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CONDUIT MORPHOLOGY AND HYDRODYNAMICS OF THE FLORIDAN AQUIFER: MOVING TO THE NEXT LEVEL—CONDUIT MODELING

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For most of the 20th Century, karst research was been driven by arguments about the position of cave development relative to the water table. Three major models were devised in which cave development occurred 1) above the water table (Vadose Theory), 2) at the water table (Water Table Theory) or 3) below the water table (Phreatic Theory). (In fact, caves develop in all three settings, depending on the hydrogeologic setting.) Hydrodynamics of conduit flow and contaminant transport dynamics through conduit networks has received scant attention as evidenced by the fact that no dual permeability models exist for cavernous aquifers. Karst hydrogeologists have been commonly heard saying, "You can't predict what happens in karst terrain because you don't know where the caves go!" This translates to most funding providers as, "Don't listen to me. I don't know what is going on." In the absence of useful results from karst hydrogeologists, hydrologic modelers resorted to applying diffuse flow equations to cavernous aquifers saying, "... at the scale of a coarse mesh digital model (with grid-block spacing of 5-10 km or more), flow in the karst springs area realistically can be treated as porous-media flow." This nonsensical statement claims that first-magnitude (>2.8 m^3/S or >100 ft^3/S average discharge) karst spring basins can be "realistically" modeled with fewer than four points. Even more disturbing is the fact that transmissivity values used to balance the water input and output are so high that they can not exist in granular media, even if the Floridan Aquifer was made of bowling balls! Such models should be immediately recognized as intellectually dishonest. They predict contaminant transport velocities that are too fast for the matrix and too slow for the conduit networks. Both permeability components are poorly modeled and accurate contaminant migration predictions are impossible.

The problem always comes back to, "We don't known where the caves go." Conduit networks require discrete models. That is, one must have some definite idea of how much cave is present; how big the caves are; where the caves go; how fast water flows through the caves; and how rapidly contaminants are diluted by conveyance through conduit networks. These are the things that hydrologists, regulators and water managers want to know about caves. How can we, the karst hydrological community, provide answers?

Understanding conduit morphology and hydrodynamics of the Floridan Aquifer involves unlearning nearly all of the classic precepts of karst hydrogeology. The Floridan Aquifer is composed of carbonate rocks of Tertiary Age and is typically about 180-460 m (600-1,500 feet) thick. It underlies the entire Florida Platform and extends northward into southern Georgia and South Carolina. This aquifer exists on a tectonically stable platform. It has never been deeply buried and is poorly cemented. Effective porosity in calcarenite units is high. Topographic relief is low and the water table is high. Nearly all of the aquifer occurs beneath the water table. Over the last 1.5 million years, during multiple glacial and interglacial stages, sea level stands have ranged from about 60 m (200 feet) above current sea level to at least 130 m (420 feet) below. Yet the width of the platform allows the coastline to shift laterally by distances commonly ranging from about 40-125 km (60-200 miles). These fluctuations make it difficult to distinguish under what conditions various caves developed and what their original hydrologic functions were. Yet it is obvious is that the Floridan Aquifer contains abundant caves and these convey the majority of ground water to a few, isolated groups of cave springs. About 76% of the spring discharge occurs through 9% of the known springs. The Floridan Aquifer supplies abundant water for irrigation, about 50% of the drinking water used by residents of the state of Florida and springs discharge about 41.6 million m^3/day (11 billion gallons/day) for sustenance of riparian and estuarine habitats. The aquifer is overlain by a nearly ubiquitous blanket of sand that serves to moderate stormwater recharge. This causes nearly steady-state flow conditions such that the large cave springs have maximum/minimum discharge ratios that are usually less than 10, unlike cave springs in mid-continent fluviokarst terrains where flashy discharge (Q_{max}/Q_{min} > 10,000) is normal. The nearly steady-state, perpetually pipe-full flow conditions, abundant well logs and exploration of underwater caves by divers, makes the Floridan Aquifer one of the easiest to study and an especially fine example of a cavernous carbonate aquifer where conduit modeling and dual permeability hydrologic modeling could be performed successfully.

Laboratory tests of core samples show that the Floridan Aquifer commonly has about 17% effective porosity. This high effective porosity has not prevented cave development but it does contribute to the importance of the diffuse flow component of the aquifer. Horizontal and vertical hydraulic permeability is typically about 0.3 Darcys (6-4 gpd/ft^2), respectively, which is slightly less than for very fine sand. Seepage of ground water through conduit walls will occur at a rate that not less than provided by these permeabilities.

