

AQUIFER CHARACTERIZATION BY QUANTITATIVE DYE TRACING
AT GINNIE SPRING, NORTHERN FLORIDA

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ABSTRACT

A project was undertaken by Karst Environmental Services, Inc., in support of Ginnie Spring Water Company, to characterize the hydrologic properties of an unconfined, cavernous aquifer, near Ginnie Spring, Florida. Ginnie Spring and eight others occur along the Santa Fe River over 1.1 km reach of the stream. All of the springs discharge from the Ocala Group limestone (Eocene), which forms the top of the Floridan Aquifer in this area. The average discharge of Ginnie Spring is 1.2 m³/sec and the combined discharge for the eight springs is 11.4 m³/sec, which increases the flow of the river by 25 percent. Four dye traces were performed with rhodamine WT. The dye was injected through cavities 0.3 to 1.8 m high, and 27 to 39 m below the water table, in four wells located 400 to 1,200 m southwest, south and southeast of Ginnie Spring. Dye from each well was detected at two or three springs separated by distances as great as 320 m. Minimum ground-water velocities ranged from 7.7 to 32 m/hr. In view of the low water table slope of 0.6 to 0.9 m/km, the dye velocities indicate cavernous flow. Yet, only 368 m of cave passage is accessible from Ginnie Spring. In the upstream direction of the flow emerges from conduits too small for divers. Dye traces even from the closest wells had well-defined multiple peaks which indicate the dye passed through braided passages. The ability of the dye to disperse to more than one spring, even though the injection point was very close to the mouth of the drainage basin, indicates that effective ground-water divides do not exist except very close to the spring. Ground water probably passes through a 3-dimensional, nearly isotropic, sponge-like network of solutional openings larger than 0.2 cm in diameter, but generally smaller than 36 cm in diameter. The ground-water flow behaves in a manner similar to Darcian flow, in that it disperses in the downstream direction, even though it is conveyed in the turbulent flow regime through a cavernous aquifer.

INTRODUCTION

Ginnie Spring

Ginnie Spring is a second-magnitude cave spring on the south bank of the Santa Fe River, Gilchrist County, Florida, approximately 11 km west of the town of High Springs (Figure 1). The average discharge of Ginnie Spring is $1.2 \text{ m}^3/\text{sec}$. The spring pool is 60 m wide and 8 m deep. The water is extremely clear, such that visibility often exceeds 30 m. A cave entrance under a limestone ledge provides access to 368 m of braided underwater passages at depths of 18 to 21 m. The cave generally extends southeast from the spring (Figure 2). Potentiometric maps (Rosenau and Meadows, 1986) show ground-water flow toward Ginnie Spring from the southwest. Ground water may flow from as far away as 10 km. The drainage area of Ginnie Spring is approximately 102 km^2 based on an average rainfall of 1.32 m/yr, an infiltration rate of 28 percent (Wilson, 1988a), and the spring's average discharge. The approximate dimensions of the drainage basin may be roughly 10 km by 10 km. Insufficient well control is available to contour the potentiometric surface of the basin with precision.

Ground Water Development Issues

Ginnie Springs is privately owned and operated as a swimming and scuba diving resort. The resort includes 378 hectares (940 acres) of land and 4 km of Santa Fe River frontage. Ginnie Springs Water Company (GSWC) proposes to build a 1.5 million liter/day water bottling facility on an undeveloped portion of the resort property. The proposed water withdrawal is small compared to irrigation wells that commonly supply as much as 26 million liters/day. However, by contract, the water bottling operation must not interfere with the recreational use of the springs.

GSWC intends to withdraw water from the Floridan Aquifer through wells, which requires a consumptive water use permit from the Suwannee River Water Management District (a Florida state agency). Issuance of the permit depends on demonstrating that the proposed ground-water withdrawal will not adversely affect any existing water supplies. The nearest existing wells are located 0.75 km west of the proposed withdrawal site, where they supply water for domestic use.

In order to market bottled water as "Ginnie Spring" water, GSWC must demonstrate to the Florida Department of Health and Rehabilitative Services that the well water would have resurged at Ginnie Spring. GSWC retained Karst Environmental Services, Inc. (KES) to collect hydrologic data, evaluate the aquifer characteristics, and prepare the necessary permit applications.

KES began a multi-phase project, in 1987, to collect the necessary hydrologic data for ground-water resource development and permitting. The first phase of the project involved measuring the discharge of the springs and the Santa Fe River on a monthly basis for a one-year period. Discharges were measured with a Marsh-McBirney electromagnetic flow gauge.

The second phase of the project involved completion of three high volume production water wells. Well sites were selected based on lineament analysis and ground penetrating radar surveys. The wells were

