Quantitative groundwater tracing and effective numerical modeling in karst: an example from the Woodville Karst Plain of North Florida

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Abstract

Quantitative groundwater tracing is being used in the Woodville Karst Plain of North Florida to characterize the hydraulic complexities of conduit flow for numerical modeling purposes. Accordingly, seven tracer tests were performed along both mapped and unmapped pathways ranging from 2.5 to 19.5 km in length utilizing between 0.7 and 4.5 kg of fluorescent tracer. Tracer recovery curves were measured at one or more points along a flow path for each tracer test. Computed mean velocities through the conduits ranged from 500 to 4560 m/day with peak concentrations between 0.12 and 125 ppb. The data obtained from the tracer tests have been incorporated into a finite element numerical model of groundwater flow in the WKP. Through-conduit velocities and mapped flow paths identified by the first five tracer tests were used in conjunction with cave map data to build discrete conduit pathways into the model framework and set flow parameters within the numerical conduits. Particle tracks generated from the resulting model were then used to highlight flow paths associated with a sinking stream that was the focus of the last two tracer tests. Subsequent tracer test results closely confirmed the model predictions. Current model results indicate that this approach will provide an effective method of realistically simulating spring flows and delineating individual springsheds within the karst basin. Further details about the tracing projects are available at www.hazlett-kincaid.com/FGS.

Background

Florida boasts one of the highest concentration of springs on the planet including 33 documented first-magnitude (discharge > 100 cfs) springs and more than 600 2nd and 3rd magnitude springs having a total discharge of more than 9,300 cfs (Scott et. al, 2002). Most of these springs are concentrated in a part of the state where the Floridan aquifer is unconfined or poorly confined; an area that extends like a crescent from Clearwater in the south up through the center of the peninsula and west across the central panhandle to Tallahassee.

Unfortunately, Florida's spring water quality has been declining markedly for more than 10 years, with the most notable problem being increasing nitrate concentrations. Within the last 5 years, increasing nutrient levels, of which nitrate is thought to be the most significant, have led to obvious and alarming changes in the water clarity and ecology of many spring basins. The problem has become so widespread and recognized that the Florida Department of Environmental Protection has sponsored two publicly advertised conferences dedicated to issue of spring protection in Florida and established the *Florida Springs Initiative*, which funds springs protection and restoration research and projects. Perhaps the most important outcome of the increasing attention given to Florida springs has been a growing recognition that the Floridan aquifer is extensively karstified and that hydrogeologic characterizations and spring protection strategies must embrace the complexities inherent to karst aquifers if they are to be meaningful and successful.

Of the all the first-magnitude springs in Florida, Wakulla Spring listed as the 3rd largest (Scott et. al, 2002) but is one of the most, if not the most, widely recognized and appreciated. It is also one of the most severely impacted. Water quality measurements have shown a 5-fold rise in nitrate levels in the spring discharge since the 1970's (Chelette et. al, 2002), an explosion in algae and hydrilla *sp* growth in the spring

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basin and upper sections of the Wakulla River, and a 30% decrease in the average apparent water clarity. These environmental declines combined with the prominence of Wakulla Spring as a premier tourist attraction in Florida, and no doubt, the proximity of the spring to the Florida State Capitol, have generated significant support for efforts aimed at understanding the causes for the declines and identifying solutions. Three probable sources of contamination to Wakulla Spring have been recognized: waste water from the City of Tallahassee SE Farm Facility, discharge from private septic systems (onsite disposal systems or OSDS), and storm water runoff that rapidly recharges the Floridan aquifer through sinkholes.

Research Objectives

The purpose of this paper is to provide an overview of a collaborative research effort aimed at understanding groundwater flow patterns and groundwater / surface water interactions in a section of the Wakulla springshed known as the Woodville Karst Plain. Collaborating entities include: the Florida Department of Environmental Protection (FDEP), Florida Geological Survey (FGS), Florida State University Geophysical Fluid Dynamics Institute (FSU-GFDI), Hazlett-Kincaid, Inc. (HKI), Cambrian Ground Water Company (CGW), the Woodville Karst Plain Project (WKPP) the Northwest Florida Water Management District (NWFWMD), and Wakulla Springs State Park (WSSP).

