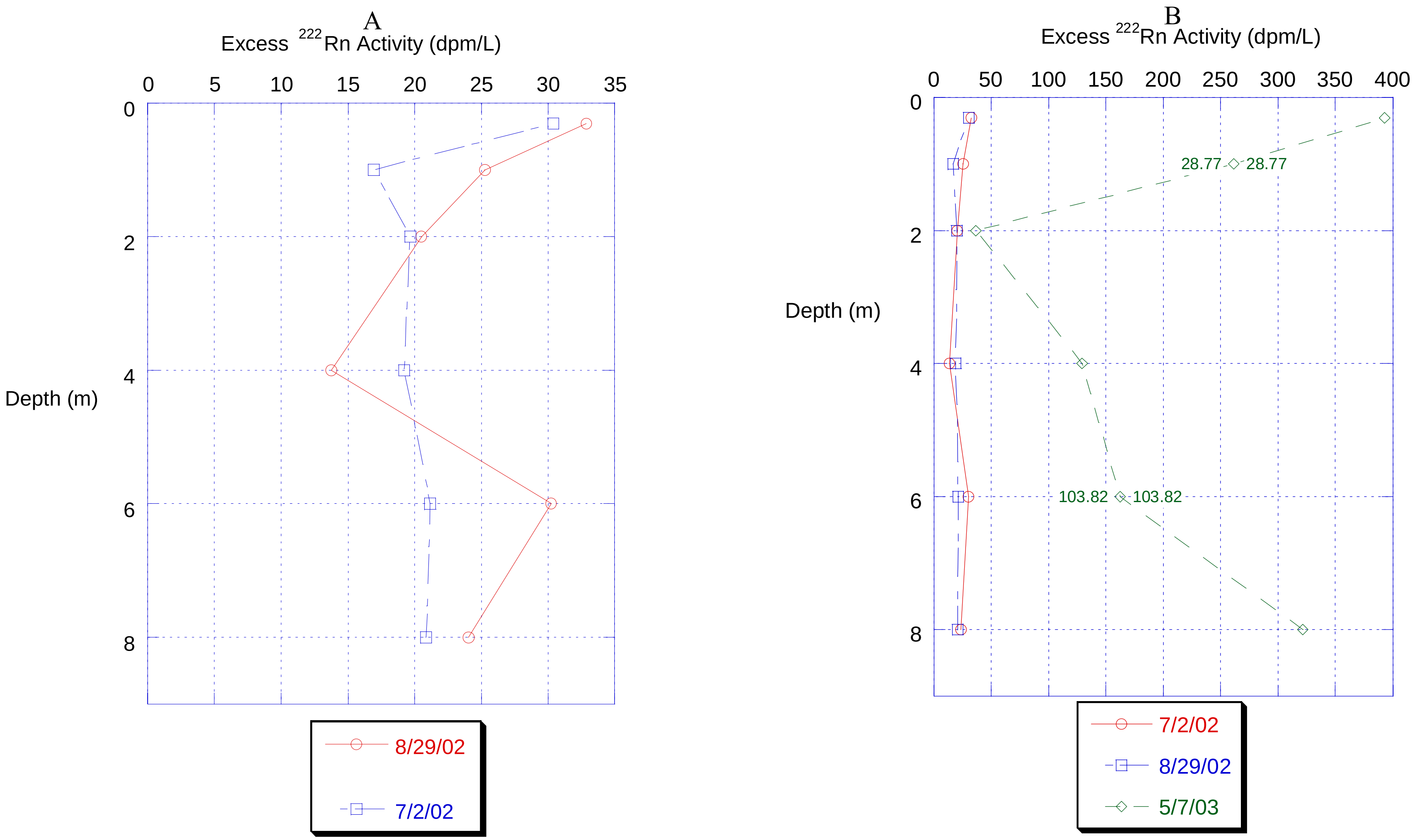


Figure 3-4. Vertical depth profiles at Vinzants Landing. A. The depth profiles of Vinzants Landing when it captured the river. B. The first two profiles as seen in graph A versus the profile taken in May 2003 when the river was flowing to the River Sink. The values at 1 m and 6 m depths are averages. Note the scale change between profile A and B.

This profile also has no pattern with depth and shows no similarity with the first two profiles

Excess ^{222}Rn, Precipitation, and River Stage

Sample Periods I to VI

Excess ^{222}Rn (dpm/L) records for the first two sample periods (May 8, 2002 and September 12, 2002) are shown in Figure 3-5 A, when river stage was 9.78 and 10.16 masl, respectively. Little to no precipitation had occurred in this area directly preceding the sampling events and all activities for both dates are less than 50 dpm/L. River stage was sufficiently low at these times that all river water flowed into Vinzants Landing and none into the River Sink.

Activities measured for sample period III (January 30, 2003) are shown in Figure 3-5 B. Approximately 40.21 cm of rain fell between September 12, 2002 and January 30, 2003, causing the river stage to rise to 10.53 masl (Figure 3-1, 3-2). Most of the ^{222}Rn activities sampled on January 30, 2003 are higher than the first two sample periods, with the highest activity of 295.0 dpm/L at Hawg Sink. Ogden Pond, Jug Sink, and Two Hole have activities similar to the first two sample periods.

By sample period IV (February 19, 2003) the river stage reached 11.49 masl and all activities returned to values less than or equal to 50 dpm/L (Figure 3-5 C). This trend of decreasing ^{222}Rn activities with increasing stage continued to sampling period five (February 27, 2003) where, at a stage of 11.51 masl, all locations, with an exception of Hawg Sink have activities less than 25 dpm/L. At that location, the ^{222}Rn activity was 97.5 dpm/L but this value also represents a decrease in activity of 33 % from its peak activity of 295 dpm/L on January 30, 2003 (Figure 3-5 C). By March 5, 2003, sample period six, the river water had risen over the lower of two staff gages and overflowed its

