Reference:

Meyer, B.A., Kincaid, T.R., and Hazlett, T.H., 2008. Modeling karstic controls on watershed-scale groundwater flow in the Floridan Aquifer of North Florida; in Sinkholes and the Engineering and Environmental Impacts of Karst, eds. Lynn B. Yuhr, E. Calvin Alexander, Jr., and Barry F. Beck, Geotechnical Special Publication No. 183, American Society of Civil Engineers, Reston, VA, pp. 351-361.

Modeling Karstic Controls on Watershed-Scale Groundwater Flow in the Floridan Aquifer of North Florida

Brent A. Meyer[1], Todd R. Kincaid[1], and Timothy J. Hazlett[2]

[1] GeoHydros, LLC, 27 Keystone Ave Reno NV 89503; PH (775) 337-8803; email: meyer@geohydros.com / kincaid@geohydros.com
[2] Danish Hydraulic Institute, thz@dhi.us

ABSTRACT: Groundwater flow in the Santa Fe River Basin (SFRB) and the Woodville Karst Plain (WKP) in northern Florida is controlled by large volume karst conduits that transport groundwater and surface water to large discharge points such as Wakulla and Hornsby Springs. Tracer tests have confirmed that these conduits receive surface water input from sinking streams throughout both regions and that water can move through these conduits at velocities greater that 1.5 km/day. Cave surveys have shown that the size and shape of these conduits repeatedly morph between large open passages more than 100 feet in diameter and highly bifurcated networks of small tubes. Groundwater / surface water exchange is reflected by tea-colored spring discharge during wet periods and clear water discharge during drought periods. The combination of these conditions presents a significant challenge to understanding and simulating regional groundwater flow patterns and their susceptibility to human-induced or natural environmental changes.

We have had great success in simulating groundwater flow in the SFRB and throughout northern Florida by constructing a finite-element model with conduits represented as embedded discrete element features. This method allows for the assignment of varying conduit area and friction parameters along the flow path. By explicitly defining the conduit network, we have been able to develop flow models that are simultaneously calibrated to head, spring discharge, stream loss, and tracer-defined conduit velocities. In doing this the model has both successfully simulated observed surface water / groundwater interactions and provided insights on the controlling mechanisms. Simulations show that under wet conditions, surface water entering through sinkholes dominates the conduit flow and suppresses the transport of groundwater whereas under dry conditions, surface water input decreases allowing for rapid transport of groundwater.

Though it is often dismissed in karst aquifers, these results demonstrate the utility of modeling if an estimated pattern of conduits can be defined through cave surveys, dye tracing, or detailed head mapping. Once a realistic pattern is established, the model itself provides an excellent tool for estimating non-observable conditions such as the effects of internal gradients on conduit-matrix interactions through calibration to heads, spring discharges, and velocities.

INTRODUCTION

Movement of groundwater in carbonate aquifers is generally through a combination of diffuse, fracture, and conduit flow. A large gradient between recharge and discharge areas coupled with heterogeneities within the bedrock facies may lead to dissolution and conduit formation. Conduits may also form through solution enlargement of tectonically formed fractures. This combination of diffuse and conduit flow regimes make karst aquifers extremely dynamic flow systems that are difficult to numerically simulate.

One of, if not the most important factor in simulating any groundwater flow regime is correctly understanding and articulating lithologic heterogeneities within an aquifer because they can significantly impact the rate and direction of groundwater flow. This effort is typically focused on describing bulk matrix permeabilities and potential anisotropies. That focus is appropriate for porous media aquifers because flow is most often continuous and diffuse. In karst aquifers however, this effort must be expanded to focus on correctly defining preferential flow paths because of the very high conductance of fractures and conduits. In order to successfully simulate flow through karst aquifers, it is therefore crucial that the modeling approach incorporate discretely defined conduits that provide for through-flow between discrete inputs and outputs and exchange with the surrounding aquifer matrix.