The specific research objectives that will be discussed include:

- Identification of flow paths between disappearing streams and down-gradient springs in the Wakulla springshed.
- Calculation of velocities and other hydraulic parameters along karstic flow pathways through the Wakulla springshed.
- Incorporation of identifiable karst flow paths and the hydraulic parameters characteristic of those flow paths into a numerical model of groundwater flow through the Wakulla springshed.

Woodville Karst Plain

The Wakulla springshed extends from the spring, which discharges from an unconfined section of the Floridan aquifer, northward and westward into a confined or poorly confined section of the aquifer through all or part of Tallahassee and into southern Georgia. Surface drainage off of the northern and western confined regions onto the exposed carbonates has created a region of extensive karstification down-gradient of the uplands (Lane, 1986) containing numerous dolines, sinkholes, karst windows, sinking streams, and springs. This extensively karstified region within the unconfined section of the springshed is a gently sloping topographic lowland that extends from just south of Tallahassee to the Gulf of Mexico, known as the Woodville Karst Plain (Hendry and Sproul, 1966).

The geology of the Woodville Karst Plain (WKP) consists of a thin veneer of unconsolidated and undifferentiated Pleistocene quartz sand and shell beds overlying a thick sequence of relatively horizontal carbonate rocks that comprise the upper Floridan aquifer. Recharge to the Floridan aquifer in the WKP occurs by: 1) sinking streams, 2) direct infiltration of precipitation through sinkholes, 3) infiltration through the variably thick sands and soils overlying the aquifer, and 4) groundwater flow into the WKP from the north. The FDEP and FGS are currently engaged in an effort to physically document all of the sinkholes and sinking streams within the WKP. To date, more than 400 sinkholes, ephemerally or perennially wet, have been mapped in the northwestern quarter of the WKP by the FLDEP, which suggests the presence of more than 1000 such features across the entire WKP. Of these 1000+ sinkholes, several are known to receive water, either perennially or ephemerally, from disappearing surface streams that drain upland regions, with flows ranging seasonally between 10^{-2} and 10^{0} m^3/s. The five largest such streams are, in order of relative average flow: Lost Creek, Fisher Creek, Munson Slough, Black Creek, Jump Creek (Figure 1).

Discharge from the Floridan aquifer under the WKP is through springs in the southern part of the region and submarine springs in the Gulf of Mexico. Wakulla Spring, with an average discharge of 11 m^3/s, is the largest inland spring in the WKP and the third largest spring in Florida. Wakulla Spring is the headwater of the Wakulla River, which flows for approximately 16 km southeast to the St. Marks River and the Gulf of Mexico. Seasonal discharge from Wakulla Spring ranges between 0.7 and 54 m^3/s (Scott et. al, 2002), which is the largest range of discharge recorded for any spring in Florida (Rupert, 1988). The Spring Creek group, which includes at least 14 underwater vents along the coast of Apalachee Bay in the Gulf of Mexico is listed as the largest spring in Florida and also displays a large range in discharge at between 8.5 and 56 m^3/s (Scott et. al, 2002). The variation in discharge at Wakulla Spring correlates closely with local rainfall, where spring hydrographs indicate that discharge responds to local storms in less than two days (Rosenau and others, 1977). The regional recharge area for these springs (and others in the WKP) has been estimated to cover 2500 km^2, including parts of Leon, Wakulla, and Jefferson Counties and portions of five Georgia counties as far as 80 km north of the Florida-Georgia border (Gerami, 1994; Davis, 1996).