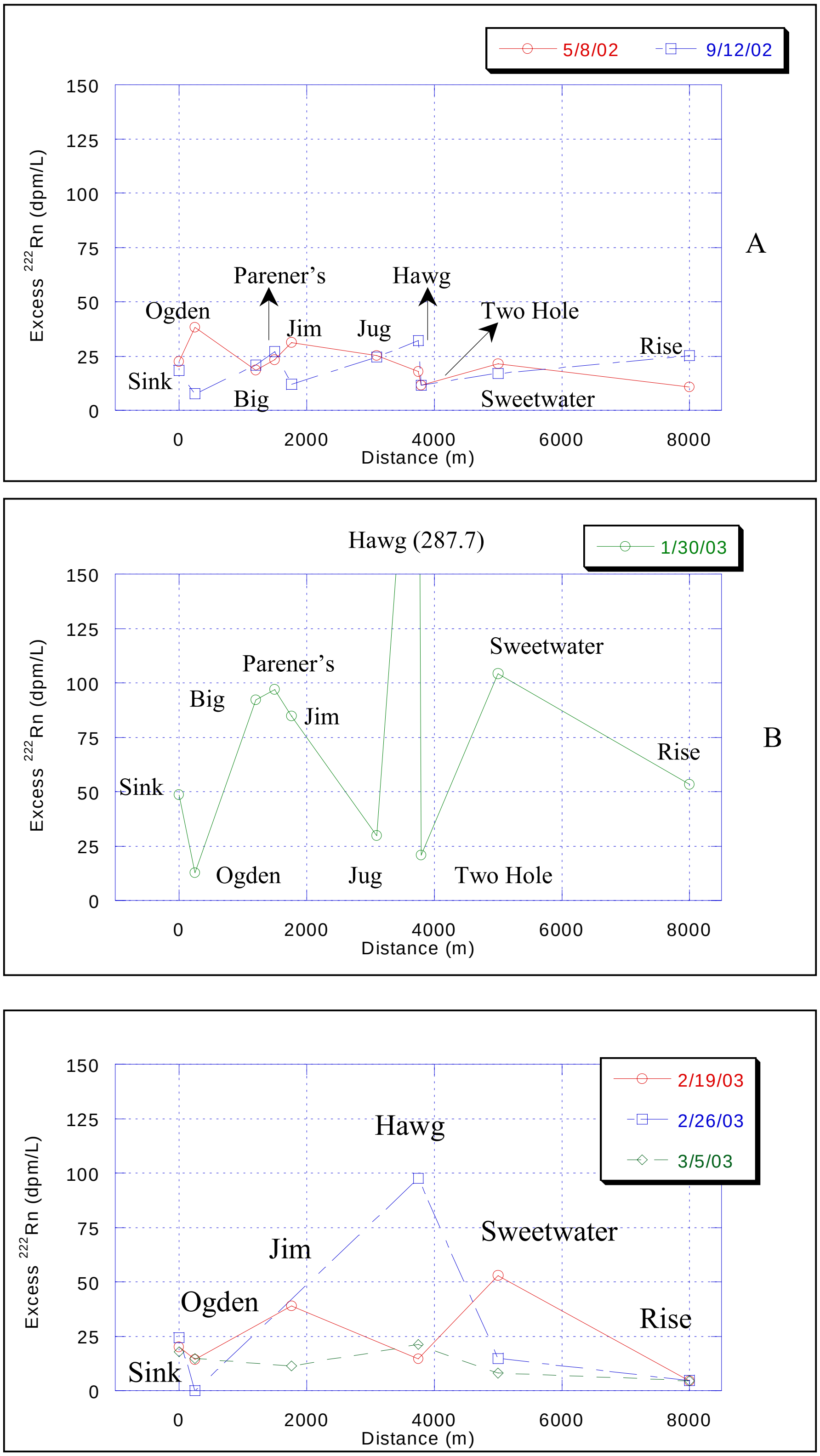


Figure 3-5. ^{222}Rn activities of samples from karst windows, the River Sink, and the River Rise versus distance along the flow path for sample dates of A. 5/8/02 and 9/12/02, B. 1/30/03, and C. 2/19/03, 2/26/03, and 3/5/03.

banks. At this time, most sample locations have activities less than or equal to 25 dpm/L (Figure 3-5 C). The relationship between the average, standard deviation, and coefficient of variation for samples collected during sample periods 1-6 are shown in Table 3-1. The averages shown on Table 3-1 do not include Hawg Sink or Ogden Lake for 2/19/03. At that time Ogden Lake had an activity of 0.09 dpm/L, which is likely in error. The different activities at Hawg Sink suggest that it may not be on a similar flow path to the other karst windows.

Table 3-1. Average, standard deviation, and coefficient of variation for each sample time.

Sample Time	Number of samples	Average (dpm/L)	Standard Devation	Coefficient of Variation
1	9	22.5	8.7	0.4
2	11	18.3	8.4	0.5
3	9	60.4	35.1	0.6
4	5	26.2	19.5	0.7
5	3	14.6	9.8	0.7
6	5	11.3	5.3	0.5

Well Samples

During the course of this study seven wells were drilled in locations throughout the field area (Figure 1-2). Six of the wells were sampled on April 30, 2003 and ^{222}Rn activities are shown on Figure 3-6. Wells 1, 2, and 3 have ^{222}Rn activities ranging from 1172 dpm/L to 732 dpm/L and are either located in the northern portion of the park (Wells 1 & 2) or up gradient (northeast) of the mapped conduit (Well 3). Wells 4, 6, and 7 have activities less than wells 1, 2, and 3 and range from 432 to 152 dpm/L. Wells 4, 6, and 7 are located in the southern portion of the study area. Well 3 is also located in the southern portion of the study area, but it is located up gradient from the other southern wells and the mapped conduit.

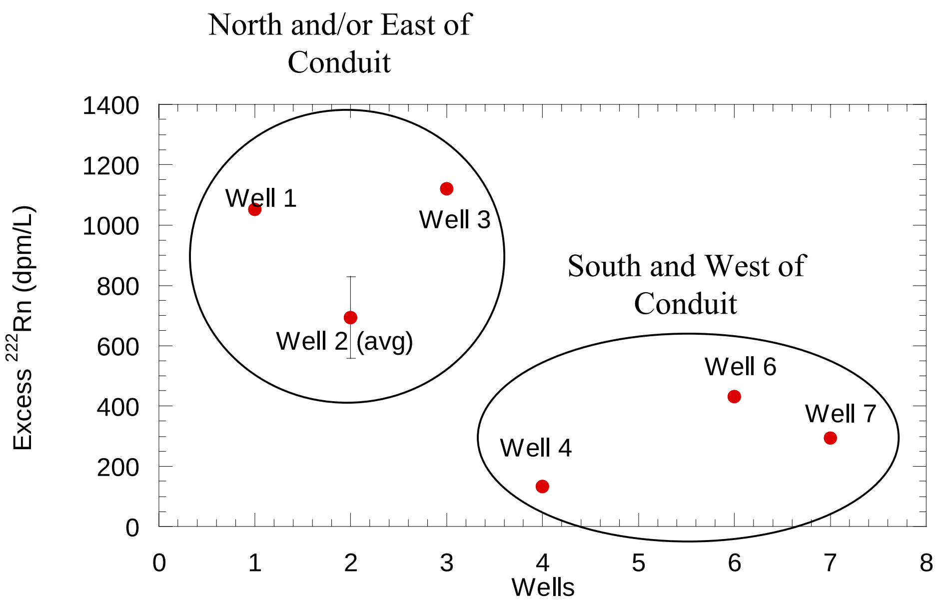


Figure 3-6. ^{222}Rn activities of wells 1, 2, 3, 4, 6, and 7. A duplicate was taken at well 2. The activity plotted is the average of the two samples taken with a range of 213 dpm/L.

Mixing Model

Mixing between the Santa Fe River and the Floridan Aquifer can be estimated by modeling the quantities of each water type in the samples. Assuming there is only two end member mixing with distinct ^{222}Rn signatures, the amount of river water in the samples (%X) can be calculated by a mixing model (Kincaid, 1998), described by

$$\%X = ((R_s - R_{aq})/(R_{riv} - R_{aq})) * 100 \qquad (1)$$

where R_s represents the activity of $^{222}{}_{ex}$Rn measured in each sample, R_{aq} is the activity of $^{222}{}_{ex}$Rn in the groundwater, which is determined by the average well activities of wells 1, 2, and 3, and R_{riv} is the amount of $^{222}{}_{ex}$Rn in the river. The River Sink has large changes in activity due to the variable input of ground and surface water in the upper Santa Fe River. Therefore, the $^{222}{}_{ex}$Rn activities for the River Sink during each sample period were used for R_{riv}. This model has been used to calculate percentages of river water in samples taken from the River Sink, Rise, and the intermediate karst windows. Figure 3-7 shows the fraction of river water for each site with respect to river stage according to values calculated using equation (1). Sample periods I and II have approximately 100% river water in each sample. Sample period III shows more variability; the X% ranges from 60 to 100%. Sample period IV, V, and VI have approximately 100% river water in each sample. Because the River Sink ^{222}Rn activities were used as the R_{riv} variable all %X values for the River Sink are 100% and are not reported in Figure 3-7.

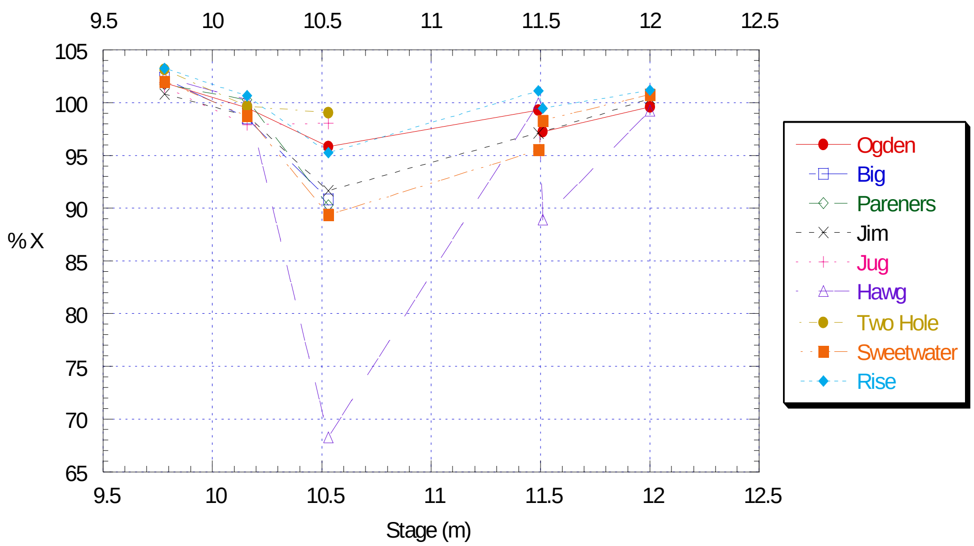


Figure 3-7. %X versus Stage (m) for each site in the study area. Lower the %X represents higher the groundwater content in the samples.