A common practice is to model karst aquifers using strictly porous media flow models (Planert, 2007, Scanlon et al., 2003, and Risser, 2006). In these models, karst features are represented by localized regions of high hydraulic conductivity that may or may not connect to known discharges. Rarely is discharge at individual springs addressed. Instead, models typically simulate bulk discharge from spring groups or along stretches of river containing numerous springs. This method allows for simulation of general flow directions, delineation of large scale catchment boundaries, and calibration to regional head measurements. However, it cannot define individual springsheds and fails to correctly simulate the rapid travel times and high groundwater velocities that are often observed and measured in karst aquifers. To be of use to water resource managers tasked with setting minimum flows at individual springs, or protecting the quality of water at small-scale features such as springs or public supply wells in karst aquifers, models must be able to accurately simulate travel times associated with both the matrix and conduit flow as well as accurately delineate the capture zones for each individual feature.

The purpose of this paper is to present a holistic method for simulating flow through the three dimensional geometry of an aquifer system by combining the porous matrix structure with interconnected one dimensional discrete features representing karst conduits. The goal of the study was to construct a groundwater flow model that simulated three-dimensional flow through a karst aquifer that could be used to calculate travel times and delineate springsheds for individual springs in a chosen watershed. The validity of this method is supported through calibration to regional head measurements as well as calibration to measured conduit velocities and individual spring discharges. We believe that the modeling method we describe here is the most accurate way to simulate groundwater flow through karst aquifers.

MODEL AREA HYDROGEOLOGIC SETTING

Physiographic Controls

The model area lies within the Santa Fe River Basin (SFRB), which occupies approximately 3,500 km^2 of north central Florida and is a major tributary basin of the Suwannee River. The basin is extensively karstified, spans part of a transition zone between confined and unconfined regions of the Floridan aquifer system (FAS), and contains numerous hydraulically active karst springs and swallets that facilitate rapid groundwater / surface water exchange. Figure 1 provides a map of the model area showing the locations of important karst features. Figure 2 provides a east-west cross-section through the model area that shows the hydrostraigraphic framework.