In addition to the sinkholes and sinking streams, cave divers have mapped numerous underwater caves within the WKP that trend for more than 16 km across the basin from north to south at depths ranging from 15 to 85 m (Werner, 2001; Woodville Karst Plain Project, 2005). The five largest mapped caves in the WKP, ordered by length of mapped conduits, are: Leon Sinks (> 23 km), Wakulla (>13 km), Chip's Hole (>4.5 km), Indian (>2.5 km), and Sally Ward (>2 km) – Figure 1. Conduit diameters within these caves range from less than 2 meters to greater than 30 meters and average approximately 10-15 meters (Kincaid, 1999; Werner, 2001).

Within one to two days after heavy or sustained rainfall, tannin-stained water flushes into the largest conduits that comprise Wakulla cave, turning the normally clear water brown and reducing visibility for cave divers. These rapid response times indicate that the caves constitute a highly integrated network of conduits that convey water recharged through sinkholes in the northern part of the region to Wakulla and Spring Creek Springs. Wakulla Spring is thought to capture the majority of the ground water flow through the northern part of the region (Rupert, 1988) where the water is conveyed to the spring by conduits in Wakulla cave.

Quantitative Groundwater Tracing

Overview

Quantitative tracer tests depend not only on the detection of a fluorescent substance at the sampling locations but rather on the observation of the trend in fluorescence (from background levels to peak concentration and back to background levels) as the dye passes the observation point. The observations are recorded on a plot of the fluorescence or concentration vs. time (breakthrough curve). Breakthrough curves offer several benefits over sporadic observations including the following:

- observation of the increase and decrease in fluorescence at the sampling point increases confidence in the assumption that the samples reflect passage of the injected tracer rather than some other anomalous source of fluorescence;
- a more accurate groundwater velocity can be calculated using the time-to- peak concentrations;
- integrating the area under the recovery curve allows an estimation of the mass of tracer recovered and thereby an estimation of the relative contribution of flow from an injection location at a sampling location; and
- evaluating the shape of the concentration vs. time plot provides for the calculation of other hydraulic parameters including: longitudinal dispersion, Reynolds and Peclet Numbers, and discharge (if it is reasonable to assume that 100% of the tracer was recovered).

Quantitative tracing is being performed in the WKP in order to gain defensible estimates of the contributions of specific pathways to the discharge at Wakulla Spring and to measure hydraulic parameters for use in numerical modeling.

Three tracers are being used in various combinations to confirm and evaluate probable flow paths between sinking streams, sinkholes, karst windows, mapped caves and springs. The tracers are the fluorescent dyes C.I. Acid Red 92 (phloxene B), C.I. Acid Red 87 (eosin), and C.I. Acid Yellow 73 (uranine or disodium fluorescein). The quantity of tracer used for each injection is estimated using the Worthrington and Smart (2002) empirical equation such that peak concentrations at the predicted discharge points are <50 μg/L. This target concentration is roughly three – four orders of magnitude above the detection limit on a filter fluorometer or spectrofluorophotometer, and 50% or more below the typical visible detection limit.

Stream and through-conduit discharges were measured at both injection and sampling locations at the outset of the tracer experiments whenever possible. Stream discharges were measured by a standard velocity-area technique. Conduit discharges were estimated by divers or calculated with in-situ velocity meters combined with cross-sectional measurements provided by the divers.