Decay Equation

Sink vs. Rise

The amount of decay that takes place over a period of time can be determined in the basic radioactive decay equation described by

$$N = N_o e^{-\lambda t} \qquad (2)$$

N is the activity of parent atoms that remain after a certain travel time (t), N_o is the original activity of radioactive parent atom, and λ is the decay constant, which is 0.263 day^{-1} for ^{222}Rn. Rearranging the equation allows calculation of travel time from calculated and measured ^{222}Rn activities.

$$t = \frac{\ln(N) - \ln(N_o)}{-\lambda} \qquad (3)$$

Table 3-2 shows how travel time, decay, and the measured activities of the samples taken at the River Sink and Rise interact. Martin (2003) was able to calculate velocities and travel time by correlating temperature peaks as water flowed through the Sink/Rise system. Travel time (t) was based on these travel times and velocities given in Martin (2003) for 2/19/03, 2/23/03, and 3/3/03, which are compared to sample periods 2/19/03, 2/26/03, and 3/5/03 of this study. No water was entering the River Sink during the first two sample periods (5/8/02 and 9/12/02); therefore, it is possible that there was no flow from the Sink to the Rise. Because of this, travel times cannot be calculated for these two dates. Martin (2003) did not have velocities calculated for a date close to sample period III (1/30/03) therefore the travel time here is from Dean (1999). Calculated activity for the River Rise ($^{222}{}_{ex}Rn$ Rise calc) was found by using equation (2), assuming the initial ^{222}Rn activity (N_o) is the activity at the River Sink. Calculated travel time ($T^{222}{}_{ex}Rn$) is the travel time found by using equation (3), where N_o is the ^{222}Rn activity of the River Sink, and N is the ^{222}Rn of the River Rise.

The measured activity of the Rise sample collected January 30, 2003 is higher than the calculated activity. For example, the measured activity of the water at the River Rise was 53.50 dpm/L, but the calculated value was 17.0 dpm/L. The last three sample

Table 3-2. Relationship between measured ^{222}Rn-activity and travel time and calculated ^{222}Rn-activity and travel time using the decay equation.

Date	Stage (m)	$^{222}_{ex}Rn$ Sink[1] (dpm/L)	$^{222}_{ex}Rn$ Rise[2] (dpm/L)	$^{222}_{ex}Rn$ Rise calc[3] (dpm/L)	Tt[4] (days)	T $^{222}_{ex}Rn$[5] (days)
5/8/02	9.78	22.55	10.6	----	----	2.9
9/12/02	10.16	18.32	8.54	----	----	2.93
1/30/03	10.53	48.6	53.5	17.00	4	----
2/19/03	11.49	20.32	4.45	13.70	1.5	5.78
2/26/03	11.51	24.25	4.62	16.34	1.5	6.31
3/5/03	>11.51	17.94	4.54	13.8	1	5.25

[1] & [2] Measured ^{222}Rn activities of the River Sink and Rise, respectively.
[3] N calculated by the equation 2 using [1] as N_o and [4] at travel time.
[4] Travel time from Martin (2003) based on river stage during the sample times.
[5] Travel time calculated by equation 3, using [1] and [2] as N_0 and N, respectively.

periods (February 19, 2003, February 26, 2003, and March 5, 2003) have a different relationship than the first three sample periods between the measured and calculated $^{222}_{ex}Rn$ activities for the River Rise. The measured activities are lower than the calculated values. For example, the measured activity of the Rise on February 19, 2003 was 4.45 dpm/L and the calculated activity was 13.7 dpm/L. Travel times for each sample period were also calculated using the decay equation. However, the calculated travel times do not correspond with the travel times from Dean (1999) and Martin (2003) and are not used in any other calculations or discussion.

Sink vs. Karst Windows

A ^{222}Rn value for each site was calculated by using equation (1) and the value of ^{222}Rn activity at the River Sink. These values are reported in Appendix Table A-1, which gives a comparison of measured and calculated ^{222}Rn activity, ^{226}Ra activity, and travel time between the River Sink and all other sites. Martin (2003) only calculated travel times for the River Sink, Parener's, Two Hole, Sweetwater, and the Rise. Travel times for the other sites (Ogden, Big, Jim, Jug, and Hawg) were calculated from velocities reported by Martin (2003)

Radon-222 activity increased from the River Sink to most karst windows on May 8, 2002, September 12, 2002, and January 30, 2003 and decreased from the River Sink to most karst windows on February 19, 2003, February 26, 2003, and March 5, 2003. Locations where this trend is not followed include Ogden Pond, Parener's Sink and Hawg Sink. Activity decreased between the River Sink and Ogden Pond for all sample periods. Parener's Sink shows a increase for all period. Hawg Sink has higher ^{222}Rn activity for all sample times, except February 19, 2003 (Figure 3-8).

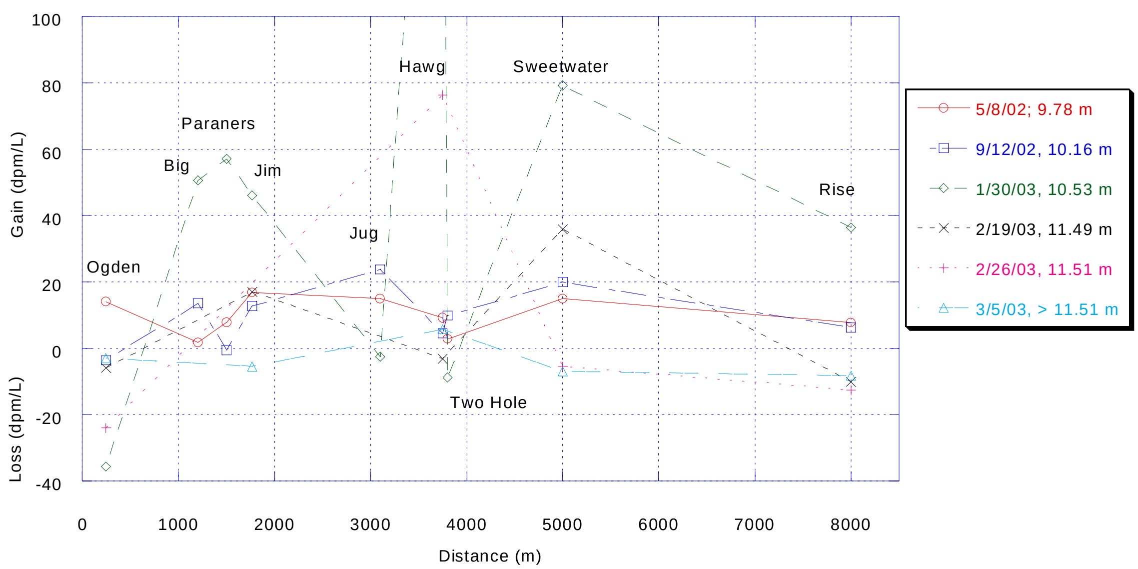


Figure 3-8. The gain or loss in activity downstream from the River Sink. If there is a gain in activity then the measured activity at the site is higher than the measured activity at the Sink. If there is a loss in activity the measured activity at the site is lower than the measured activity at the Sink. Activity at Hawg Sink for January 30,2003 sample time is 295 dpm/L.

Gas Exchange Equation

To determine the amount of ^{222}Rn that is lost to the atmosphere by evasion, Elsinger and Moore (1983) and Ellins et al (1990) used the gas exchange equation.

$$C^d = C^u\, e^{-[D/(zhv)]\, x} \qquad (4)$$

C^u and C^d are the ^{222}Rn activities up and downstream. D is the molecular diffusivity of ^{222}Rn, which is 1.2 x10^{-9} m^2/s at 23°C and h, v, and x are the average stream depth, velocity and distance between sample locations, respectively. The variable z is the thickness of stagnant film layer at the surface of the stream. Elsinger and Moore (1983) found the thickness of the stagnant film of the Pee Dee River in South Carolina to be between 19 and 48 µm. Within this range, the thickness of the stagnant film layer does not significantly effect the calculations (< 1%) therefore the average of this (33.5 µm) is used for the current study. However, if the thickness of the stagnant film decreases to lower than 19 µm, the calculations are effected. Even though this equation is not for karst environments, it was used to establish a first order estimate of the amount of evasion occurring in the Sink/Rise system. This equation assumes that both stream and the air above it constitute two well - mixed reservoirs with uniform vertical activities separated by a stagnant film of water (Ellins, 1990). The amount of exchange is mainly governed by flow - generated turbulence (Ellins, 1990); however, the thicker the film the slower the rate of transfer.