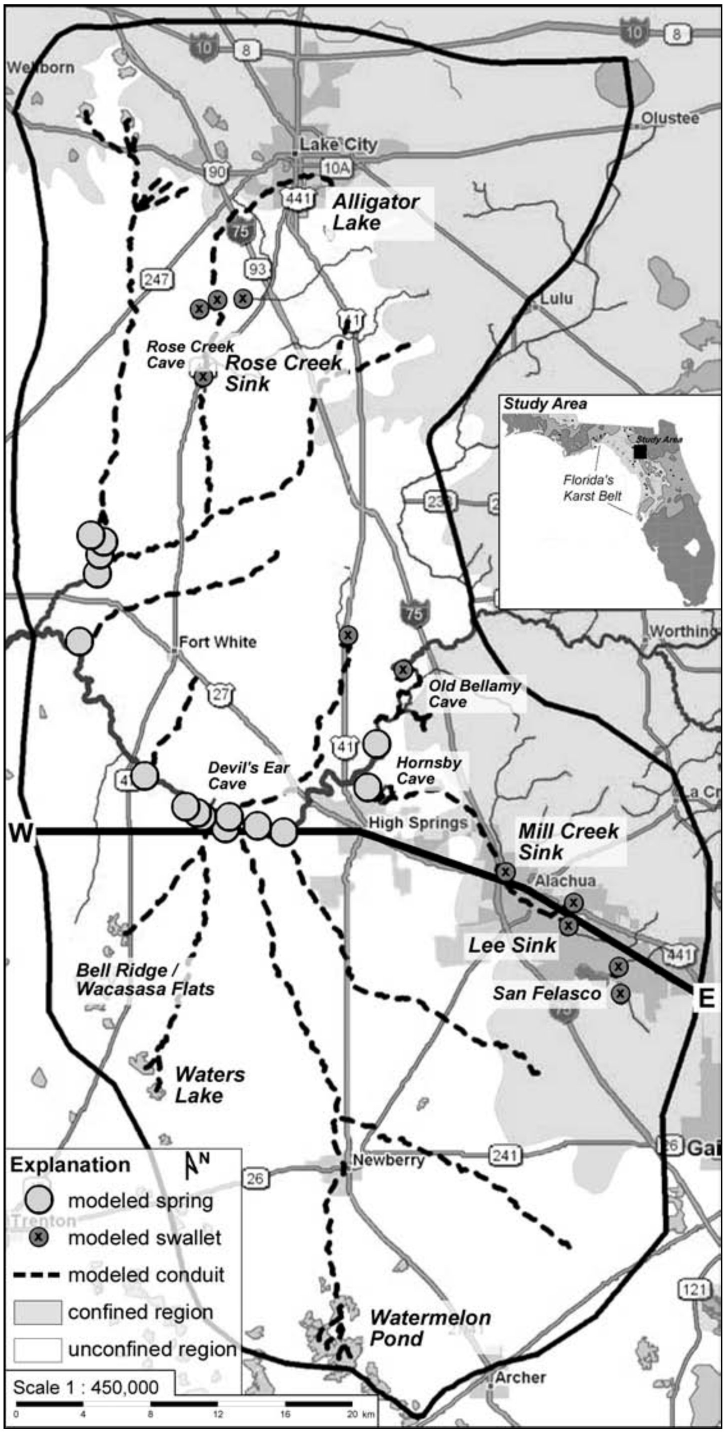

Figure 1. Model area & key karst features.

The Santa Fe River (SFR) generally flows from east to west. It originates in the eastern part of the basin, which is part of the Northern and Central Highlands physiographic province. Throughout that region, the Floridan aquifer system is confined and overlain by clay and limestone sediments of the Hawthorn Group and variably thick undifferentiated sands and clays. Clay sediments in the Hawthorn Group create a variably thick confining unit over the FAS that is broken in places by fracturing and sinkholes (Meyer, 1962 and Williams et al., 1977). The presence of the confining unit has fostered the development of wetlands including solution depressions and sinkhole lakes, and significant surface drainage including several creeks and streams in addition to the SFR and its two major tributaries. The overlying sands and clays create a discontinuous surficial aquifer system.

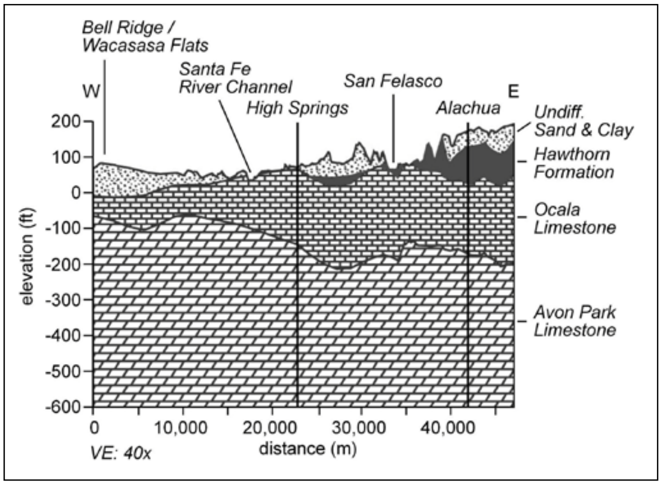

Figure 2. Hydrostratigraphic Framework.

Near the town of High Springs, the SFR flows off of the highlands onto the Gulf Coastal Lowlands physiographic province where the Floridan aquifer system is unconfined and either exposed at the land surface or overlain by variably thick surficial sands and clays. Evidence of karstification becomes significantly more apparent in the transition zone between the two regions where the SFR and all of the smaller streams and creeks disappear underground through swallets, and in the western part of the basin that contains several resurgences including that of the SFR, numerous springs and sinkholes, many dry and saturated (underwater) caves, and a marked decrease in overland drainage. The only two rivers that flow across the Gulf Coastal Lowlands are the SFR and its last tributary, the Ichetucknee River. Both are located along topographic lows and only exist as perennial streams due to significant discharge from the FAS at numerous first magnitude (>= 2.8 m^3/sec) and second magnitude springs (<2.8 m^3/sec).

A physiographic subregion called the Bell Ridge or Wacasassa Flats (Vernon, 1951) is a swampy area approximately 8 km wide and 40 lm long trending southward along the southwestern side of the model area. The region is a structural low in the Ocala Limestone that has been filled with Miocene and Pleistocene siliciclastics (Rupert, 1988) that are thought to have low permeability resulting in the presence of wetlands and lakes during periods of high precipitation. The largest of these surface water bodies are Waters Lake, Watermelon Pond, and Cow Creek are known to drain after floods through restrictive swallets.