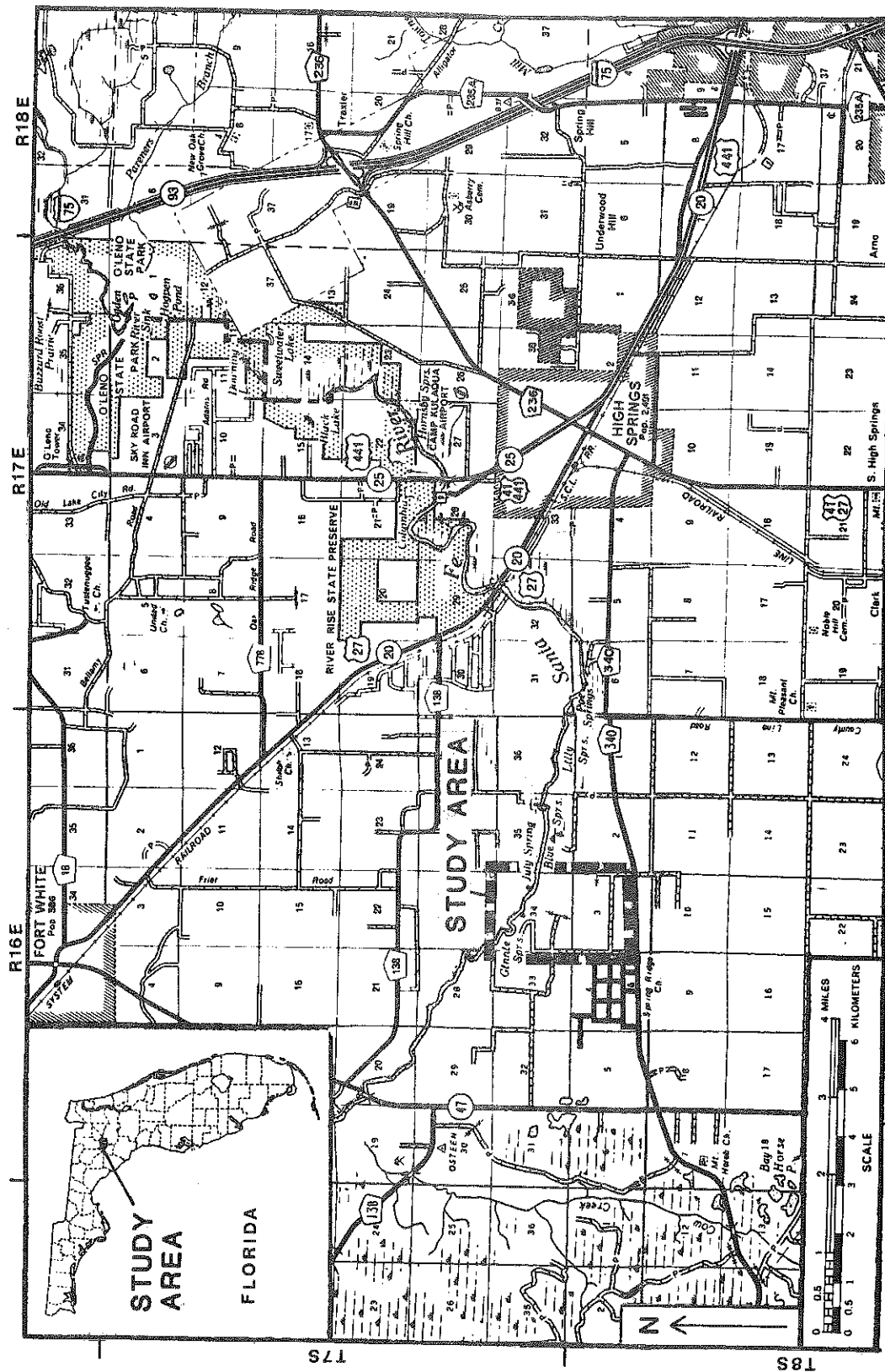


Figure 1. Location of Ginnie Spring, Gilchrist County, northern Florida. Modified from General Highway Maps, Florida Dept. of Transportation (1979).

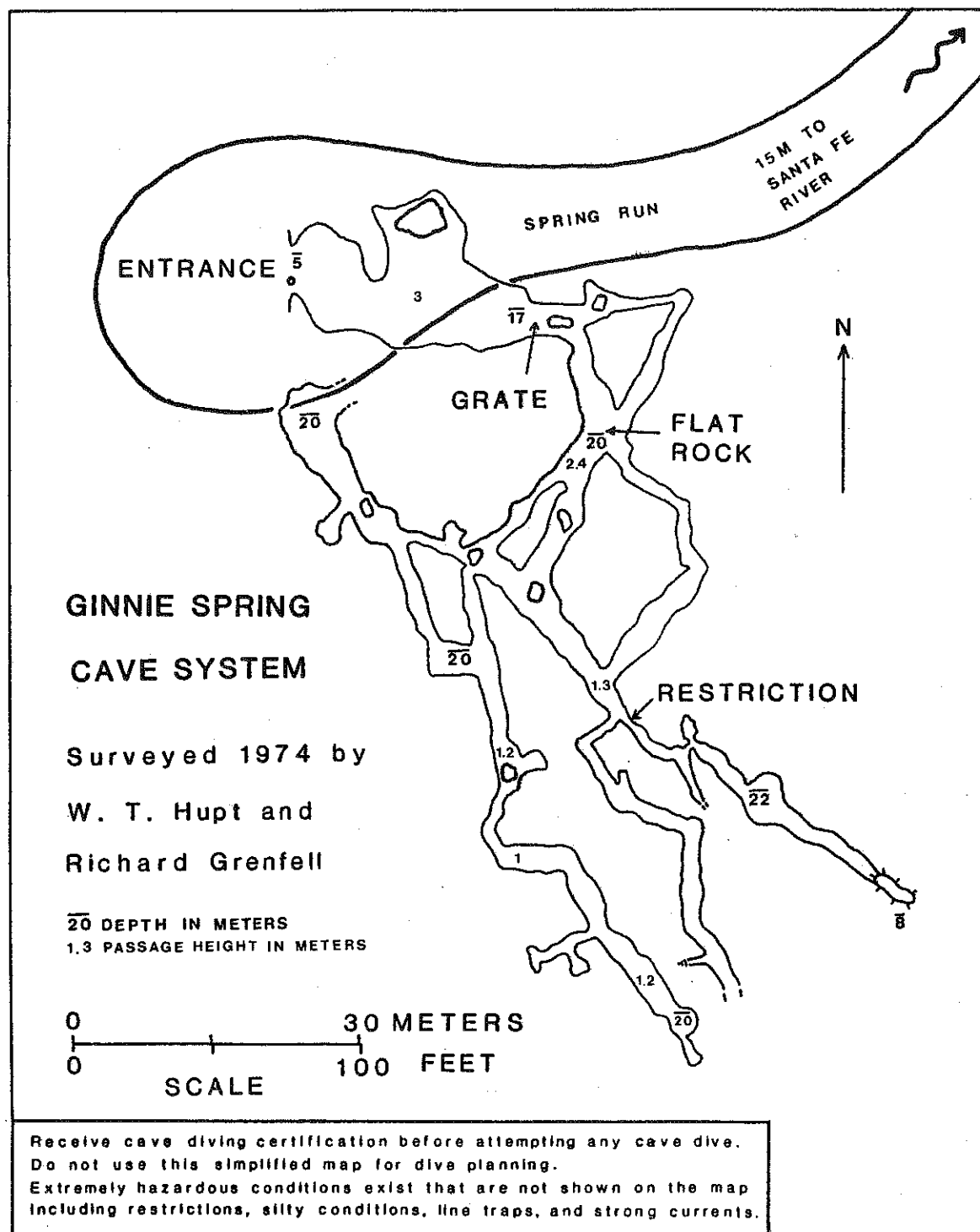


Figure 2. Map of Ginnie Spring Cave System, showing braided passages.

drilled and completed in late 1987. All of the wells intersected cavities, as will be discussed below.

In the third phase, quantified dye traces were performed from each of the three new wells and one previously existing well (the "Shop Well"). The dye traces did not affect the recreational use of the springs. The amount of dye was carefully calculated to produce an invisible peak concentration. The hydraulic performance of the aquifer was evaluated, in part, based on the dye tracing results, as will be discussed below.

Pumping tests are planned in 1988, as the final phase of aquifer characterization. Test results are not available at the time this paper was prepared, but general knowledge of the Floridan Aquifer will be used to put the dye tracing results in perspective.

BACKGROUND

Springs

In addition to Ginnie Spring, eight other springs are located along the Santa Fe River within 0.55 km upstream and downstream from Ginnie Spring (Figure 3). Three of the springs, Devil's Eye, Devil's Ear, and July Spring, are connected by cave passages and serve as distributary outlets for a single ground-water drainage basin that extends north and northeast from the springs. The cave is known traditionally as the Devil's Eye System. More than 11,000 m of underwater cave passages have been surveyed upstream from the spring group (Figure 4). Much of the passage is a complex, interconnected, braided network with depths ranging typically from 21 to 27 m. The deepest known passage extends to 38 m. The combined discharge of the three springs is $8.1 \text{ m}^3/\text{sec}$, making them a newly recognized first-magnitude spring group. In the list of first-magnitude springs in Florida prepared by Rosenau and others (1977), the Devil's Eye Group would rank as the 10th largest. Devil's Ear, the largest single spring vent in the group, discharges an average of $3.5 \text{ m}^3/\text{sec}$ and is a first-magnitude spring by itself. The spring is located in the floor of the Santa Fe River. The difficulty of obtaining direct discharge measurements for the spring explains, in part, why it was not previously recognized as a first-magnitude spring.