Color Absorbance vs. Activity

Figure 3-9 and 3-10 suggest that the initial hypothesis of absorbance may not be correct. Figure 3-9 shows activity vs. absorbance values for the River Sink in samples collected on 1/30/03, 2/19/03, and 3/5/03. Contrary to expectations, the sample with the lowest absorbance has the highest activity. In Figure 3-10, the sample with the highest activity has the lowest absorbance; however, the sample with the second highest activity also has the highest absorbance. The relationship between absorbance and stage can be seen in Figures 3-11A, B, and C. Figure 3-11 A. gives averaged absorbance values for each site versus stage and Figures 3-11 B and 3-11 C. plot Ogden and Hawg sinks versus stage. R^2 values for the regression curves on Figure 3-11 A, B, and C are 0.888, 0.854, and 0.9589, respectively. All graphs show an increase in absorbance with the increase of stage.

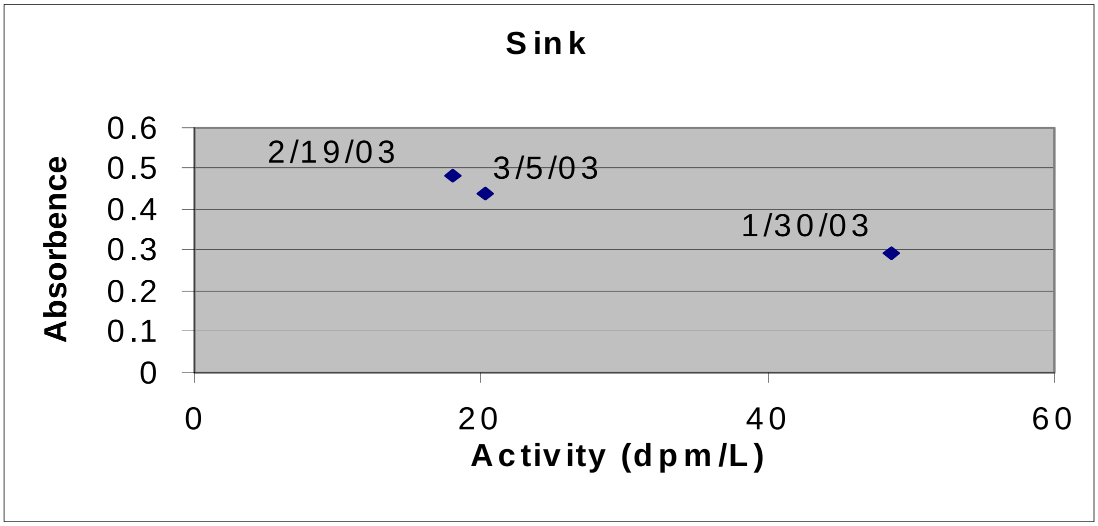


Figure 3-9. ^{222}Rn activities of the River Sink at various sample periods vs. Absorbance. The sample with the highest activity has the lowest absorbance.

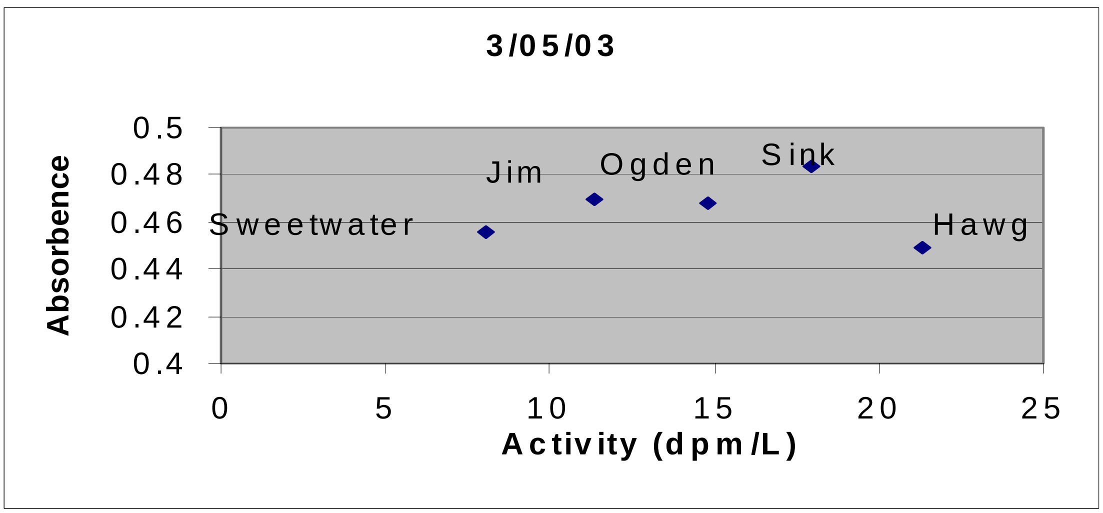
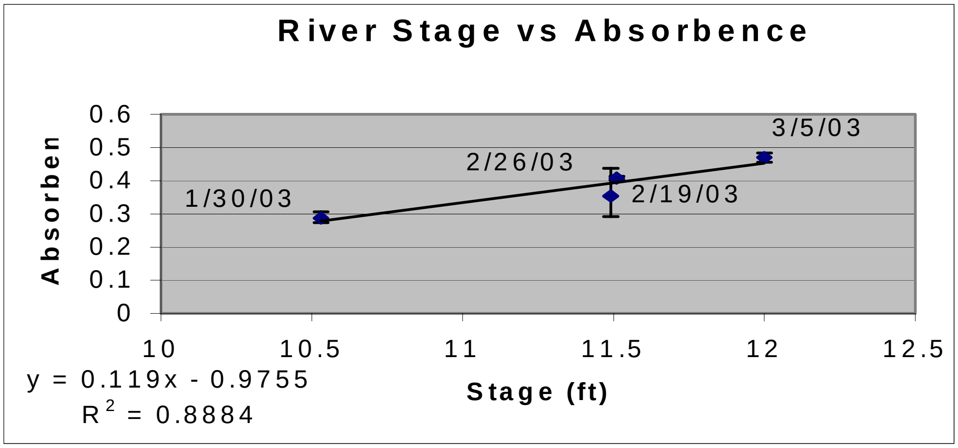
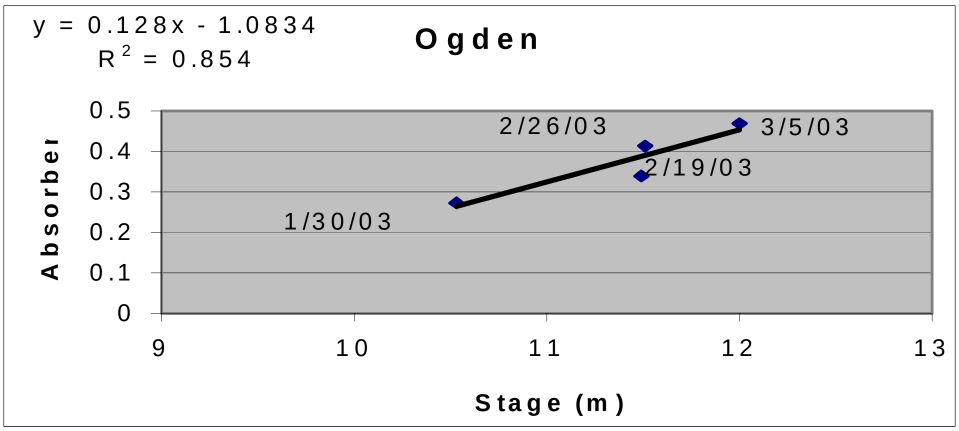


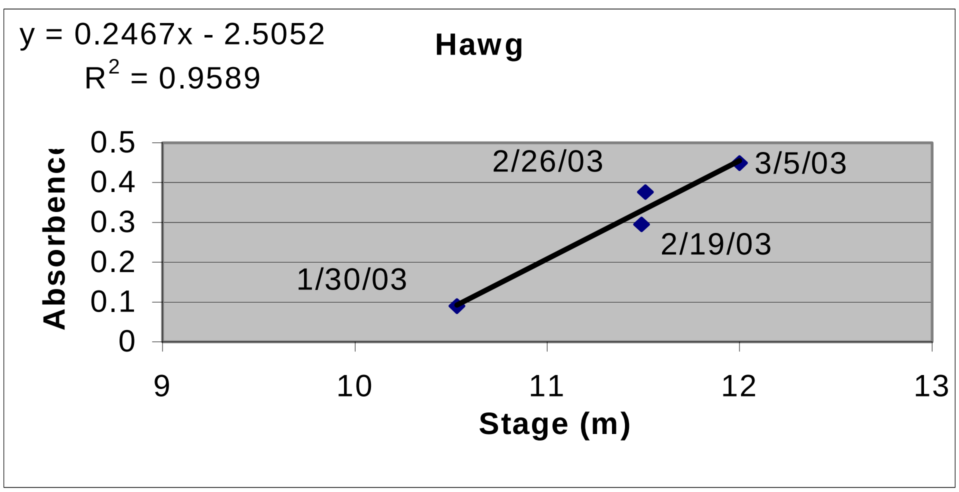
Figure 3-10. ^{222}Rn activities of samples taken at Sweetwater Lake, Jim Sink, Ogden Pond, the River Sink, and Hawg Sink on 3/5/03.