Recharge

Aquifer recharge in the SFRB occurs through diffusive infiltration through the sediments covering the limestones that comprise the FAS and through swallets that deliver runoff and stream flow directly into the aquifer. Swallet-spring connections are most readily marked by tea-colored discharge during high flow periods. Inflow rates through the swallets are determined by the size of the connecting conduits and can be inferred by the magnitude of water level fluctuations in the swallet basins and their drainage rates. Table 1 provides a list of the major swallets in the basin and an estimate of their drainage area and inflow rates.

Discharge

Springs constitute the primary form and locations of groundwater discharge in the model area. Many of these springs are known to discharge a combination of older groundwater and very recent recharge occurring through swallets in the rivers and streams in the region (Kincaid, 1999). Springs that primarily discharge older groundwater are characterized by consistent clear water discharge whereas those that primarily discharge recent recharge from swallets are characterized by flashy discharge of tea colored water. Those that discharge a mix of the two waters tend to be marked by clear water discharge during low rainfall periods and progressively darker water discharge during high rainfall periods. Classifying the springs in terms of the type of discharge and estimating the range in mixing is important to effective model calibration. Table 2 lists the major springs in the basin that were specifically included in the model along with their maximum-recorded discharge and primary discharge type.

Table 1. Characteristics of Modeled Swallets

Swallet	Drainage Area (km^2)	Inflow Rate (m^3/sec)
Rose Creek Complex		
Alligator Lake	24	0.8
Rose Sink	70	2.8
Clay Hole Sinks	67	2.8
San Felasco Complex		
Mill Sink	36	2.8
Lee Sink	32	0.4
Burnetts Lake	28	0.6
Turkey Creek	32	0.4
Blues Creek	20	0.4

Table 2. Characteristics of Modeled Springs

Spring	Discharge Type	Max Discharge (m^3/sec)	Modeled Discharge (m^3/sec)
Dogwood	GW	0.6	0.5
Gilchrist Blue	GW	2.3	2.9
Ginnie	GW	1.6	1.7
Hornsby	SW	10.0	9.6
Ichetucknee Group (6 springs)	Mixed	5.4	4.9
Lilly	Mixed	1.1	1.3
Poe	Mixed	1.4	1.3
July	Mixed	3.3	2.6
Santa Fe River Rise	SW	12.5	12.4
Twin	GW	0.6	0.6

Saturated Caves

The SFRB contains numerous saturated caves that collect and deliver groundwater from swallets and the aquifer matrix to springs. Several of these caves have been mapped and can therefore be classified by their pattern and the primary source of recharge (Palmer, 1991). Caves that receive water primarily from the aquifer matrix (autogenic recharge) consistently deliver crystal clear water to the springs at a relatively constant rate. They tend to be smaller in diameter and trend up-gradient into the aquifer from the springs to which they connect in a dendritic or braided pattern. Caves that primarily receive water from sinking streams (allogenic recharge) on the other hand carry water of varying clarity at highly variable flow rates. They tend to be larger in diameter, longer, and connect springs to one or more swallets and sinkholes in a dendritic pattern. A third type of system that was not described by Palmer (1991) includes caves that have developed parallel or sub-parallel to the Santa Fe River and circulate water between springs and siphons in the river channel. Table 3 lists the six cave systems that were included in the model and denotes their classification.

Table 3. Characteristics of Modeled Caves

Cave	Type	Length (m)
Old Bellamy	Allogenic	15,387
Devil's Ear	River	7,179
Hornsby	Allogenic	5,680
Rose Sink	Allogenic	1,299
Mill Creek	Autogenic	1,115
Ginnie	Autogenic	348

MODEL SETUP

Approach

Conduit flowpaths were simulated by using the 1D discrete feature elements of the finite-element code FEFLOW(Wasy, 2008). FEFLOW provides 1D discrete feature elements which can be mixed with the porous matrix elements in three dimensional models. Three different laws of fluid motion can be defined within the discrete features, Darcy, Hagen-Poiseuille, or Manning-Strickler laws. We used the Manning-Strickler formulation because all conduit flow in the model area is best represented as fully-saturated channel flow.

In this model, the upgradient end of most discrete features are connected to a known surficial recharge point, such as a sinkhole or a lake. The downgradient end of each discrete feature is connected to known springs (Figure 1). The recharge and discharge points are represented by constant head boundaries. Wherever possible, head assignments for springs, lakes and sinkholes were determined based on stage measurements (SRWMD, 2008). Where such data was not available, head assignments for springs and sinkholes were estimated from topographic maps.