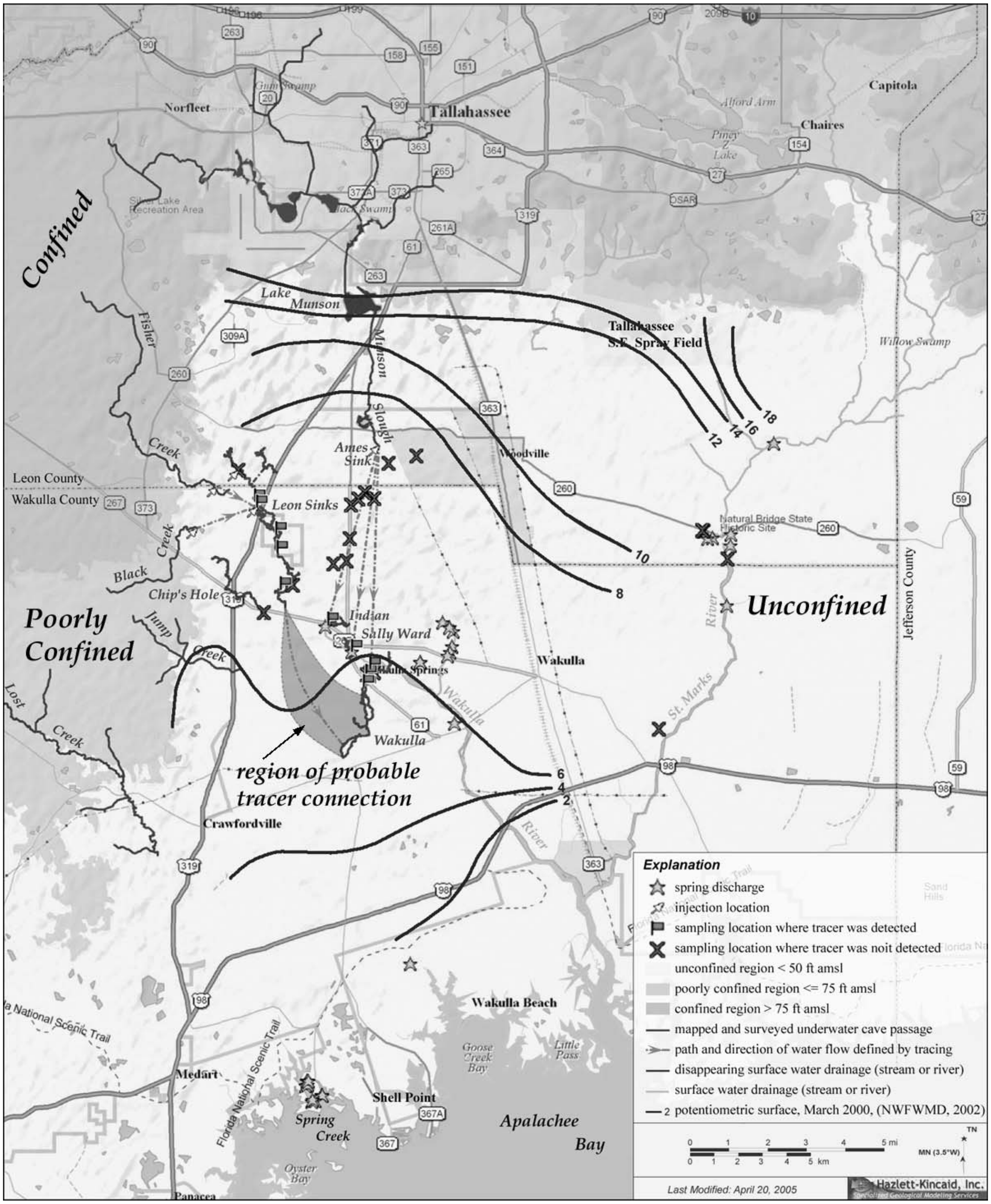

Figure 1. Map of the Woodville Karst Plain showing the transition zone between confined and unconfined conditions in the Floridan aquifer relative to the significant hydrologic features (rivers and lakes, sinking streams, underwater caves, the Gulf of Mexico – *Apalachee Bay*, and the potentiometric surface of the upper Floridan aquifer as mapped by the NWFWMD in March 2000). All traced groundwater pathways are marked by the dashed lines with arrows pointing in the direction of flow except for those traced through the caves, which flow down-gradient (southeast) through the Leon Sinks and up the apparent gradient through the Wakulla cave toward Wakulla Spring. Note that the dip in the six-foot contour of the potentiometric surface reflects the traced groundwater pathway through that region of the basin toward Wakulla cave. Also note the relative position of Wakulla and Spring Creek Springs, which suggests an overflow / underflow relationship. A larger, color version of this map is available at www.hazlett-kincaid.com/FGS.