The other nearby springs, Deer, Twin, Sawdust, Dogwood, and Little Devil's, are smaller, having average discharges that range from 0.10 to $0.59 \text{ m}^3/\text{sec}$, as shown in Table 1. Dogwood Spring is a pool 12 m wide and 3.6 m deep. At the bottom of the pool, a limestone cave, too small to enter, discharges an average flow of $0.59 \text{ m}^3/\text{sec}$. The cave extends southeast from the pool. A good hydrologic connection exists between Dogwood Spring and many of the wells through which dye traces were performed, as will be discussed later.

Upstream from Devil's Ear Spring, the Santa Fe River conveys an average flow of approximately $34.1 \text{ m}^3/\text{sec}$. The combined discharge of Ginnie Spring and the eight nearby springs averages approximately $11.4 \text{ m}^3/\text{sec}$. The spring flow increases the volume of the Santa Fe River by 25 percent.

Water in the Santa Fe River is usually very low in turbidity, but is stained dark brown (very much like coffee) by tannin and humic acids from decaying vegetation. During floods the river occasionally rises high enough to cover the springs, but the flow at Ginnie Spring has never been

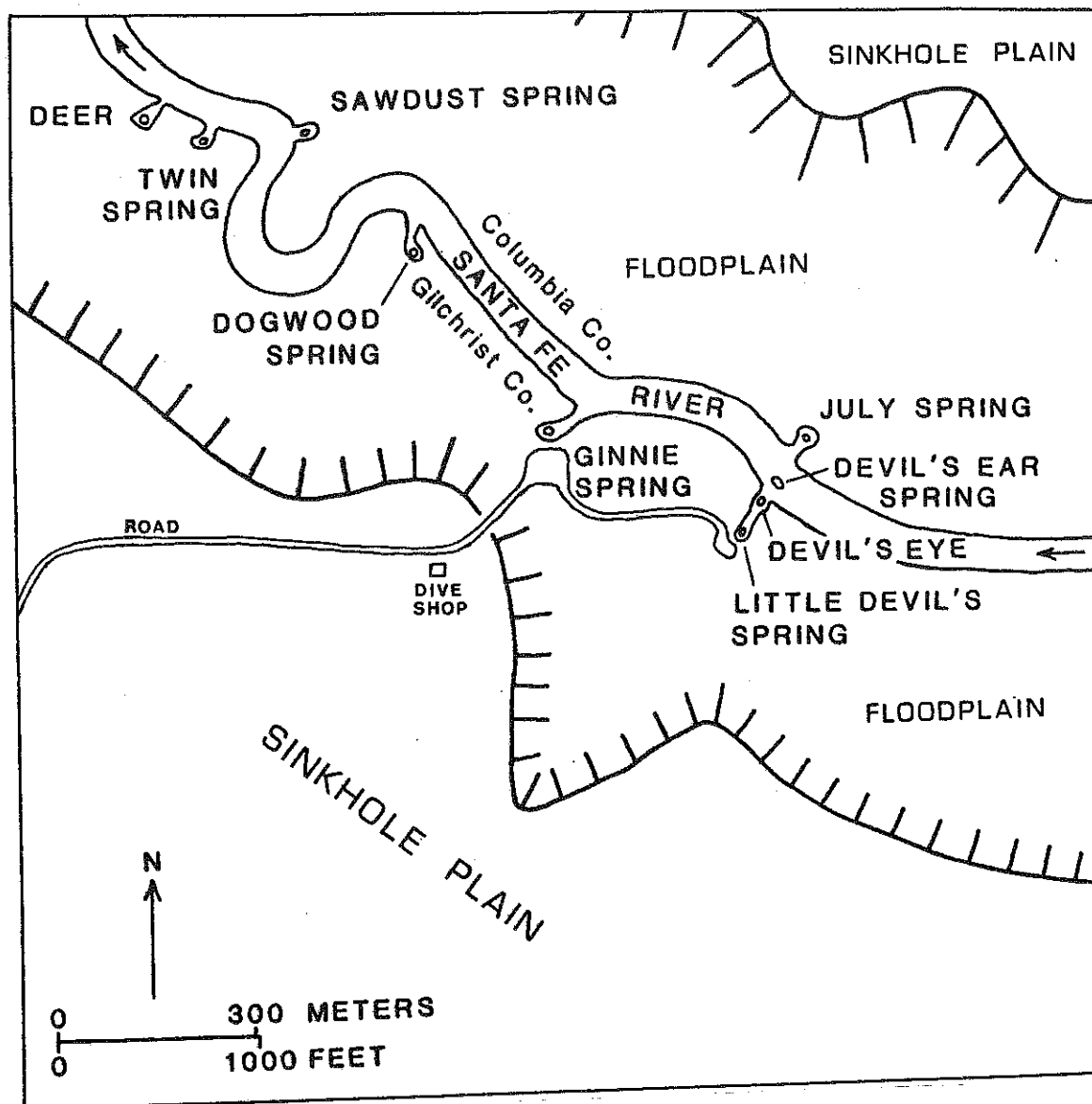


Figure 3. Springs along the Santa Fe River in Section 34, T.7S., R.16.E., Gilchrist and Columbia Counties, Florida.