Conduit Assignments

The discrete conduit features were assigned along pathways determined by a combination of three data sources. Whenever possible, the discrete feature follows the mapped course of a known conduit based on cave surveys performed by divers. Cave maps were available for all of the caves listed in Table 3 but the maps did not cover the full extent of the probable conduit flow paths and maps were not available for several other highly probable conduit pathways.

In those cases, conduit flow paths were assigned such that swallets connected to the nearest down-gradient springs following troughs indentified in a potentiometric surface map constructed from water levels reported for a high-water synoptic period that could not be explained by groundwater withdrawals or vertical leakance. This method for conduit assignment was supported by groundwater tracing and geochemical studies performed in the region (Butt et al, 2006; Butt and Murphy, 2003). Butt, et al. (2006) confirmed a connection between Mill Creek and Lee Sinks and Hornsby Spring. Butt and

Murphy (2003) confirmed a connection between Rose Creek and Clay Hole Creek and several springs along the headwaters of the Ichetucknee River. In both studies, the average travel rate was approximately 500 m/d. This was assumed to be the maximum conduit flow rate in the study region as these dye-traces connected the regions largest sinkholes with the regions largest springs.

The Manning-Strickler discrete feature requires the assignment of two parameter values, a conduit area and a roughness coefficient. Knowing the desired discharge rate at each spring (Q) from flow measurements, and assuming a maximum conduit velocity (V), the area (A) of each discrete feature can be calculated, A=Q/V. Estimating the slope of the water in the conduit from potentiometric maps allows for a close initial estimate of the required roughness coefficient using the equation:

$$V = (k/n)(A/P)^{2/3}S^{1/2}$$

where P is wetted perimeter, S is slope, k is a unit conversion parameter, and n is the manning number. The final value for n was determined through model calibration.

This approach allows the model to address important hydrologic features on a scale of less than 10 m to several kilometers. Initial settings for conduit diameter and roughness were based on reports and descriptions from the cave explorers. They were then through the model calibration process varied to account for a more realistic description of the main conduits and a halo of high permeability surrounding the conduits due to intensified karstification. This method allowed us to more realistically simulate the influence of conduits on the surrounding aquifer matrix.

Our conceptual model for assigning conduit parameters can be described as a “Conduit Tree”. We assumed that flow near discharge points occurs mainly within large conduits with limited halo flow. Up-gradient from the discharge point, large single conduit flow paths morph into a system of interconnected smaller conduits. In the flow model, these smaller conduit systems are still represented as a single discrete feature with a cross-sectional area equal to that of the larger conduit down-gradient, but the assigned roughness coefficient increases due to more surface area along the flow path. If a conduit is fed by two or more tributary conduits, the area of the tributary conduits summed to that of the single conduit down-gradient from the split. The size of tributary conduits was determined through calibration to head measurements near the assigned conduit.

Model Construction

The model was designed as a four layer, three dimension flow model. The upper layer represents a discontinuous surficial sand aquifer, the second layer represents a sand and clay confining unit, and the lower two layers represent the FAS. The upper two layers defined the region between land surface and the top of the FAS. Land surface elevations were imported directly into the model from USGS 7.5 minute digital elevation models with a 30 m grid spacing. The elevation of the top of the confining unit was interpolated from 176 borehole logs and geologic maps covering the study region. The FAS was split into two layers to accommodate an internal slice to which the discrete feature conduits were assigned. The elevation of the top of the FAS was interpolated from 476 borehole logs located in the ten counties surrounding the study area. The elevation of the conduit slice was estimated at 15 m below msl from conduit depth measurements taken by divers (Figure 2).

The focus of this study was to model flow through the FAS. In addition, calibration data for the surficial aquifer and confining unit were severely limited. Therefore, hydraulic conductivities assigned in the upper two layers were taken from literature values given for the material types present. Materials in the upper two layers were assumed to be isotropic. The sands in the upper most layer were defined as coarse, medium, or fine grained based on GIS soil coverages (SSURGO, 2006) and were assigned hydraulic conductivity values of 43 m/d, 17 m/d, and 0.02 m/d respectively. Sand and clay mixtures in layer two were assigned a hydraulic conductivity of 0.004 m/d. Clays in layer two were assigned a hydraulic conductivity of 0.0004 m/d.