Logistics

Water-tracer solutions were injected by direct release into sinking streams or with a peristaltic pump into underwater conduits at specifically targeted locations. Sampling was performed at water-filled sinkholes, springs, and underwater conduits at specifically targeted locations. In order to overcome problems with residence times in sinkholes and divergent flows between siphoning conduits and springs, WKPP cave divers were enlisted whenever possible to install 3/8" polyethylene tubing from the land surface to target sampling and injection locations within the underwater caves through the springs and sinkholes. Sampling was then performed through the use of volunteers that collected grab samples from the tubes on a daily or twice-daily basis or automatic water samplers that collected regular samples from a covered bucket that continuously received water from the tubes via a peristaltic pump. Tables 1 and 2 provide a brief summary of the characteristics of the injections and sampling locations used in the six tests discussed in this paper.

Table 1. Summary of injection and sampling strategies.

Injection Location	ID	Date	# Sampling Stations	Sampling Dur. (hours)	# Detection Points	Tracer	Quantity Injected (kg)
Sullivan Sink	SS	7/1/2002	1	53	1	AR92	0.7
Cheryl Sink	CS	7/1/2002	1	5	1	AR92	0.1
Fisher Creek Sink	FCS	5/22/2003	3	87	1	AY73	1.5
Black Creek Sink	BCS	11/19/2003	7	300	7	AY73	3
Emerald Dark Water Tunnel	EDWT	2/5/2004	11	204	10	AY73	3
Ames Sink	AS	8/11/2004	24	566	5	AY73	3

Table 2. Summary of sampling locations at which tracer was detected during one of the six tracer tests listed in Table 1, mode of sampling, and position of sampling tubes where relevant.

Sampling Location	ID	Type	Tube Length (m)	Tube Depth (m)	Injections Detected
Cheryl Sink	CS	Sinkhole	15	10	SS
Emerald Sink	ES	Sinkhole	35	18	CS
Emerald Dark Water Tunnel	EDWT	Cave	215	40	FCS, BCS
Fish Hole Sink	FH	Sinkhole	10	5	BCS
Upper River Sink	URS	Sinkhole	20	10	BCS, EDWT
Turner Sink	TS	Sinkhole	35	15	BCS, EDWT
Wakulla K-Tunnel	WK	Cave	150	86	EDWT
Wakulla Spring	WS	Spring	100	15	BCS, EDWT, AS
Indian Spring	IS	Cave	275	46	AS
Sally Ward Spring	SW	Cave	215	80	AS

Results

Figure 2 (right) shows four normalized breakthrough curves (conc. / peak conc.) for the first two through-conduit traces (SS-CS & CS-ES) and the first two sinking stream – conduit traces (FCS-EDWT & BCS-EDWT). The straight-line and conduit distances (m), if mapped, are shown next to the respective curves. The shape of the curve correlates to the distance of the flow path.

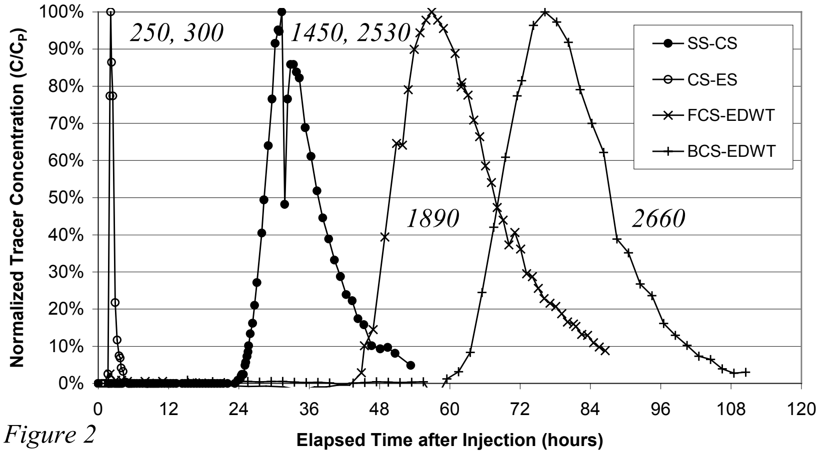

Figure 2

Figure 3 (right) shows four breakthrough curves measured after the EDWT injection from sampling stations located in Leon Sinks cave (URS & TS) and Wakulla cave (WK & WS). The double peaks evident at the URS and TS are attributed to either a bifurcation in the flow path or temporary sequestration of the tracer in one of the large mapped chambers in the Leon Sinks cave. Straight-line and probable conduit distances (m) between consecutive stations are shown next to the respective curves.