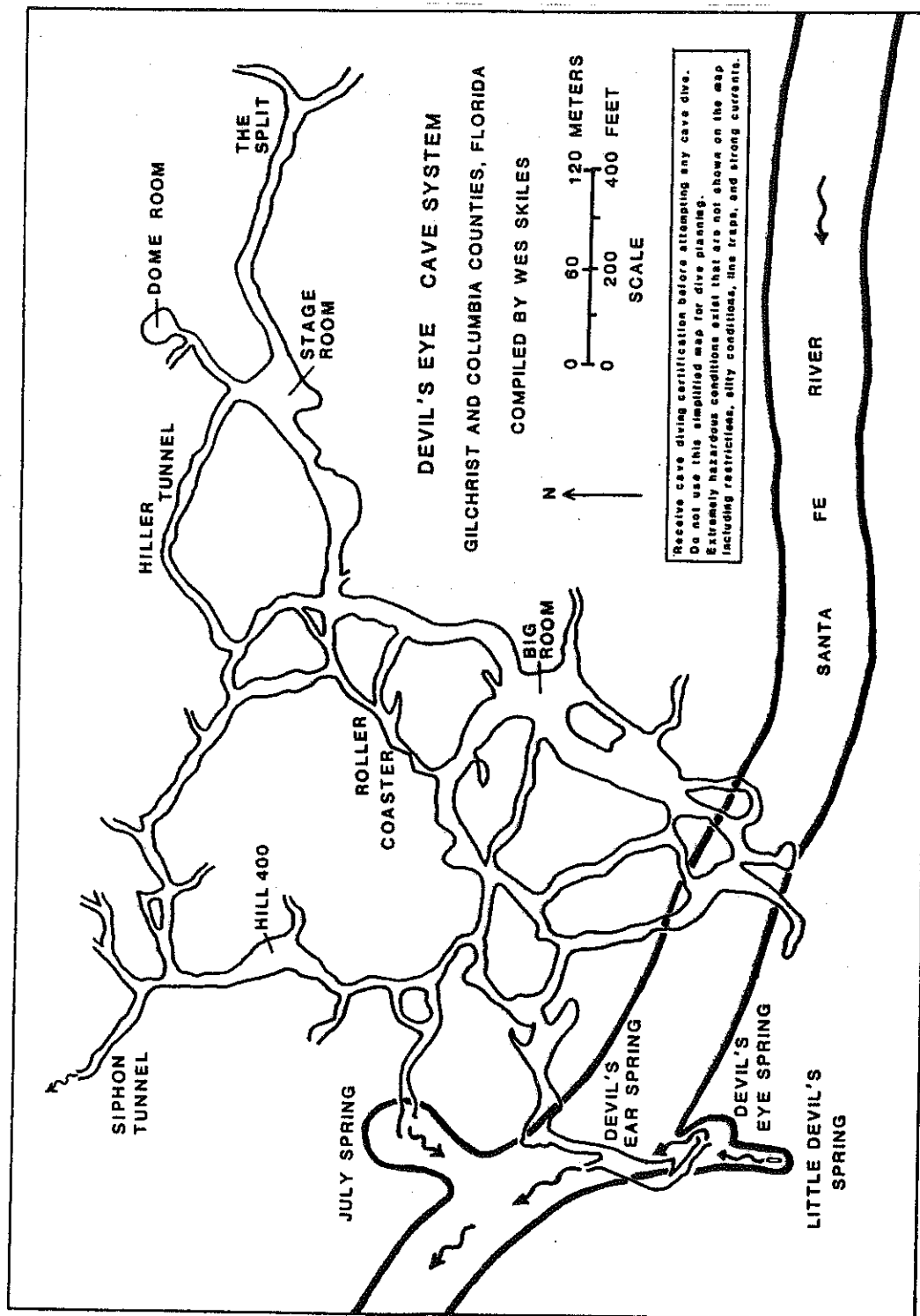


Figure 4. Map of the Devil's Eye Cave System, Gilchrist and Columbia Counties, Florida. More than 11,000 m of passage has been surveyed by line and compass. The entire cave is underwater.

observed to reverse. Under flood conditions the clear spring water is discharged, at a reduced rate, beneath the dark river water. At the Devil's Ear Spring group, flood conditions also reduce the spring discharge, but the spring water becomes moderately stained with tannin, because the cave extends beneath the river and some river water is probably flowing down, into the cave, through small karstic openings.

TABLE 1

AVERAGE DISCHARGE OF GINNIE SPRING AND NEARBY SPRINGS,
GILCHRIST AND COLUMBIA COUNTIES, FLORIDA

<u>Spring</u>	<u>Average Discharge (m³/sec)</u>
Ginnie	1.2
July	2.1
Devil's Ear	3.6
Devil's Eye	2.4
Little Devil's	0.44
Dogwood	0.59
Twin	0.48
Deer	0.10
Sawdust	0.45

Physiography

The normal stage of the Santa Fe River is 6.4 m above national geodetic vertical datum (NGVD). One hundred-year floods extend as high as 11.9 m NGVD. The floodplain of the river is a forested wetland, ranging from 425 to 670 m wide. Above the floodplain, the land rises to elevations of 15 to 23 m NGVD. The land above the floodplain is a very low relief sinkhole plain. White (1970) called it the High Springs Gap in the Western Valley physiographic region, but it is, more simply, a northern extension of the Newberry Plain (Williams and others, 1977). See Figure 5. In the vicinity of Gilchrist County, the Newberry Plain is bounded on the south by the Brooksville Ridge, which is a slightly elevated sandy upland, and on the southwest by Waccassasa Flats, a poorly drained, but slightly lower area of clayey sediment, which fills a graben (Puri and others, 1967). To the north and east, the plain is bounded by the Cody Escarpment, which marks the boundary of the area where the limestone is overlain by clayey sediments of the Hawthorn Group (Miocene).

Stratigraphy

The sinkhole plain is covered by sand and clay that average approximately 6 m thick. The proportion of sand and clay varies widely. The sand is usually assigned a Pleistocene age. A few small sand dunes, stabilized by vegetation, are recognized in the area. The clay was mapped as Alachua Formation (Miocene) by Puri and others (1967). The clay is greenish-gray, waxy and phosphatic. It is thought to be dominantly a terrestrial deposit. The lithostratigraphic viability of the Alachua