A



B



C

Figure 3-11. Absorbance values taken during the study. A. Average absorbance for all the samples collected. B. Absorbance values for Ogden Pond. C. Absorbance values for Hawg Sink. Each graph covers samples collected on 1/30/03, 2/19/03, 2/26/03, and 3/5/03.

CHAPTER 4
DISCUSSION

Precipitation and River Stage

River stage varies little during the summer months due to low amounts of rainfall and high evapotranspiration rates (~ 14 cm/month) (e.g. Gordon, 1998). However, low evapotranspiration rates (~ 5 cm/month) during the fall and winter months cause higher stage fluctuations than the summer, particularly during associated times of increased precipitation and passage of cold fronts (e.g. Gordon, 1998). During the winter months of this study, river stage increased rapidly with rainfall: between March 3-7, 2003, 2.27 cm of rainfall caused an increase of stage by 1.24 meters (Figure 3-1and 3-2). In all of June 2002, 11.07 cm of rain fell; however, evapotranspiration caused river stage to decrease by 0.03 m during this time.

Depth Profiles

Assuming that surface water loses ^{222}Rn to the atmosphere and sources of ^{222}Rn are from the Hawthorn group and solid material in the Floridan Aquifer, there should be an increase of ^{222}Rn with depth in the sinkholes. However, depth profiles in this study indicate that the water has heterogeneous ^{222}Rn activities with depth.

All profiles taken from the River Rise and Vinzants Landing reflect heterogeneous activities with depth that may reflect mixing between river water and groundwater (Figures 3-3 and 3-4). The main difference between the profiles shown in Figures 3-3 and 3-4 is that Vinzants Landing has its highest activities at the surface. The lithology of the sinkholes should not have an impact over the activity; however, this is unknown. It is possible that the high activities seen at both sites are due to higher amounts of sediment mixing with the waters. Chung (1973) and Berelson et al (1982) indicate that the increase in ^{222}Rn activity with depth (which should be seen in depth profiles) is due to fluxes of sediment caused by turbidity currents within the water column. ^{226}Ra is bonded with the sediment and the decay to ^{222}Rn causes the increase in activity. Both of these studies are conducted in coastal environments in the Santa Barbara and San Nicholas basins, California. Even though the environments differ from the current study, they provide an analog for what could occur at Vinzants Landing and the River Rise.

Excess ^{222}Rn

Three capturing processes control the ^{222}Rn activity in the karst windows of the Santa Fe River: mixing of low activity surface water and ^{222}Rn rich ground water, atmospheric evasion, and radioactive decay. All three processes depend on the flow through the Sink/Rise System. During the first two sample periods, all water in the Santa Fe River was captured by the sinkhole at Vinzants Landing. The river stages for these two dates are 9.78 masl and 10.16 masl, respectively. Martin and Screaton (2002) suggest that during low flow conditions, the conduit will have a lower head than the matrix and will act as a drain for the surrounding matrix porosity (Figure 4-1 A). With no water flowing into the River Sink, groundwater should be the main influence over the ^{222}Rn activities measured from the samples taken at these times and even during 5/8/02 and 9/12/02 water seemed to be resurging at the River Rise (i.e., the River Rise was not dry). Therefore the conduit should have water with high ^{222}Rn activity that may approach values found at the wells (~200 to ~1200 dpm/L).

Flow rates are slow at low stage conditions (~10.00 masl), with travel times from the River Sink to the Rise of approximately 8 days or longer (Dean, 1999; Martin &

Dean, 1999). However, if there is no flow entering the River Sink, then travel times are indeterminable. Slow to no flow in the Sink/Rise system, combined with ^{222}Rn's short half-life (3.84 days), indicates that radioactive decay will reduce the activities. This also allows longer time for evasion of ^{222}Rn to the atmosphere. Figure 4-2 indicates that more evasion does occur during slow flow, but not enough to account for the low activity. Rainfall prior to sample period I and II is minimal therefore there is no dilution caused by surface water recharge. Therefore, it is possible that the diffuse flow from the matrix to the conduit is slow enough that significant decay occurs. This along with other factors such as radioactive decay within the conduit and evasion probably account for the low activities during these sample periods.

Prior to sample period III, 18.8 cm of rain fell and caused the river stage to rise to 10.53 masl, which is considered average river stage based on the hydrograph of river stage for the study period (Figure 3-2). Some ^{222}Rn activities are higher than seen during the first two sample periods. Travel time from the Sink to the Rise is approximately four days on the basis of the stage vs. travel time relationship in Dean (1999). More rapid travel time may prevent most evasion and decay allowing ^{222}Rn activities to stay elevated. For example, calculated ^{222}Rn activity (N from equation 2) for Ogden Pond (Appendix Table A-1) during sample period III is 48.3 dpm/L, but activity from the River Sink (N_o) is 48.6 dpm/L. Also, results from the gas exchange equation (Appendix Table A-3) show that at Ogden Pond only 0.17 dpm/L was lost to evasion. Both of these results indicate that the quicker travel time creates less loss of activity due to radioactive decay and evasion. Another possible explanation for the elevated ^{222}Rn activities is that an increase in diffuse flow from the rain has created a more rapid influx of ^{222}Rn rich water

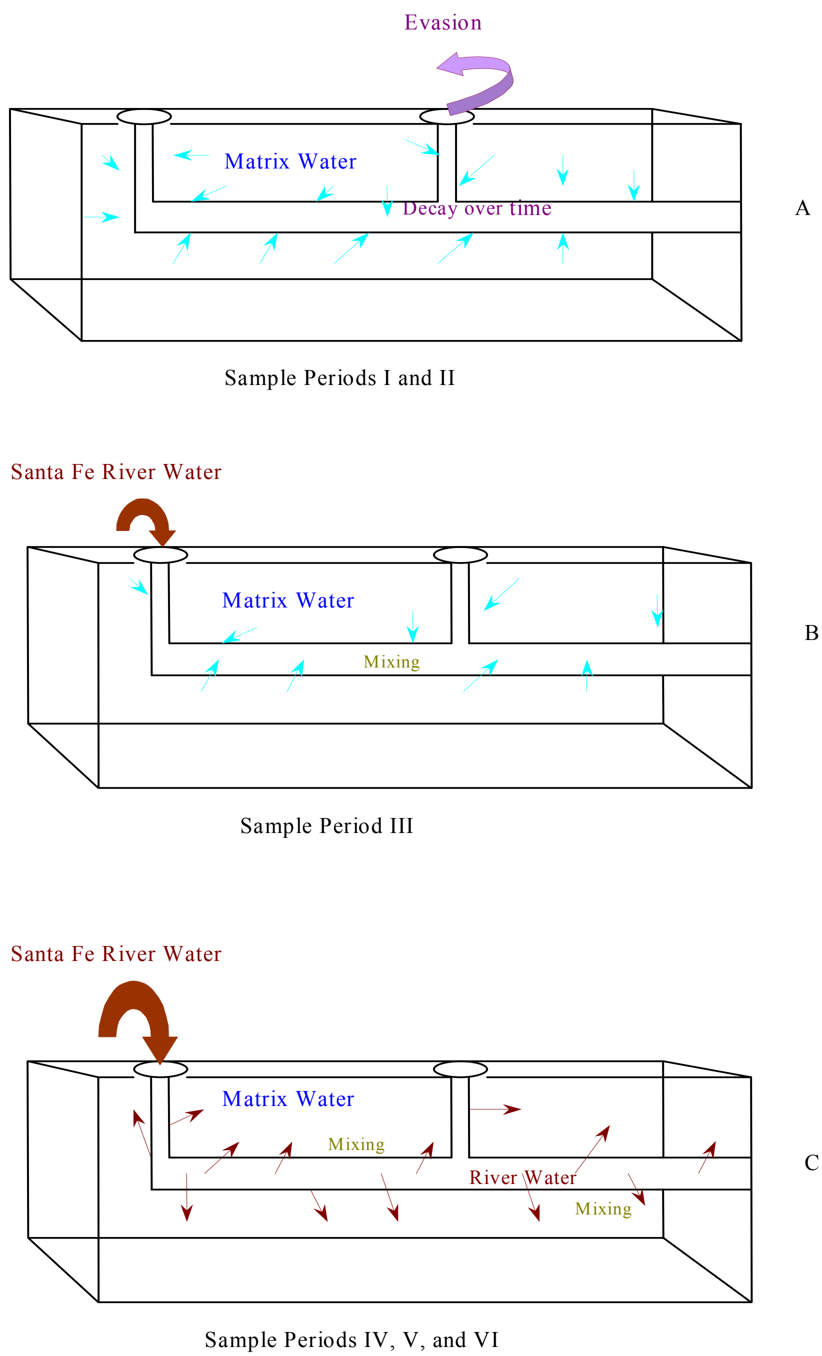


Figure 4-1. A conceptual model of interactions between the Floridan Aquifer and water in conduits during the sample periods. A. No water is entering the River Sink; therefore, the matrix water enters the conduits. Since there is little flow through the Sink/Rise system at this time, the water in the conduits decays. B. River water is now flowing to the River Sink and water from the matrix is entering the conduit and mixing with the river water. There is flow in the system and the decay is minimal. C. The river is flooding and the abundant amount of river water in the conduit is now moving to the matrix.