Transmissivities, based on pump tests, commonly range from about 100,000 to over 4,000,000 to gpd/ft, which, as noted above, are so high that they cannot exist in granular media. These very high transmissivities are usually explained as the "average" between laminar flow in the matrix of the bedrock and turbulent flow through conduits. Regardless of the ability of these values to make the inputs and outputs match, their use also leads to estimates of ground water velocities that are too fast for the matrix and too slow for the conduits. Essentially, velocities in both permeability components are poorly modeled using diffuse flow equations. Contaminant transport estimates will be wrong by about 1.5-2 orders of magnitude in both the matrix and the conduits. Integrated diffuse/conduit flow models have not been developed because discrete models of the conduit network are commonly, regarded as impossible to formulate. Can conduit network morphology be predicted in the Floridan Aquifer without first exploring and mapping the entire network? The following sections describe various types of commonly available data that can be used to characterized the conduit networks.

Groups of up to 400 wells in Polk, Orange, Marion and Madison Counties, Florida, show that caves, more than 0.3 m (1 foot) high, are commonly intercepted. The probability of intercepting a cave is commonly about 25% per 30 m (100 feet) of drilling, and rises to about 50% in some zones in Orange County. Caves are most common in zones ranging from about 122 m (400 feet) below sea level in Orange County to 213 m (700 feet) deep in Polk County. The increase in cave abundance with depth contradicts results in most other karst areas. Turbulent flow is often noted in caves more than 100 m (300 feet) below the water table, and has been observed directly by divers and tested by quantitative dye tracing.

Cave porosity in the Floridan Aquifer ranges from a minimum of 0.5% in Polk County where the aquifer is thickly mantled to as much as 16% in certain restricted zones or areas, such as the Madison County (Florida) Landfill Superfund Site. Floridan Aquifer cave porosities commonly range from about 2.5-6% based on analysis of logs for groups of wells in Orange County and Marion County.

In the Floridan Aquifer, the reported heights of caves intercepted by wells ranges from less than 0.3 m (1 foot) to at least 27.4 m (90 feet) and the reported heights have the expected J-shaped distribution, in which small caves are more abundant than large ones. The median height of 128 cavities, intercepted by 400 wells in Polk County was 4 feet, and the geometric mean was 0.76 m (2.5 feet). The intercepted cave height obviously is not necessarily the true (maximum) cave height, but the average intercepted cave height can be estimated by analysis of height/width ratios measured in underwater caves.

Fifteen mapped underwater caves (34 km or 21 miles of passage) in Florida have provided 339 height/width ratios for humanly traversable conduits. These surveyed caves can be characterized as tubes having elliptical cross-sections. The geometric mean height/width ratio is 0.32 indicating that most caves are about three times wider than they are high. Only 8% of all mapped underwater caves are taller than they are wide. It can be shown by simple geometry that conduits having elliptical cross-sections have a maximum height that is 1.27 times the average intercepted height. Applying this result allows the intercepted cave heights to be adjusted and indicates that in Polk County, Florida, the geometric mean cave is about 0.98 m (3.2 feet) high, 2.9 m (9.4 feet) wide and has a cross sectional area of about 2.19 m^2 (23.6 ft^2). This provides a basis for using cave height data from wells as a sample of conduit size distribution. Conduit height/width data strongly indicate that caves form along bedding planes. They are not necessarily fracture or joint controlled. Therefore, contrary to popular opinion, mapping photo lineaments is not an effective way of identifying cavernous flow paths in the Floridan Aquifer.

Most mapped underwater caves in Florida have anastomotic patterns. Peacock Springs and Devil's Eye are examples of anastomotic patterns. Some crude branchwork patterns, such as Madison Blue Spring and Lafayette Blue Spring, are also known. Many springs, even large ones such as Wakulla Spring, serve as tap-offs for flow that partially bypasses the spring and emerges further downstream at a more distant spring. Distributary spring systems appear to be common.

Cave maps are particularly valuable for determining the orientation of cave passages and conduit cross-sectional dimensions. For example, in the Ichetucknee Spring drainage basin, Columbia County, Florida, 139 mapped cave passage segments had a bimodal distribution with a primary mode of N 72° W and secondary mode of N 9° E. The primary mode is nearly perpendicular to the nearly north-south slope of the water table. Caves need not necessarily convey flow in a direction parallel to the potentiometric gradient. The frictional resistance in a conduit is so low that caves may convey turbulent flow even if they have a gradient that is only a small fraction of the maximum.

Cave density in the Floridan Aquifer, in the north half of the Floridan Peninsula, can be estimated as not less than 1,638 km/km^3 (4,224 $miles/mi^3$), which is very high, yet it might be much higher is some zones or areas. If distributed uniformly, then the average distance between cave passages would be about 100 m (327 feet) both horizontally and vertically. Obviously not all of these passages can be conveying water that is flowing fast enough to be in the turbulent flow regime. Most of these conduits have probably been abandoned by fast flowing water. They are collapsed or plugged by sediment. Analysis of cave lengths for 223 surveyed caves in the Florida Peninsula shows that the median cave length is 38 m (125 feet). This is probably a reasonable measure of typical abandoned cave segment length.