Model boundaries were chosen such that they incorporated the probable extent of the catchment zones for all of the major SFR springs but not so broad as to include the catchments of the neighboring Suwannee River or the capture zone for the City of Gainesville municipal supply wells. Boundary conditions along all external boundaries, except for the Bell Ridge / Wacasasa Flats divide, were set as constant head with head values defined by measurements in boundary wells and linearly interpolated between these wells. The Bell Ridge / Wacasasa Flats divide was assigned as a no-flow boundary.

Sinking streams, lakes, and wetlands were assumed to be in full contact with the surficial aquifer. Based on this assumption, these hydrologic features were assigned as internal constant head boundaries in the upper most layer. The Santa Fe and Ichetucknee Rivers, Cow Creek, and all springs and sinkholes were assumed to be in full contact with the FAS. These hydrologic features were assigned as internal constant head boundaries in layer three. Head values assigned to the Santa Fe and Ichetucknee Rivers and selected springs, sinkholes, and lakes were determined from stage measurements. All other head assignments were estimated from topographic maps.

RESULTS AND DISCUSSION

Calibration

The flow model was calibrated to 124 head measurements made across the model region (Figure 3). All of the head values used for calibration were measured during the relative high-water period of May, 2005. The drought that persisted throughout most of 2003 and 2004 ended in September 2004 with the arrival of hurricane Frances which dropped over 20 inches of rain over the month. While precipitation was average during January and February 2005, above average precipitation fell on the model region during March, April, and May. A high-water period was chosen for calibration as it was assumed that the effect of the conduits on the potentiometric surface would be most prominent when the aquifer was at maximum conveyance. Using a high-water scenario also allowed for the assumption that all sinking streams in the model area were flowing and that all springs were at or near maximum measured discharge.

Calibration to measured head was performed through an iterative process of changing matrix conductivity and location of conduit flowpaths within the matrix. The aquifer matrix was allowed to have four conductivity zones. Low matrix conductivity was assumed to exist under the Central Highlands regions reasoning that the aquifer would have been protected from karstification by the confining unit. A second low conductivity zone was assumed to exist under the Bell Ridge / Wacasassa Flats region due to the presence of siliciclastics and the possible difference in depositional history in this region.

The unconfined region of the FAS was assumed to be a high conductivity zone as this region contains several known conduit systems and displays a high number of surface karsts features. The unconfined region south of the Santa Fe River was allowed to be calibrated independently of the unconfined region north of the Santa Fe River because the regions differed with respect to overlying material. The limestone of the southern unconfined region is exposed at the surface or covered by less than ten feet of sand, while the limestone of the northern unconfined region is consistently overlaid by a thick layer of sand reaching a thickness of greater than 40 feet in many places.

The assumption was that the thick northern sands may have retarded karstification and led to silicification and void filling in the FAS. Target calibration values were to be within +/- 0.84m of measured values, a value representing an acceptable error of 5% of the total head change within the FAS in the model area (5.3 to 22.0 m).

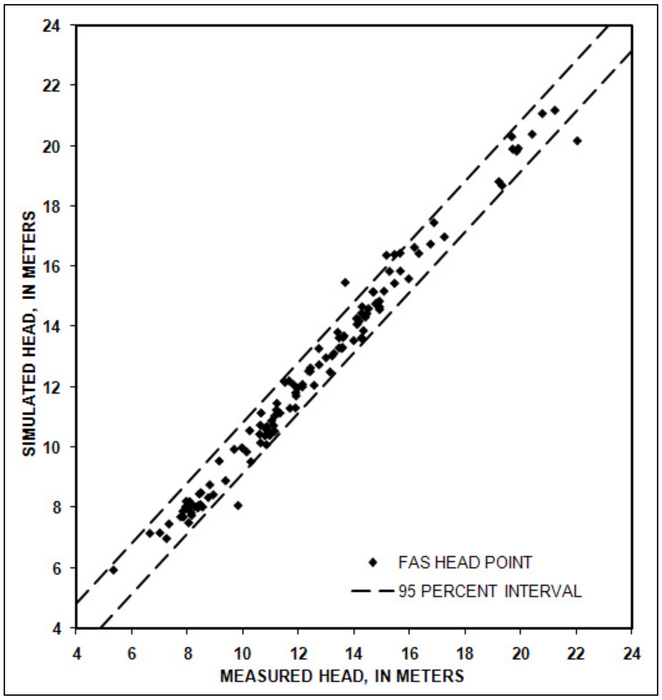

Figure 3. Model Calibration: Simulated vs. Measured Head in the Floridan Aquifer.