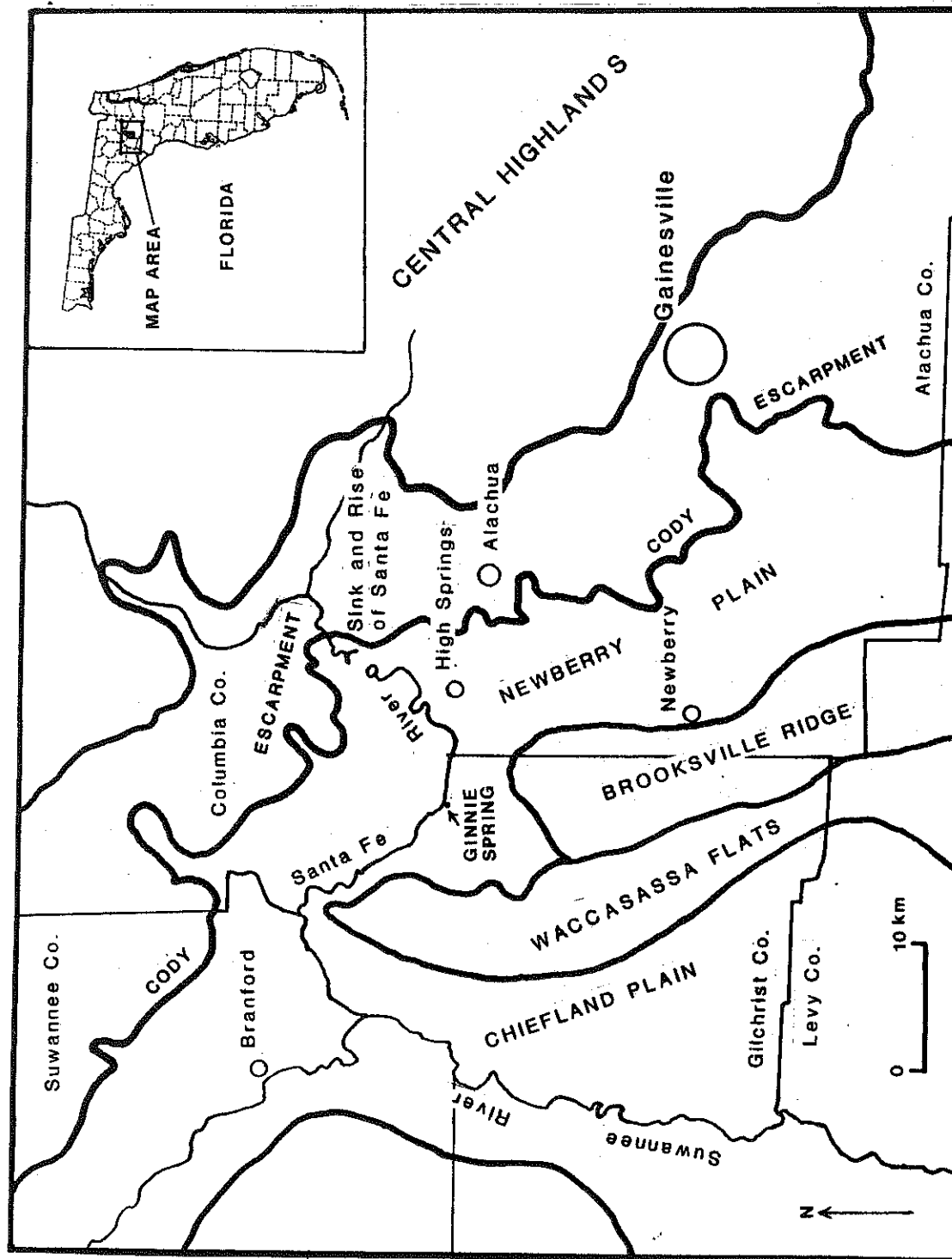


Figure 5. Physiographic regions of north-central Florida, adapted from White (1970) and Williams and others (1977). Ginie Spring is located on the Newberry Sinkhole plain.

Formation is questionable, but it is beyond the scope of this paper to address the problems.

Underlying the unconsolidated material is approximately 25 to 34 m of limestone and dolomite of the Ocala Group (Eocene). Limestone in the Ocala Group is white to cream, chalky to finely crystalline, soft, porous, finely granular, coquinoïd limestone composed primarily of foraminifers and mollusks. Secondary dolomite occurs in discontinuous beds. Underlying the Ocala Group is the Avon Park Formation (Eocene), which ranges from 91 to 106 m thick (Puri and others, 1967). The Avon Park Formation consists of finely crystalline dolomite, calcitic dolomite, and limestone. Most spring vents are developed in the lower part of the Ocala Group. However, nearly all cave passages are developed near the Ocala/Avon Park contact or in the upper part of the Avon Park Formation.

Structure

At Ginnie Spring the Eocene limestone strata dip northeast at approximately 2 m/km. The Santa Fe River generally flows parallel to strike in the study area. Eleven km southwest of Ginnie Spring, Puri and others (1967), mapped a graben 3 to 5 km wide. The graben extends generally south through Gilchrist County. The maximum vertical displacement in the graben is approximately 12 m.

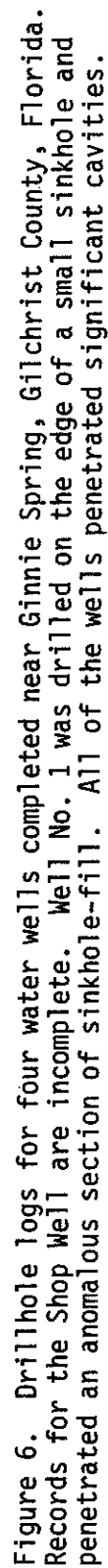
Floridan Aquifer

In the vicinity of Ginnie Spring, the Ocala Group forms the top of the Floridan Aquifer, which comprises at least 425 m of Eocene carbonate strata. The aquifer is well known for both its cavernous porosity and high intergranular porosity. Transmissivities commonly range from 10,000 to more than 100,000 m²/day (Faulkner, 1973; Wolansky and Corral, 1985). Yet, Darcian ground-water flow has been repeatedly shown to exist in the Floridan Aquifer for large-scale pumping tests (Hickey, 1984).

A regional potentiometric map, prepared by Rosenau and Meadows (1986), shows that ground water flows northeast, from Wacasassa Flats, toward the Santa Fe River, at gradients of approximately 2 m/km. Dye traces and water levels in wells show that within 1 km of the Santa Fe River, the water table slopes north and northwest. The water table slope near the river is also much lower; ranging from 0.6 and 0.9 m/km. The Floridan Aquifer is unconfined in the area south of Ginnie Spring, because the top of the limestone is above the water table.

DYE TRACES

Four quantified dye traces were performed using rhodamine WT. The dye was injected through cavities 0.3 to 1.8 m high, and 27 to 39 m below the water table, in four wells located 400 to 1,200 m southwest, south and southeast of Ginnie Spring (Figure 3). Stratigraphic sections for each well are shown in Figure 6. Well No. 1 was drilled on a buried sinkhole and penetrated an anomalous section consisting of black muck (decomposed peat) at depths of 7.6 to 22.8 m. Nonetheless, a 0.9 m high cavity was penetrated at a depth of 27.4 m. All of the wells were cased to the top of the bedrock, and open (uncased) throughout the limestone.



The amount of dye injected in each well ranged from 0.91 to 7.31 l (Table 2). The dye was followed ("chased") with 1,830 to 4,390 liters of water to make the dye move out of the well and into the aquifer. Samples of water were collected at the surface of the spring pools and from the Shop Well. The dye concentrations for the trace from the Shop Well were measured with a Turner Designs Model 10 Fluorometer. The dye concentrations for the traces from the other three wells were measured with a Turner Model 111 Fluorometer. The fluorometers were calibrated according to the procedures described by Wilson and others (1986).

TABLE 2
AMOUNT OF RHODAMINE WT* INJECTED FOR GROUND WATER TRACING

<u>Well</u>	<u>Volume of Rhodamine WT (liters)</u>	<u>Mass of Dye (kg)</u>	<u>Volume of Injection Fluid (l)</u>
Shop	0.91	0.211	1,829
No. 1	1.83	0.424	1,829
No. 2	5.49	1.274	3,657
No. 3	7.31	1.969	4,389

*Dye concentration was 20% by weight and the specific gravity was 1.16.

Maps of the dye traces from each well are shown in Figure 7. The dye travel times and the average dye velocities are summarized in Table 3. Dye from Wells No. 1, 2, and 3, passed through the Shop Well. All four of the wells passed dye to Dogwood Spring; although the connection between the spring and Well No. 3 was faint. The Shop Well and Wells No. 2 and 3 also passed dye to Ginnie Spring. A faint positive was detected at Ginnie Spring for Well No. 1. However, Well No. 1 showed a strong positive at the Shop Well, which itself showed a strong positive at Ginnie Spring. Consequently, it is reasonable to assert that water from Well No. 1 must also emerge at Ginnie Spring. The amount of dye used for the trace from Well No. 1 was simply insufficient to produce a strong positive.