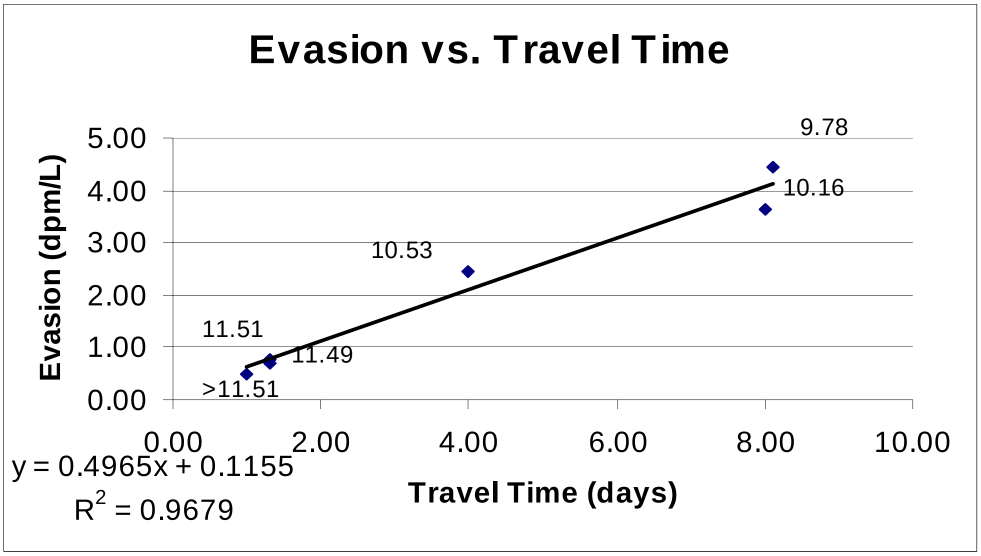


Figure 4-2. Evasion at the River Rise increases as travel time increases. The numbers by the data points indicate river stage at the various sample times.

(ground water) to flow into the conduit and mix with the incoming river water (Figure 4-1 b). A similar flow of groundwater to conduit was observed using Cl^- concentrations in the water. At stages of 10.45 to 10.70 masl, Dean (1999) saw an increase in Cl^- by 24.7% to 43.2 % from the River Sink to Sweetwater Lake, which he interpreted to indicate that ground water flowed to the conduits. Compared to the first two sample periods, the current study reports an increase in ^{222}Rn during this stage of greater than or equal to 80, this is probably due to the activity being lower than expected during the first two periods.

An increase in diffuse recharge should cause an increase in flow from the matrix to the conduit; therefore, most sites should show a higher activity than the first two sample periods. However, Ogden Pond, Jug Lake, and Two Hole Sink have activities similar to the first two sample periods. It is unclear as to why Ogden Pond, Jug Lake, and Two Hole Sink differ from the other samples. Of all the karst windows, Hawg Sink has the highest ^{222}Rn activity at 295.0 dpm/L. A study conducted by Sprouse (2004, in process) reports calcium concentrations of approximately 60 mg/L and an alkalinity of ~140 mg/L for

Hawg Sink in January 2003. Compared to the chemistry of the other sinks, these concentrations are high and are possible indicators of ground water input. Along with the high ^{222}Rn activity measured at Hawg Sink, this may indicate that it is not on the same flow path as the other sinks and could represent an unmapped groundwater source.

During sample periods IV, V, and VI, the river stage was 11.49, 11.51, and >11.51 masl, respectively. During sample period VI, elevation of the Santa Fe River was greater than the staff gage located at the River Sink preventing stage measurements and an exact stage value. At this time, it was observed that the river overflowed the banks on the southwestern portion of the Sink and began to flow over land. The travel times from the Sink to the Rise are 1.3 days for 2/19/03 and 2/26/03 and 1 day for 3/5/03 (Martin, 2003). These rapid travel times prevent a large loss of activity due to radioactive decay and evasion. For example, the calculated activity for the River Rise is ~ 4 dpm/L less than the River Sink (Table 3-2) and the gas exchange equation indicates that only 0.5 dpm/L was lost to evasion.

A possible cause for the observed low activities is dilution by rainwater. Two days prior to sampling on February 19th, 7.57 cm of rain fell, 1.06 cm of rain fell the week before sampling on February 26th, and 3.4 cm fell the week prior to March 5th. It takes 15 days for secular equilibrium between ^{226}Ra and ^{222}Rn to be reached. If the surrounding sediments have been previously flushed with water, then a pulse of water within 15 days of the first pulse, that flushed the system, will have less ^{222}Rn activity. However, depending on the timing of the water pulses, it is still possible that rainwater would gain ^{222}Rn activity as it moves through the sediment column and a dilution effect from the rainwater and groundwater mixing in the matrix would not be seen. It is most likely that the low activities seen at the various sinks during the sample periods are due to dilute ^{222}Rn-activity water entering the conduit at the River Sink. Based on Cl^- concentrations, Dean (1999) reported that at approximately 11.9 masl most of the water at the River Rise originated from the River Sink, suggesting that there is little loss of water from matrix porosity to the conduit during high flow. Martin (2003) supported this conclusion and suggested that heads are higher in the conduit then in the matrix when water is leaving the conduit and flowing to the matrix. Therefore, the river water in the conduit is flowing out into the matrix (Martin and Screaton, 2002) (Figure 4-1 c). Color absorbance values also indicate that the water with in the karst windows is consistent with an origination at the River Sink. At most of the karst windows, there is an increase in absorbance with an increase in stage (Figures 3-11, 12,and 13), which suggests that higher flow rates flush the ground water from the conduit.

Radioactive Decay Along the Flow Path

At times of low flow, groundwater input and radioactive decay should be the main controls over the ^{222}Rn activities of the karst windows. The low ^{222}Rn activities in samples collected at the River Rise on May 8, 2002 and September 12, 2002 (Figure 3-4 A) indicate that radioactive decay and evasion control the water's activity. Samples collected January 30, 2003 have higher activities and a quick travel; therefore the effects of decay and evasion may not be as strong.

Radon-222 activities calculated from equation (2) are not corrected for atmospheric evasion. However, results of equation (4) indicate that approximately 4.5 dpm/L and 3.6 dpm/L are lost by evasion for May 8th and September 12th, respectively and only 2.5 dpm/L is lost for January 30th (Appendix Table A-3). For each of these dates, the calculated ^{222}Rn activities for the River Rise from equation (2) are approximately twice the measured activities, which indicate that the measured activities are higher than if decay was the only influence over the water ^{222}Rn activity (Table 3-2). Therefore, there is some source of ^{222}Rn to the water (i.e., ground water).

Samples taken from the River Rise on February 19, 2003, February 27, 2003, and March 5, 2003 all have measured ^{222}Rn activities that are lower than calculated activities, (Table 3-2, and Figure 3-8). Travel times during these sample periods are shorter (1-1.5 days) than the half-life of ^{222}Rn (3.84 days) suggesting that a lesser amount of decay will occur. The calculated activities for the River Rise are not much lower than the activities at the River Sink, indicating that not much decay has occurred. For example, the calculated activities at the River Rise for 2/19/03, 2/26/03, and 3/5/03 are all approximately 5 dpm/L less than the activities at the River Sink. The amount of evasion for 2/19/03, 2/26/03, and 3/5/03 was calculated to be 0.75, 0.71, and 0.48 dpm/L, respectively and the amounts of evasion during 5/8/02, 9/12/02, and 1/30/03 are 4.45, 3.62, and 2.45 dpm/L, respectively. According to the Gas Exchange equation, this indicates the quicker travel times also prevent most evasion. Figure 4-2 indicates that the amount of evasion decreases with increasing travel time. The low ^{222}Rn-activity river water is not mixing with the high ^{222}Rn-activity groundwater within the conduit but moving out into the matrix. Other processes thus appear to control the loss of ^{222}Rn from the conduit.