Table 4. FAS Conductivities

Calibration Zone	Horizontal Hydraulic Conductivity (m/day)
Confined Region: Central Highlands	4
Unconfined Region: North	170
Unconfined Region: South	690
Wacasassa Flats	4

Figure 3 shows that in the final model configuration, the modeled head at all but five well locations fell within our target calibration range. The final horizontal hydraulic conductivity for the four conductivity zones is listed in Table 4. Vertical hydraulic conductivity was assumed to be uniform across the model region equal to the lowest calibrated horizontal conductivity value. All assigned conductivity values fall within literature values reported for karst limestones.

The model was also calibrated to discharge at 15 first and second magnitude springs throughout the region. Target discharge flux was equal to the maximum recorded discharge at each spring. Table 2 shows a comparison between modeled and measured spring discharge. Spring discharge was calibrated by changing conduit cross-sectional area and roughness coefficient parameters. In some regions near the Santa Fe River, assigned conduit areas were larger than estimates made by divers. This was allowed because we assumed that flow not only occurs within the large divable conduits, but also within a halo of smaller fractures and conduits surrounding the main pathway.

Simulated Karstic Flow Paths

Once the model was acceptably calibrated, it was seeded with a uniform grid of "initiation points". Using the particle tracking feature in FEFLOW, flow paths starting at each initiation point were exported (Figure 4). The exported pathline field allowed for delineation of springsheds and pumping well catchment areas. The effectiveness of combining discrete conduit features into the porous media can be readily seen in the pathline export as most flowpaths starting in the matrix material converge onto a conduit before finally discharging at a spring. Furthermore, the flow pathlines can be exported with isochrone markers at assigned time intervals so that travel times for flow from anywhere in the basin to a spring discharge can be estimated.