Dye from both the Shop Well and Well No. 1 was detected at Little Devil's Spring. The dye concentrations in Little Devil's Spring, from the Shop Well, were high enough and consistent enough to be a convincing positive trace, but the average velocity of the dye was twice as high as for all other dye traces. Well No. 1 contributed a very faint, erratic positive at Little Devil's Spring. The dye travel time was similar to that from the Shop Well. At present the dye traces to Little Devil's Spring are problematic. The high dye velocity between the two wells and Little Devil's Spring has been observed twice but stands out as an anomaly. The volume of flow is small for such high velocities. Additional work is required to confirm and explain the drainage relationships between the wells and Little Devil's Spring.

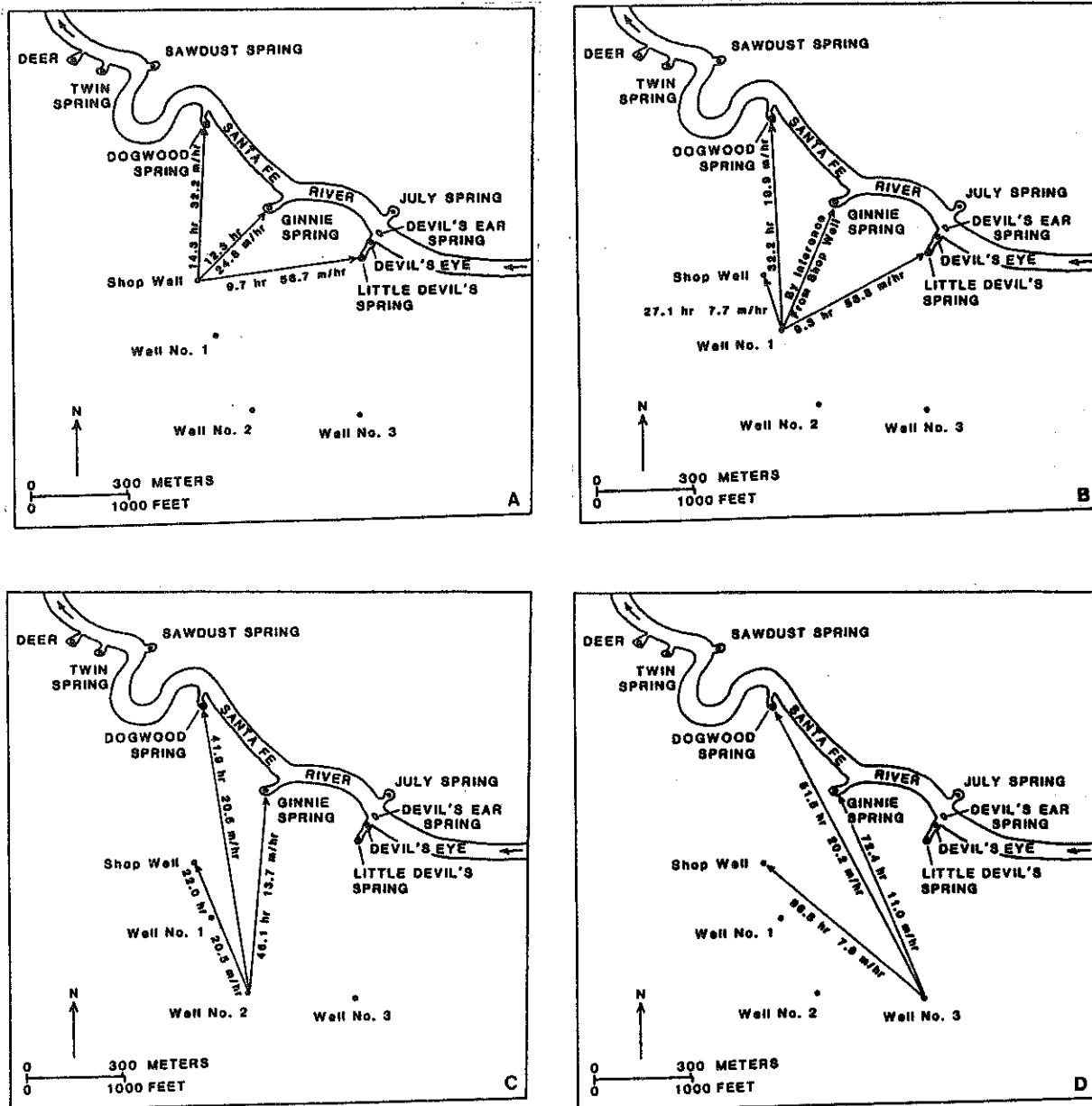


Figure 7. Direction, average dye flow time, and average dye velocity for dye traces from four wells near Ginnee Spring, Florida. Each diagram shows section 34, T.7S., R.16E., Gilchrist and Columbia Counties, Florida.

TABLE 3
DYE TRAVEL TIMES AND VELOCITIES

Release Point	Detection Point	Minimum Distance (Meters)	Average Flow Time (Hours)	Average Velocity (m/hr)	Average Conductivity (m/hr)
Shop Well	Ginnie	305	12.3	24.8	22,600
Shop Well	Dogwood	460	14.3	32.2	34,000
Shop Well	Little Devil's	550	9.7	56.7	55,900
Well No. 1	Shop Well	210	27.1	7.7	8,100
Well No. 1	Dogwood	640	32.2	19.9	21,000
Well No. 1	Little Devil's	550	9.3	58.8	62,000
Well No. 2	Shop Well	450	22.0	20.5	21,600
Well No. 2	Ginnie	630	46.1	13.7	14,500
Well No. 2	Dogwood	860	41.9	20.5	21,600
Well No. 3	Shop Well	760	96.8	7.9	8,300
Well No. 3	Ginnie	800	72.4	11.0	11,600
Well No. 3	Dogwood	1,040	51.5	20.2	21,300

The consistent dispersion of the dye to more than one spring shows that effective ground-water drainage divides do not exist even within a few hundred meters of the spring outlets. Ground water diverges in the downstream direction, rather than flowing only into higher order conduits. This indicates that an extensive three dimensional network of braided conduits and/or sponge-like, interconnected solutional openings must exist in the aquifer.

Additional evidence for braided conduits can be seen in the shape of the dye concentration curves for the dye trace from the Shop Well, which is a typical case. Figure 8 shows how the dye concentrations at Dogwood and Ginnie Spring varied over time. Multiple peaks, defined by numerous points on the ascending and descending limbs, are apparent on the graph. The only explanation for the multiple peaks is that, at some point along the flow path, part of the flow was diverted through a lower order conduit and eventually returned to the original conduit. Braided passages are commonly seen in underwater cave systems in northern Florida based on the mapping experience of the second author. Multiple dye peaks, through a phreatic cavern system, have not been interpreted as representing braided passage conditions previously, except for the conditions in the alpine Castleguard Aquifer reported by Smart (1988).