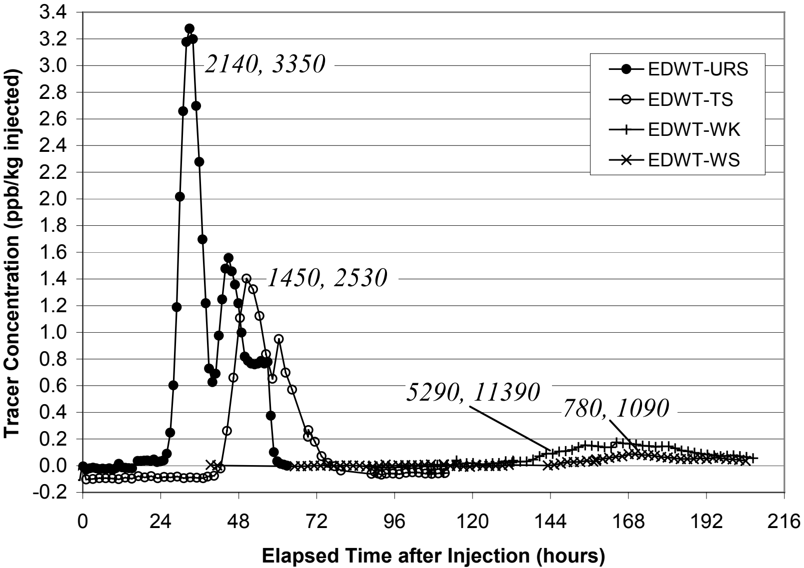

Figure 3

Figure 4 (right) shows recovery curves from the AS injection as measured at three springs (IS, SW, & WS). The IS curve is best defined and by comparison to the SW and WS data indicates significantly higher tracer mass recovery that was not conserved along a potential subsequent path to SW and WS. Also note the apparent skewed tailing edge of the curve that may indicate a prolonged release from storage. Straight-line distances between injection and sampling locations are shown next to the curves.

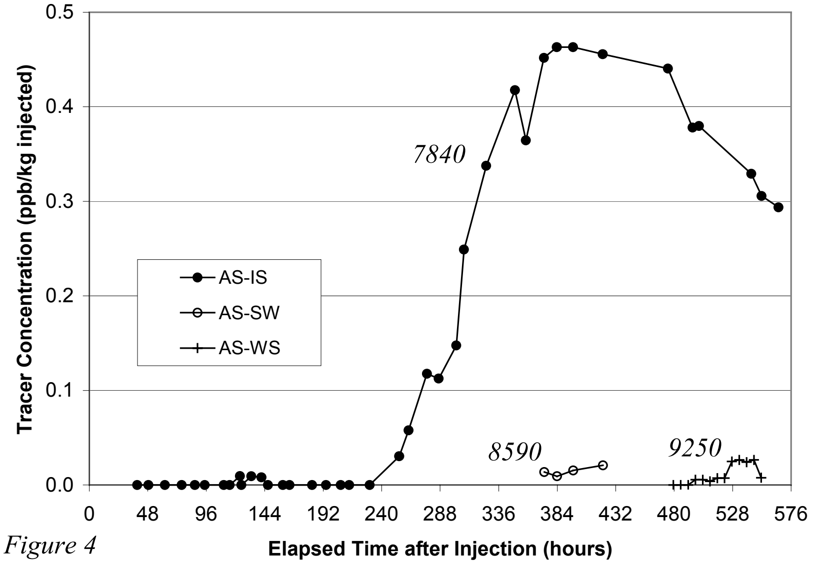

Figure 4

Figure 5 (right) shows the measured change in tracer velocity along the flow path measured through and between the Leon Sinks and Wakulla caves after the SS and EDWT injections. Note that the first-arrival velocity tracks and is faster than the peak velocity along each section except the last section of the conduit to Wakulla Spring.