Steve Worthington has compiled extensive data about the average velocity of ground water flow through caves as determined from quantitative dye traces. He and his co-authors have shown that the global average velocity of ground water in caves ranges typically from about 0.2-20 cm/S and the median velocity is about 2 cm/S. Data for 22 dye traces and in situ water velocity measurements in caves in northern Florida is essentially the same as the reported global average. The similarity of velocities is the result of a general reduction in potentiometric gradients caused by the development of caves, which then tend to dewater the host aquifer. Gradients in Florida are usually 0.00019-0.0019 (1-10 feet/mile) and the average gradient along the west coast of the peninsula is about 0.00047 (2.5 feet/mile) based on measurements from potentiometric surface maps.

Flow through conduits can be modeled using the Darcy-Weisbach equation, or other similar equations. The primary difficulty in using conduit flow equations has been the friction factor (f). Hydrodynamic textbooks commonly recommend an "f" value of 0.1 for concrete pipes that might have a similar roughness value as natural conduits in carbonate rocks. This value is far too low to account for all friction losses, most of which occur at a few isolated constrictions or collapses in the conduit network. Other researchers have estimated total apparent friction factors for conduit networks ranging from 24 to 340. This range also appears to apply to caves in the Floridan Aquifer, although only three systems have been analyzed so far. Based on a limited number of analyses, the global median and the median for the Floridan Aquifer both appear to be about 100. Application of this value to hydrodynamic analysis shows that the median velocity (2 cm/S) can supply about 28 m^3/S (1,000 ft^3/S) through a 30-m (100-ft) diameter conduit at a gradient of 0.00019 (1 ft/mile). This hydrodynamic result seems consistent with results of cave exploration. Conduits larger than 100 feet wide and springs larger than 28 m^3/S (1,000 ft^3/S) are very rare in Florida under existing potentiometric gradients.

Ground water discharging from many north Florida cave springs is noted for its great clarity. Such clear water often represents diffuse recharge from the surficial sand. Under these conditions, the surface area of the cave wall must be large enough to allow infiltration of ground water to the conduit network that is equal to the discharge at the spring. The surface area of the cave cannot be less than equal to average spring discharge divided by the laboratory permeability times the average hydrologic gradient. Gradients can be determined from wells. Seepage through the walls of many caves in the Floridan Aquifer is probably not less than that for medium sand or about 260 Darcys. Any applicable permeability value may be substituted into this calculation.

If the drainage area of a cave spring is known, and if the average velocity of ground water being conveyed through the conduit network is known (from dye tracing), then it is possible to estimate the total volume of the cave, which must be equal to the volume of water that is in transit at any one time in the system. Total cave volume is equal to discharge times the average transit time. For example, consider a 260-km^2 (100-mi^2) drainage area that supplies an average discharge of 28 m^3/S (100 ft^3/S) to a single spring vent. This spring discharge can be maintained if the average recharge is about 356 mm/yr (14 inches/yr), which is completely reasonable for many karst terrains in Florida. (Other drainage basins may have different recharge rates and active cave densities.) For simplicity, assume that the basin has the shape of a quarter circle and the spring is located at the apex of the quarter circle. The average flow distance to the spring is 12.8 km (7.98 miles) and the average flow velocity is 2 cm/S. Therefore the average transit time is about 638,000 seconds (7.4 days) and the total volume of the cave is about 1.8 million m^3 (63.8 million ft^3). If the geometric mean passage cross sectional area is about 2.19 m^2 23.6 ft^2, then the total length of the conduit network is about 824 km (512 miles), which is equivalent to a density of 3.17 km of active cave/km^2 (5.12 miles of active cave/mi^2) of drainage basin. If the conduit network is arranged in a uniform, single plane, rectangular grid (any appropriate geometry may be substituted) the average distance between cave passages is about 700 m (2,300 feet). At this point, a hypothetical, but geologically reasonable, discreet conduit model has been synthesized. The actual cave locations are not known, but the amount of cave present has been reasonably inferred. According to this model, the average distance over which diffuse flow models can be applied is about 350 m (1,150 feet). Beyond this, one must assume that the diffuse flow has been intercepted by an integrated conduit drainage network.

In order to solve for flow, the entire drainage area can be divided into polygons of bedrock matrix that contribute diffuse flow to a horizontal well (conduit segment between passage junctions). Known (surveyed) cave passages could be incorporated into such a model along with known stream sinks. The drainage basin can now be modeled using well-known diffuse flow equations. One level must be added to the model to specify how flow from one conduit segment is connected to the next downstream conduit segment. Flow in the conduit network must be conveyed at reasonable velocities consistent with dye tracing results and other direct observations. This conceptual model, or various modifications and improvements of it, might provide a basis for modeling diffuse flow, conduit flow and surface water interactions in the cavernous Floridan Aquifer. Given that conduit water velocities and gradients fall in a narrow range for the entire world, conduit models developed for the Floridan Aquifer might represent reasonable ranges for conduit systems in other carbonate aquifer.