If the loss of radon from the River Sink to the River Rise is not due to evasion what is causing this? It is possible that the water in the conduit takes a longer time to travel through the system than the temperature tracking indicates. Alternatively, it is possible that the loss in activity is from mixing with a low ^{222}Rn activity water source. Old

Bellamy Cave Exploration Team have mapped a main conduit which enters the system from the east (Old Bellamy Cave Exploration Team, unpublished report); however, there are no known surface water sources for the eastern system, suggests that it does not supply dilute water. With the large amount of precipitation (> 20 cm) that occurred during the later sample periods it is possible that the loss of activity is caused by a influx of low activity surface water that travels to the conduit.

With a few exceptions (Ogden Pond, Parener's Sink, and Hawg Sink) the other sample sites used in this study agree with the ^{222}Rn activities at the Rise. Ogden Sink has calculated activities higher than the measured activities during all sample periods but May 8, 2002. This could be caused either by less mixing with radon-rich ground water, more degassing, or a combination of both. Parener's Sink shows a decrease in activity on 9/12/02; however, it is so slight (-0.5 dpm/L) that it is smaller than analytical error of the measurement. Hawg Sink shows an increase in activity from the River Sink during every sample period but February 19, 2003 indicating a different source of groundwater not available to the other karst windows.

Distribution of ^{222}Rn in the Groundwater

Regional groundwater flow is from the northeast to the southwest (Miller, 1997); therefore the wells on the eastern side of the conduit should sample groundwater that is not influenced by water from the conduits. Martin (2003) indicates that local water flow is towards the conduit during base flow conditions. Samples from the wells were collected at a stage of 11.05 masl. Water collected from wells 1, 2, and 3 have a higher activity than wells 4, 6, and 7. Well 1 and 3 are located in the eastern portion of the study area and the measured activity of 1173 and 1134 dpm/L, respectively, suggests that they are influenced by the groundwater. Even though Well 2 is on the western side of the conduit, the high activity (733 dpm/L), which is measured, indicates that it is also influence by the matrix water. Wells 1 and 2 are located in the northern portion of the park, in which they are in closer proximity to the Hawthorn Group, which is a source of ^{222}Rn. Wells 4, 6, and 7 are in the southwestern portion of the park, just west of the River Rise. The low activities measured at these wells (152, 432, and 294 dpm/L, respectively) indicate that may be influenced by the mixing between the river and ground water within the matrix.

It is uncertain as to whether the Hawthorn provides more ^{222}Rn activity to the area then the limestone within the Floridan Aquifer. Crandall (1996) found that surficial aquifer water influenced by the Hawthorn Group had ^{222}Rn activities of $\geq$ 1200 dpm/L. Smoak et al. (2000) found ^{226}Ra activities for the Floridan to be approximately 6 dpm/L. Wells 1, 2, and 3 have similar ^{226}Ra activities, which indicates that the ^{222}Rn activities of the water measured in Smoack et al (2000) might also be relatively high. Well 1, 2, and 3 activities are also similar to those found in Crandall (1996). Therefore, at this point the ^{222}Rn activities provided by the Hawthorn Group and the ^{222}Rn activities provided by the Floridan Aquifer limestone are indistinguishable.

Well activities were used as an end member (Raq) in the mixing equation. Kincaid (1998) was able to use this model successfully and found the amount of river water to be between 50 and 90 %. The %X, in this study, range from approximately 60 to > 100. Figure 3-7 suggests that during sample periods I, II, IV, V, and VI primarily river water is in the conduit and that during sample period III water in the karst windows is influenced by ground water. However, previously discussed results suggest that this is not the case. Water chemistry data from Dean (1999) indicated that water within the karst windows was influenced by ground water. The ^{222}Rn activities during sample periods I and II are low, which is the result of radioactive decay and atmospheric evasion, not an influx of river water. Therefore, in a future study of the Sink/Rise system more end members need to be defined and quantified than what was provided by equation (1). Such end members include influx of radon from the surrounding sediment and the influx of radon from the Hawthorn Group. It is also important to use a variety of tracers, each with distinct geochemical behavior, such as $\delta^{18}O$, Cl^-, SO_4^{-2}, as well as ^{222}Rn, to better constrain surface and ground water mixing.

CHAPTER 5
CONCLUSIONS

Karst aquifers are important hydrologic systems and provide potable water to most of our world. Therefore, it is necessary to understand the hydrologic characteristics of these aquifers. One characteristic is the abundance of sinking streams, which allow for mixing between the surface and ground water. These streams have potential to carry pollutants that, once mixed with the potable groundwater, could spread quickly and harm thousands of individuals. Natural tracers that record mixing of surface and ground water would be valuable to developing an understanding of mechanisms and quantities of mixing.

Results from this study suggest that ^{222}Rn activity varies with stage. During low stage, the low ^{222}Rn activities suggest a loss of activity to decay and evasion. In the future, to determine the exact amount of evasion that is occurring the stagnant film thickness needs to be corrected for the Santa Fe Sink/Rise system. During base flow, the high ^{222}Rn activities suggest mixing between the river and ground waters within the conduit. During high stage, low activities indicate there is little to no mixing between the river and ground waters; river water is flowing from the conduit to the matrix. The results also indicate that Hawg Sink may not be on the main flow path.

Furthermore, results indicate that a two end-member-mixing model is not adequate to quantify the amounts of water involved in the mixing. In the future, when modeling the quantities of water involved in mixing, other end members, such as, decay, evasion, and sediment input need to be defined. The effects of lithology on the ^{222}Rn activities cannot be determined at this time. This is something that should be resolved in the future. Other future work involves more depth profiles at other locations, as well as, the River Rise and Vinzants Landing to fully understand vertical mixing with depth. Radon-222 may prove to be a useful tracer of mixing between surface and ground water; however, other tracers, such as Cl^- and $\delta^{18}O$ should be used to support the results from the measured ^{222}Rn activities and further analysis of the complex karst system, the Santa Fe River Sink/Rise system needs to continue.

APPENDIX
MEASURED AND CALCULATED ^{222}RN, TOTAL ^{226}RA, TRAVEL TIME, AND EVASION FOR ALL SITES

Table A-1. Travel time, measured and calculated ^{222}Rn, and total ^{226}Ra

Location	Date	Stage (m)	* Travel Time (days)	^ $^{222}{}_{ex}$Rn calc (dpm/L)	** $^{222}{}_{ex}$Rn (dpm/L)	** ^{226}Ra (dpm/L)
River Sink	5/8/02	9.78	--	--	38.21	-0.25
	9/12/02	10.16	--	--	14.21	0.00
	01/31/03	10.53	--	--	12.64	1.34
	02/19/03	11.49	--	--	14.28	-2.49
	2/26/03	11.51	--	--	0.09	-1.45
	3/5/03	<11.51	--	--	14.8	1.62
Ogden	5/8/02	9.78	>0.24	>24.17	22.55	2.02
	9/12/02	10.16	0.24	17.73	18.32	1.59
	01/31/03	10.53	0.126	48.3	48.6	1.64
	02/19/03	11.49	0.025	20.18	20.32	-2.45
	2/26/03	11.51	0.025	24.08	24.25	1.14
	3/5/03	<11.51	< 0.025	<17.81	17.94	0.26
Big	5/8/02	9.78	> 1.16	>16.62	18.43	1.25
	9/12/02	10.16	1.16	13.5	27.09	1.15
	01/31/03	10.53	0.61	41.41	92.10	1.41
	02/19/03	11.49	0.119	--	--	--
	2/26/03	11.51	0.119	--	--	--
	3/5/03	<11.51	<0.119	--	--	--
Parener’s	5/8/02	9.78	>1.45	>15.42	23.37	1.17
	9/12/02	10.16	1.45	12.53	12.01	1.32
	01/31/03	10.53	0.756	39.8	96.96	-0.44
	02/19/03	11.49	0.15	--	--	--
	2/26/03	11.51	0.15	--	--	--
	3/5/03	<11.51	<0.15	--	--	--
Jim	5/8/02	9.78	> 1.71	>14.38	31.20	-0.39
	9/12/02	10.16	1.71	11.68	24.48	0
	01/31/03	10.53	0.89	38.61	84.79	1.64
	02/19/03	11.49	0.25	21.8	38.93	0.53
	2/26/03	11.51	0.25	--	--	--
	3/5/03	<11.51	<0.25	<16.73	11.36	0.51