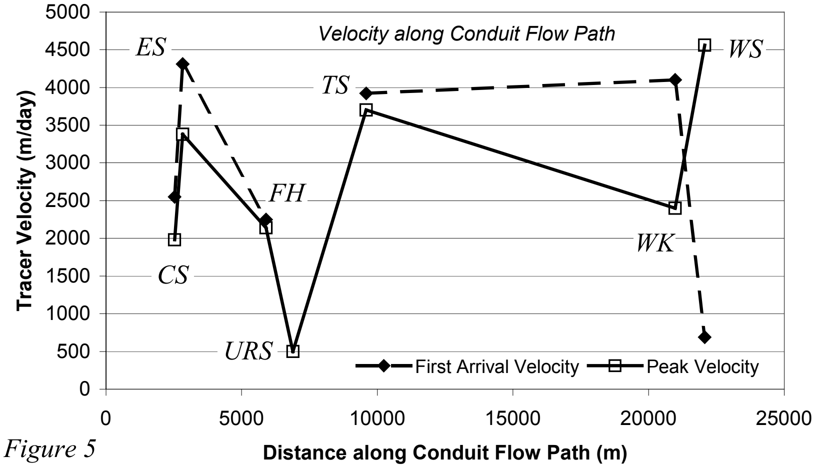

Figure 5

Numerical Modeling

A groundwater flow model of the WKP has been developed using the finite element software, FEFLOW, which primarily allows us the advantage of incorporating the fluid-filled conduits as discrete flow features embedded in a finite element mesh. The model is currently 3-D, having three surfaces: land surface, a second and third slice to accommodate the caves, and a bottom slice. The model is approximately 300 m thick. Initial flow conditions are from north to south, from the upland confined region to Apalachee Bay in the Gulf of Mexico. The major spring discharges included in the model are St. Mark's, Wakulla, and Spring Creek. The mapped caves are included explicitly in the model as a concentration of finely discretized nodes with sides parallel to the trend of the mapped conduits.