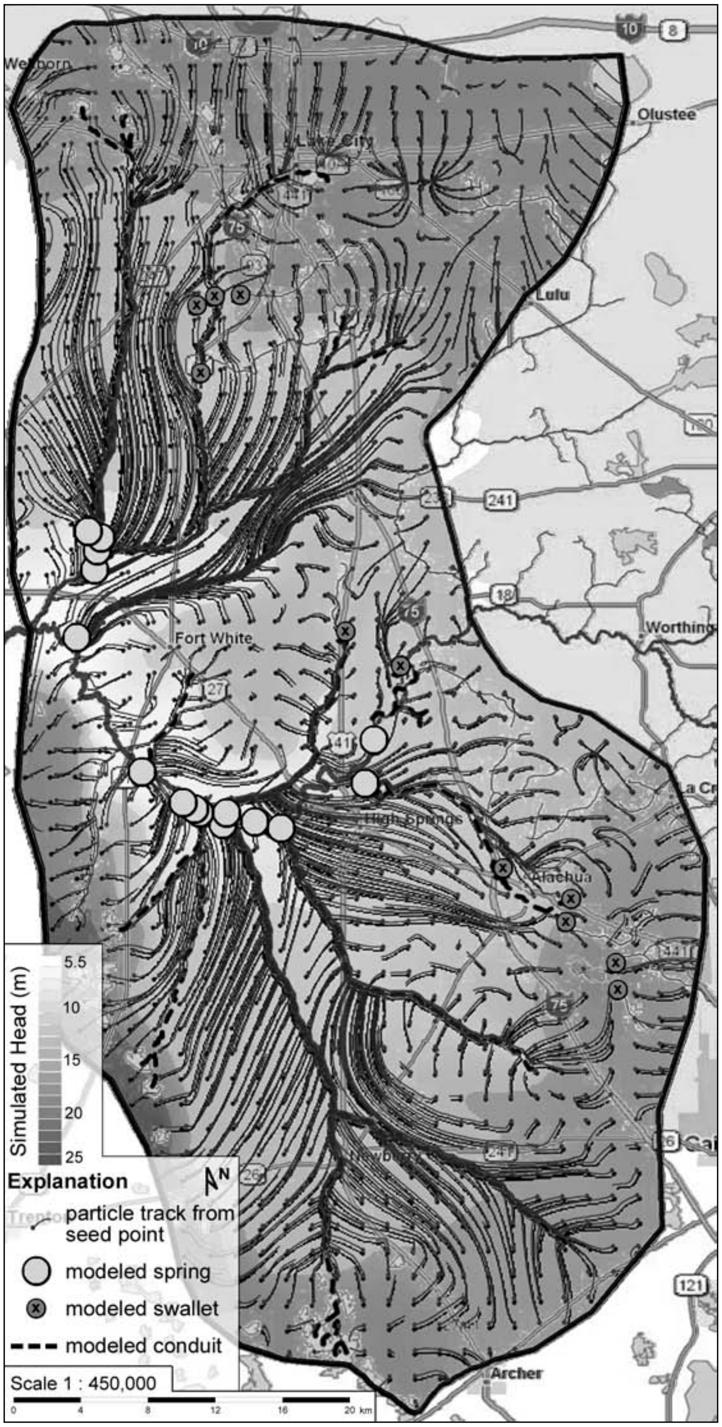

Figure 4. Simulated conduit-controlled groundwater flow patterns.

CONCLUSIONS

This paper presents a method of numerically modeling the complexities of groundwater flow through a karst aquifer by assigning discrete features representing conduit flow into a porous media flow model. This method produces an accurate simulation of flow through karst where matrix flow converges onto preferential flowpaths (conduits) before arriving at discharge points (springs). The advantages of this method are that catchment areas for individual springs or spring groups can be delineated and travel times to discharge can be calculated. This method provides a powerful tool for water resource managers tasked with protecting the quality and quantity of water in a karst environment. Areas leading to rapid transport to springs can de identified for zoning purposes, response scenarios for contamination events can be run, and impacts resulting from increased use on minimum flows and levels can be analyzed.

The confidence of the results derived from the method presented in this paper is dependent on the amount of hydraulic data available for model construction and calibration. Based on our work and the degree to which we were able to calibrate our model to heads, discharges, and observed conduit flow velocities, we believe that the value of hydraulic data (head and discharge) far exceeds that of geologic delineations (lineament analyses, geophysical maps, etc). Furthermore, where this data is lacking, it is critical to include reasoned estimates of individual spring discharges and swallet inflow rates. Omitting that data and/or estimates of those values will lead to a dramatically different depiction of groundwater flow patterns and velocities. Hopefully, the detail and effective calibration achieved in this modeling effort will help renew interest in or affirm the need for collecting relatively easy to obtain hydraulic data, such as stage and flow for rivers, springs, and sinkholes and aquifer water levels.

REFERENCES

Butt, P. L., S. Boyes and T. L. Morris. 2006. Mill Creek and Lee Sinks Dye Trace Alachua County, Florida July-December, 2005. Alachua County Environmental Protection Department.

Butt, P. L. and G. J. Murphy. 2003. Dyal and Black Sinks Dye Trace Columbia County, Florida May-September, 2003. Florida Department of Environmental Protection.

Kincaid, T.R. 1998. Rapid River Water Intrusion to the Unconfined Floridan Aquifer, Environmental & Engineering Geoscience, vol. 4, no. 3, College Station, Texas.

Meyer, F. W. 1962. Reconnaissance of the Geology and Ground-Water Resources of Columbia County, Florida Geological Survey Report of Investigation 30.

Palmer, A. N. 1991. Origin and morphology of limestone caves, Geological society of America Bulletin, vol. 103, no. 1, pp. 1-21.

Rupert, F. R. 1988. The Geology and Geomorphology of Gilchrist County, Florida. Florida Geological Survey Open File Report 18.

SRWMD. 2008. Suwannee River Water Management District. www.srwmd.state.fl.us/.

SSURGO. 2006. Soil Survey Geographic Database. U.S. Department of Agriculture, Natural Resources Conservation Service. Available at http://soils.usda.gov.

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

Wasy. 2008. FEFLOW 5.3 Software. Details at http://www. wasy.de.

Williams, K. E., D. Nicol and A. F. Randazzo. 1977. The Geology of the Western Part of Alachua County, Florida. Florida Geological Survey Report of Investigation 85.