Table A-1. Continued

Location	Date	Stage (m)	* Travel Time (days)	^ $^{222}{}_{ex}Rn$ calc (dpm/L)	** $^{222}{}_{ex}Rn$ (dpm/L)	** ^{226}Ra (dpm/L)
Jug	5/8/02	9.78	> 2.99	>10.23	25.18	2.41
	9/12/02	10.16	2.99	8.31	32.05	1.64
	01/31/03	10.53	1.56	32.25	29.71	1.11
	02/19/03	11.49	0.43	--	--	--
	2/26/03	11.51	0.43	--	--	--
	3/5/03	<11.51	<0.43	--	--	--
Hawg	5/8/02	9.78	> 3.62	>8.55	17.82	-0.18
	9/12/02	10.16	3.62	6.94	11.51	1.28
	01/31/03	10.53	1.89	29.48	287.66	376.24
	02/19/03	11.49	0.52	17.67	14.62	-2.58
	2/26/03	11.51	0.52	21.08	97.50	-0.84
	3/5/03	<11.51	<0.52	<15.60	21.29	0.78
Two Hole	5/8/02	9.78	> 3.67	>8.63	11.45	1.16
	9/12/02	10.16	3.67	7.01	16.93	2.51
	01/31/03	10.53	1.91	29.5	20.74	0.95
	02/19/03	11.49	0.53	--	--	--
	2/26/03	11.51	0.53	--	--	--
	3/5/03	<11.51	<0.53	--	--	--
Sweetwater	5/8/02	9.78	> 4.82	>6.33	21.37	0.13
	9/12/02	10.16	4.82	5.14	25.10	0
	01/31/03	10.53	2.52	25.11	104.37	1.37
	02/19/03	11.49	0.7	16.97	52.94	-1.87
	2/26/03	11.51	0.7	20.26	14.83	1.44
	3/5/03	<11.51	<0.70	15	8.08	0.38
River Rise	5/8/02	9.78	> 8 days	>2.76	10.6	-0.11
	9/12/02	10.16	8 days	2.24	8.537	1.24
	01/31/03	10.53	4	17.01	53.5	-0.07
	02/19/03	11.49	1.3	14.46	4.45	-0.08
	2/26/03	11.51	1.3	17.26	4.62	-0.08
	3/5/03	<11.51	1	12.78	4.54	0.36

* Travel time (days) is based on Dean (1999) and Martin (2003)
** Measured activities of ^{222}Rn and ^{226}Ra
^ Activities calculated using the decay equation

Table A-2. Excess ^{222}Rn and total ^{226}Ra for Depth Profiles and Wells

Sites	Sample Dates	$^{222}{}_{ex}Rn$ (dpm/L)	^{226}Ra (dpm/L)
Rise 1m	6/5/02	3.69	1.56
Rise 2m	6/5/02	7.12	2.24
Rise 4m	6/5/02	1.91	1.17
Rise 6m	6/5/02	3.04	2.47
Rise 8m	6/5/02	3.36	0.68
Rise 10m	6/5/02	4.77	1.86
Vinzants 0.3048m	7/2/02	32.86	1.16
Vinzants 1m	7/2/02	25.25	1.10
Vinzants 2m	7/2/02	20.51	0.76
Vinzants 4m	7/2/02	13.78	0.81
Vinzants 6m	7/2/02	30.22	-2.18
Vinzants 8m	7/2/02	24.04	1.52
Rise 0.3048m	7/2/02	13.23	1.30
Rise 1m	7/2/02	7.14	1.24
Rise 2m	7/2/02	3.63	2.43
Rise 4m	7/2/02	3.02	2.05
Rise 6m	7/2/02	2.78	0.75
Rise 10m	7/2/02	2.39	0.88
Vinzants 0.3048m	8/29/02	30.37	0.51
Vinzants 1m	8/29/02	16.94	2.19
Vinzants 2m	8/29/02	19.69	0.80
Vinzants 4m	8/29/02	19.23	0.73
Vinzants 6m	8/29/02	21.19	1.60
Vinzants 8m	8/29/02	20.88	0.79
Vinzants 0.3048m	5/7/03	392.93	0.24
Vinzants 1m (1)	5/7/03	275.38	0.30
Vinzants 1m (2)	5/7/03	247.76	0.65
Vinzants 2m	5/7/03	36.78	0.92
Vinzants 4m	5/7/03	129.25	0.66
Vinzants 6m (1)	5/7/03	110.52	1.15
Vinzants 6m (2)	5/7/03	213.93	0.70
Vinzants 8m	5/7/03	321.54	0.17

Table A-2. Continued

Sites	Sample Dates	$^{222}{}_{ex}Rn$ (dpm/L)	^{226}Ra (dpm/L)
Rise 0.3048m	5/7/03	31.55	0.22
Rise 1m (1)	5/7/03	123.60	0.49
Rise 1m (2)	5/7/03	8.79	0.98
Rise 2m	5/7/03	149.79	0.41
Rise 4m	5/7/03	186.74	0.14
Rise 6m (1)	5/7/03	27.76	0.13
Rise 6m (2)	5/7/03	23.24	0.78
Rise 8m	5/7/03	61.23	1.32
Rise 10m	5/7/03	110.25	-0.34
Well 1	4/30/03	1051.82	-7.08
Well 2 (1)	4/30/03	762	4.76
Well 2 (2)	4/30/03	625.87	1.94
Well 3	4/30/03	1120.69	0.77
Well 4	4/30/03	131.96	-0.36
Well 6	4/30/03	431.61	5.78
Well 7	4/30/03	293.61	1.49

Table A-3. Gas Exchange Equation

Site	Date	C^{d} (dpm/L)	Amount of Evasion (dpm/L)
Ogden Pond	5/8/02	22.40	0.15
	9/12/02	18.19	0.13
	1/30/03	48.43	0.17
	2/19/03	20.31	0.01
	2/26/03	24.23	0.02
	3/5/03	17.93	0.01
Parener's Sink	5/8/02	21.82	0.73
	9/12/02	17.72	0.60
	1/30/03	47.77	0.83
	2/19/03	20.25	0.07
	2/26/03	24.17	0.08
	3/5/03	17.88	0.06
Big Sink	5/8/02	21.64	0.91
	9/12/02	17.58	0.74
	1/30/03	47.56	1.04
	2/19/03	20.23	0.09
	2/26/03	24.15	0.10
	3/5/03	17.86	0.08
Jim Sink	5/8/02	21.48	1.07
	9/12/02	17.45	0.87
	1/30/03	47.38	1.22
	2/19/03	20.18	0.14
	2/26/03	24.08	0.17
	3/5/03	17.81	0.13
Jug Lake	5/8/02	20.71	1.84
	9/12/02	16.82	1.50
	1/30/03	46.48	2.12
	2/19/03	20.07	0.25
	2/26/03	23.95	0.30
	3/5/03	17.72	0.22
Hawg Sink	5/8/02	20.34	2.21
	9/12/02	16.52	1.80
	1/30/03	46.05	2.55
	2/19/03	20.02	0.30
	2/26/03	23.89	0.36
	3/5/03	17.67	0.27

Table A-3. Continued

Site	Date	C^d (dpm/L)	Amount of Evasion (dpm/L)
Two Hole Sink	5/8/02	20.31	2.24
	9/12/02	16.50	1.82
	1/30/03	46.02	2.58
	2/19/03	20.02	0.30
	2/26/03	23.89	0.36
	3/5/03	17.67	0.27
Sweetwater Lake	5/8/02	19.65	2.90
	9/12/02	15.97	2.35
	1/30/03	45.23	3.37
	2/19/03	19.92	0.40
	2/26/03	23.77	0.48
	3/5/03	17.59	0.35
River Rise	5/8/03	18.10	4.45
	9/12/02	14.70	3.62
	1/30/03	20.10	2.45
	2/19/03	19.58	0.74
	2/26/03	23.36	0.89
	3/5/03	17.44	0.50

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BIOGRAPHICAL SKETCH

Lauren A. Smith was born to Roger D. Smith and Martha A. Smith on August 30, 1977, in Ft. Hood, Texas. Shortly after her birth, her family moved to Dublin, Georgia, and has lived there ever since. After graduating from Dublin High School in 1995, Lauren attended Furman University in Greenville, South Carolina, where she graduated, in 2000, with a B. S. in earth and environmental science. Later that year, she moved to Florida to begin graduate school at the University of Florida. She worked as a teaching assistant for undergraduate classes and as a research assistant. She is currently seeking employment in the environmental industry.