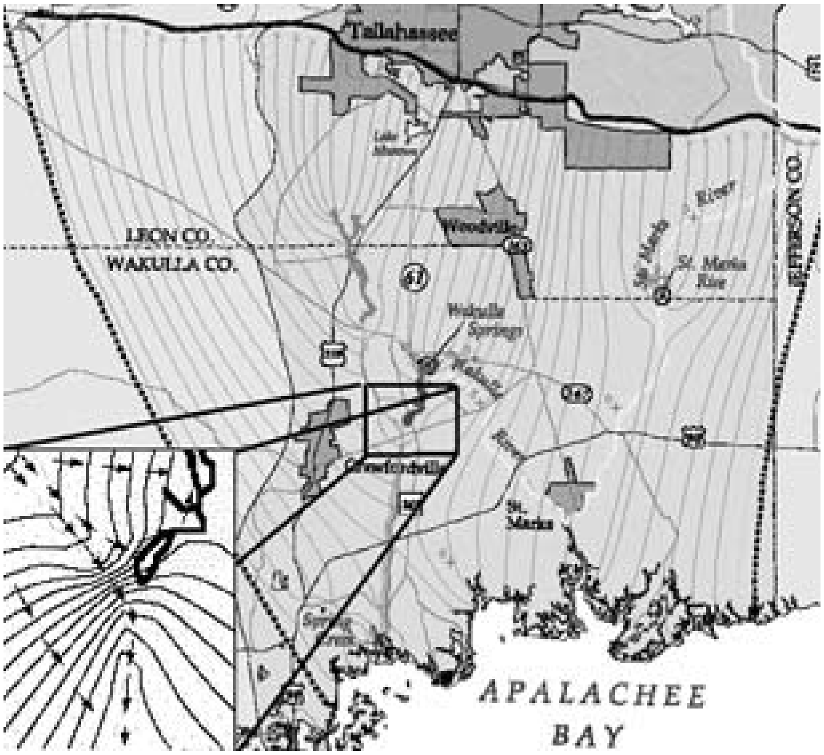

Figure 6. Groundwater particle tracks in the WKP showing the modeled capture zones of the caves and springs. Inset shows potentiometric surface lines and bifurcating flow through caves: to the south to Spring Creek Spring and to the north to Wakulla Spring.

The model is therefore constructed as a porous media using an extreme contrast in hydraulic conductivity ($1x10^5$) between the matrix and conduit nodes. At present, model simulations are only roughly calibrated to heads and spring flows. Groundwater flow paths and velocities along the mapped and traced pathways in the resulting simulations are being qualitatively compared to the results of the tracer testing.

One of the most compelling features of the groundwater modeling results thus far is that it has been reasonably successful in predicting/confirming the results of the tracer testing. For example, one simulation predicted that water flowing from Ames Sink, north of Wakulla, would first go to Indian Springs, which was ultimately established by tracer testing. This would seem to indicate that the dominant hydraulic features in the basin are the caves. Another compelling proof of the viability of this modeling approach is the successful simulation of a groundwater divide across the southern section of Wakulla cave wherein groundwater entering the Wakulla system from the west splits and heads both north toward Wakulla Spring and south toward the Spring Creek Springs. The presence of such a divide has been anecdotally reported by the WKPP exploration divers (Kincaid, 1999) and confirmed by the EDWT tracer test (Figures 1 and 3).

Discussion

The combination of tracer testing and modeling has considerably augmented our understanding of the hydrology of the WKP. The Q-Tracer program (EPA, 2002) has been used to evaluate recovery curves and calculate hydraulic parameters. Computed mean velocities through the conduits ranged from 400 to 6000 m/day with peak concentrations between 0.27 and 21 ppb. Calculated longitudinal dispersivities ranged from 12 to 74 and Reynolds Numbers were all well within the turbulent range. The tests have established direct connections between three of the largest disappearing streams in the basin and Wakulla Spring, and between the two largest mapped caves: Leon Sinks and Wakulla Caves. The results also revealed that velocities typically inferred from groundwater ages and Darcy calculations underestimate travel times through the WKP by at least three orders of magnitude.

Scenario testing within the finite element model framework has both predicted flow patterns that were subsequently confirmed through tracer testing and provided support for relationships that have, as yet, only been inferred. For example, a hydraulic connection between the Spring Creek springs and Wakulla Springs has been inferred, but has not been mapped in the field. Nonetheless, the modeling has shown that it is possible for fluids coming through the Leon Sinks cave to flow to both Wakulla and Spring Creek springs. This model prediction supports the observation that the two springs have an overflow/underflow relationship. Scenario testing has also shown that the hydraulic system behaves more like a confined aquifer than an unconfined aquifer. That the simulations bear out confined system behavior stems from the fact that the conduits are pressurized (a much preferable term to confined) with respect to the surrounding matrix and therefore contain a pressure head in disequilibrium with the atmosphere. This model predicted behavior is supported by the long-tailing behavior of the AS-IS breakthrough curve. In addition, these numerical modeling results support conclusions drawn by Worthington and others (2000) that conduits carry the majority of flow through karst aquifers while the matrix supplies the bulk of the storage.

As the model framework becomes more refined, it will be calibrated to all available data, including unique data on flow being collected at various locations in the caves. Even in this early stage of development, model predicted head configurations and particle tracks throughout the catchment are significantly more detailed than those predicted by previously published MODFLOW models (Davis, 1996). The conclusions that can be drawn from the modeling at this point are: 1) fluid flow across the basin is dominated by the caves and 2) complex interactions between the caves and the matrix, as well as among the caves themselves can be simulated better than before, with what is essentially a porous media model.

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