At the time the dye trace from the Shop Well was performed, the discharge of the springs was approximately average. Based on the discharge and the dye concentrations, 66 percent of the dye emerged at Dogwood Spring, 25 percent emerged at Ginnie Spring, and 9 percent emerged at Little Devil's Spring. The total dye recovered was essentially 100 percent, which lends credence to the dye trace to Little Devil's Spring, despite the rapid velocity, as discussed above. Nearly complete recovery of the dye is expected for cavernous ground-water drainage systems in

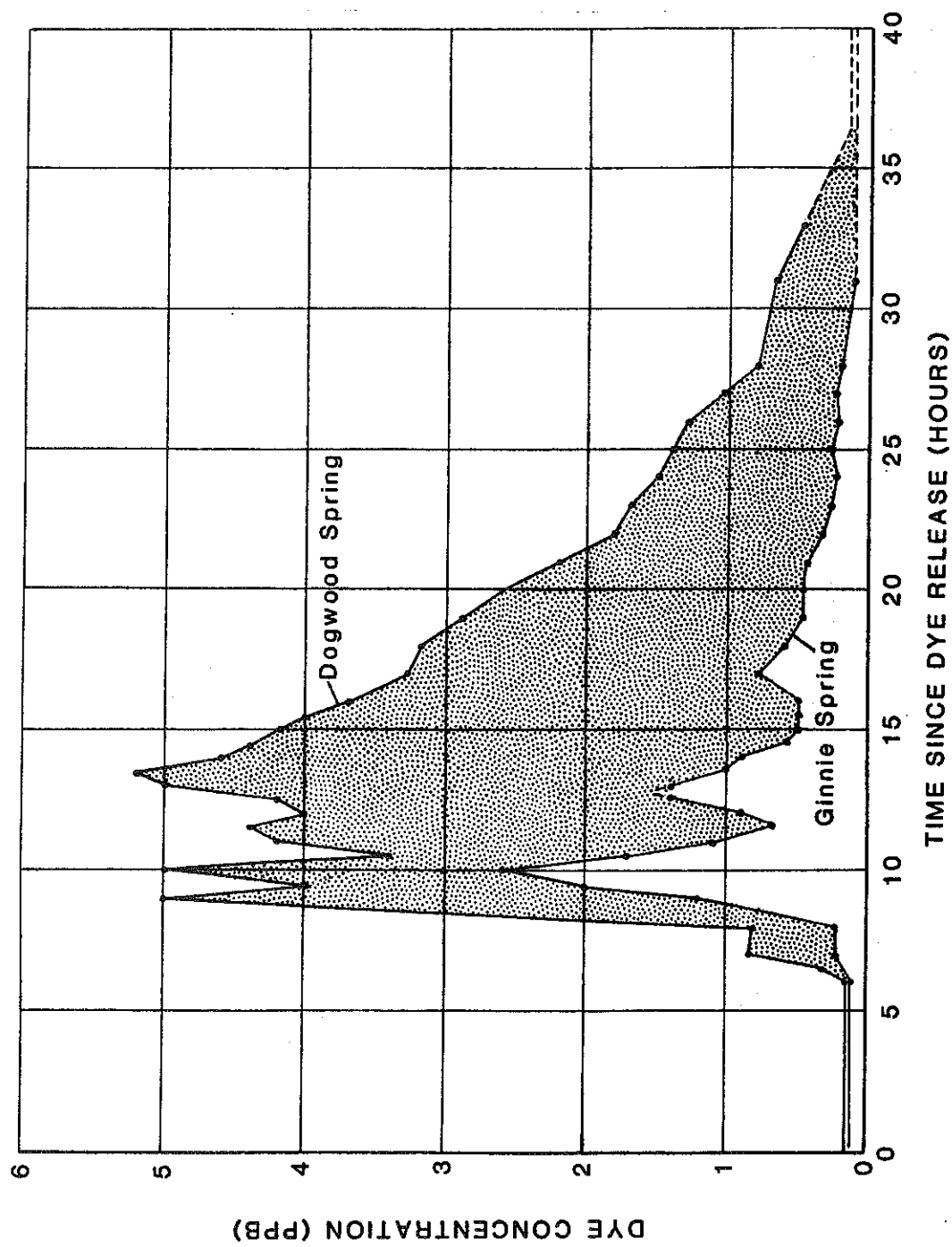


Figure 8. Dye concentration curves for Dogwood and Ginnie Springs for the dye trace from the Shop Well. Multiple peaks indicate that the dye has passed through braided conduits.

northern Florida because of low levels of turbidity, clay, and organic matter in the ground water. Ginnee Spring typically discharges nearly three times as much water as Dogwood Spring, but the latter spring discharged approximately two and one-half times as much dye. Hydraulic connections are generally better between the wells and Dogwood Spring, than between the wells and Ginnee Spring.

Ground-water velocities, based on straight-line distances between the wells and springs (excluding Little Devil's Spring), are consistently in the 7.7 to 32.2 m/hr range. The average velocity for flow from the wells to the springs is 20 m/hr (0.56 cm/sec). Assuming an average water table gradient of 0.9 m/km, then the hydraulic conductivities (velocity divided by gradient) range from 8,100 m/hr to 33,400 m/hr. This is a relatively close grouping for conductivities, and the values far exceed the conductivity of coarse gravel, which is approximately 35 m/hr. Even considering the difference between apparent velocity, used in Darcy's Law, and the actual minimum velocities measured in the dye traces, the difference in conductivities is still, at least, two or three orders of magnitude.

Flow in round pipes is usually turbulent for Reynold's numbers larger than 2000. Based on this Reynold's number and the average velocity of dye movement, in the vicinity of Ginnee Spring, turbulent flow would certainly exist in passages larger than 36 cm in diameter. Cave passages are usually much rougher and more irregular in cross section than manufactured pipes, so turbulence may begin at diameters much less than 36 cm. The likelihood of turbulent flow and the high conductivities indicate that most of the dye was conveyed through caverns.

The width of the dye curves, shown in Figure 8 and Table 4, is particularly significant for characterization of the aquifer. Although most of the dye is undisputably conveyed through caverns, the width of the dye curves is unusually large, and the tails of the curve may represent the emergence of dye that was conveyed through a more diffuse flow system.

Dye pulses from the wells initially appeared in the springs between 6.5 and 20.5 hours after the dye was released, yet, pulses persisted for periods usually ranging from 25 to 124 hours. The width of the dye curves was typically 4 to 6 times greater than the breakthrough time indicating that the dye did not travel as a concentrated pulse. Dye curves for dendritic caves at, or near, the water table in the Midwest, usually have widths that are only 1 or 2 times greater than the breakthrough time (Smoot and others, 1987). The proportionately wider dye curves in the Ginnee Spring area are tentatively explained as the product of significant amounts of ground-water flow through small, interconnected networks of solutional openings. The openings are smaller than caves, but larger than intergranular spaces. They will be defined as "spongework" and described in the following section.

Conductivity Components in the Floridan Aquifer

General

Despite the known occurrence of cave systems and the demonstrated rapid velocity of ground-water flow through the caverns, it is important to recognize that smaller flow paths exist in abundance. The Floridan

TABLE 4

DYE TRAVEL TIMES

		Columns				
Release Point	Detection Site	A	B	C	D	E
		Time to Leading Edge of Dye (Hr:Min)	Time to Peak Dye Concentration (Hr:Min)	Time to Dye Centroid (Hr:Min)	Time to Trailing Edge of Dye (Hr:Min)	Dye Curve (D-A-E) (Hr:Min)
Shop Well	Ginnie Spg.	6.50	10.00	12.33	31.50	25.00
	Dogwood Spg.	6.50	13.50	14.27	31.50	30.00
	Little Devil Spg.	8.50	9.50	9.72	15.50	7.00
Well 1	Shop Well	4.55	6.37	27.12	64.22	59.67
	Dogwood Spg.	16.25	26.82	32.17	86.57	70.32
Well 2	Shop Well	5.67	11.45	22.03	86.62	80.95
	Ginnie Spg.	14.33	27.15	46.15	117.67	103.34
	Dogwood Spg.	20.57	27.18	41.93	109.33	88.76
Well 3	Shop Well	19.50	21.25	96.77	130.02	110.52
	Ginnie Spg.	19.17	46.50	72.42	142.17	123.00
	Dogwood Spg.	10.60	17.75	51.45	134.85	124.25

Notes:

- 1) Some points estimated from general slope of dye concentration curve.
- 2) Time interval between the first or last positive sample and preceeding or following background sample, respectively, has been divided equally to estimate time to leading edge and time to trailing edge.

Aquifer contains four components of conductivity: 1) intergranular and moldic pore space, 2) joints, 3) small solutional openings (spongework) that convey ground water in the laminar flow regime, and 4) large solutional openings (caverns) that convey ground water in the turbulent flow regime. All of these flow paths are important for establishing the character of the aquifer, but spongework is perhaps the most important and will be discussed in some detail.

Pores

The carbonate rocks of the Floridan Aquifer have a high degree of primary porosity because they have never been deeply buried. The high primary porosity distinguishes the Floridan Aquifer from the more thoroughly cemented carbonates of the Midwest and Appalachian Mountains. The biospar rudites of the Floridan Aquifer may have effective porosities of 10 to 30 percent. Nothing other than diffuse flow would be expected through the primary pores.

Joints

Joints are present in the carbonate rocks of the Floridan Aquifer. Most of the joints form an orthogonal network of master and cross joints, but outcrops are poorly exposed, so the joint spacing and orientation has not been adequately sampled. Many underwater cave passages appear to be developed along segments of joints. By themselves, joints form only a small fraction of the total porosity in the Floridan Aquifer.

Bedding Planes

Bedding planes, although commonly cited in the literature as a preferred "flow path" for ground water movement, are NOT openings through which ground water is conveyed. They are vertical grain size discontinuities across which lithologic changes occur that distinguish two adjoining beds of rock. Bedding planes, therefore, do not contribute to the conductivity of the aquifer. However, because of lithologic variation, ground water may be perched upon, or confined by, a bed, and solutional openings, such as anastomoses, may develop at the contact between beds. Also, unconformable contacts may serve as zones of high conductivity where paleo-epikarstic zones are preserved.

Spongework

Many intergranular flow paths have been enlarged, by solution, into sponge-like networks of interconnected macroscopic openings. As defined here, the diameter of the openings may range from diameter of the sediment grains to the largest diameter in which laminar flow can exist under typical conditions. Near Ginnie Spring, the lower limit is taken to be 0.2 cm (the upper limit of sand-sized carbonate grains), and the upper limit is approximately 36 cm, at which diameter, nearly all flow is turbulent. Larger or smaller upper limits may apply depending on the hydraulics of the system.

Spongework may constitute 20 to 50 percent of the aquifer, by volume, based on outcrop observations. Such openings are common in cores and drillers often report "honeycomb" zones which represent intervals of

extensive spongework development. Also, the walls of underwater caves, in northern Florida, are usually rough and pitted with spongework openings that are confluent with the main conduit.

Spongework appears to be the result of extended solutional enlargement of intergranular flow paths under laminar conditions promoted by the combination of high primary porosity and low hydraulic gradients. The vuggy, irregular shape of the interconnected voids that form the spongework indicates that ion diffusion under laminar flow has dominated the development of the voids. One should note that the development of spongework may have been aided, also, by mixing-zone dissolution, which occurred as sea level fluctuated in the geologic past (Back and others, 1986, and Beck, 1987).

Even though significant caverns exist, pump tests commonly show that the Floridan Aquifer behaves in a manner described by Darcian equations (Hickey, 1984). The extensive development of spongework allows the aquifer to have extremely high transmissivities and yet behave in a dominantly Darcian manner.

Caverns

In the Ginnie Spring area, turbulent flow probably occurs in all passages more than 36 cm in diameter, so by definition, passages of at least this minimum diameter function as caves, without regard to the common, subjective definition that caves are natural openings large enough to admit a person. Caverns comprise only 2.5 percent of the aquifer by volume, based on the proportion of cavities reported by drillers (Wilson, 1988b). Because of spongework in the walls of the large conduits, the caves are best thought of as pipes with permeable walls. Flow can be lost or gained through the walls depending on the stage of flow. Additional research is needed to determine the amount of water lost or gained through the walls along the length of conduits so that the standard equations for pipe flow can be modified to include this variable. Caves, in the Floridan Aquifer, tend to transport ground water, rather than serving as the most important form of storage.

CONCLUSIONS AND SUMMARY

Ginnie, Dogwood, and possibly Little Devil's springs are hydrologically related. The springs are not merely distributary outlets for a cavernous flow system; rather, the springs are interconnected by a pervasive, three dimensional, nearly isotropic network of spongework and braided caverns. In the unconfined Floridan Aquifer, near Ginnie Spring, the water table is not a determinant surface that causes all ground water to flow perpendicular to the equipotential contours. Miniscule differences in hydrostatic pressure and the presence of solutional openings (spongework and braided caverns) interact to form a probabilistic space in which water has a finite chance of flowing to one of multiple outlets depending on the effect of divergence along the interconnected flow paths.

Despite the extensive development of caverns, the aquifer behaves, in a bulk sense, according to Darcy's Law, because of braided conduits, extensive development of spongework, and low hydraulic gradients that allow laminar flow to persist in solutional openings that may be as large

as 36 cm. The pervasiveness of the spongework and caverns gives the aquifer transmissivities on the order of 100,000 m²/day. The high transmissivities result in low draw-downs at short distances from supply wells, especially if the wells are completed in caverns.

The proposed withdrawal of 1.5 million liters/day of ground water will not significantly affect the nearest neighboring wells. The withdrawal rate is equal to 0.9 percent of the average discharge of the three springs. The effect of ground-water withdrawal will likely be proportionate on the three springs because of the high transmissivity of the aquifer.

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