Geological Society of America
Special Paper 404
2006

Monitoring well responses to karst conduit head fluctuations: Implications for fluid exchange and matrix transmissivity in the Floridan aquifer

Jennifer M. Martin
Elizabeth J. Screaton
Jonathan B. Martin
Department of Geological Sciences, University of Florida, Box 112120, Gainesville, Florida 32611, USA

ABSTRACT

Karst aquifers with high primary-porosity matrix, such as the Floridan aquifer, have the potential for movement of water between conduits and matrix, with important implications for karst development and the maintenance of groundwater quality. The Santa Fe River Sink and River Rise conduit system, along with the surrounding unconfined Floridan aquifer in north-central Florida, provides a study area to test and quantify conceptual models of exchange between conduits and matrix. The Santa Fe River sinks underground and flows for ~5 km before reemerging at a first-magnitude spring, the River Rise. During February and March 2003, we recorded discharge rates into the Santa Fe River Sink and out of the River Rise along with hydraulic heads at the River Sink, River Rise, and matrix monitoring wells. Comparison of conduit and monitoring-well hydraulic heads allowed us to track the changes in hydraulic gradient between conduits and wells as a discharge peak passed through the conduits, and the observed head differences between the wells and conduit show a linear relationship with gains and losses of water from the conduit system. The responses of heads at three of the monitoring wells to changes in head within the conduits suggest a transmissivity between 950 and 160,000 m²/d, and analysis suggests that the values depend on the scale of measurement. These results demonstrate the potential for transmissivity determinations in karst aquifers by passive monitoring and are consistent with previous observations that transmissivity of karst aquifers varies with the scale over which it is measured.

Keywords: karst, aquifer, Floridan, transmissivity.

INTRODUCTION

Hydrologic processes in karst aquifers are clearly important considering that more than a quarter of the world's population lives on, or obtains its water from, karst aquifers. In the United States, ~20% of the land surface is karst and 40% of potable groundwater originates from karst aquifers (Quinlan and Ewers, 1989). Over the past 40 yr, karst hydrologic research has undergone a significant shift. From the initial concept that caves were hydrologically isolated from the flow field, during the 1970s and 1980s, karst hydrology came to signify primarily the hydrologic properties of conduits (White, 2002).

Martin, J.M., Screaton, E.J., and Martin, J.B., 2006, Monitoring well responses to karst conduit head fluctuations: Implications for fluid exchange and matrix transmissivity in the Floridan aquifer, *in* Harmon, R.S., and Wicks, C., eds., Perspectives on karst geomorphology, hydrology, and geochemistry—A tribute volume to Derek C. Ford and William B. White: Geological Society of America Special Paper 404, p. 209–217, doi: 10.1130/2006.2404(17). For permission to copy, contact editing@geosociety.org.

In the last decade, however, researchers have begun to realize that an accurate representation of the hydrologic system must consider conduit, fracture, and matrix flow components and describe the relationship among them (White, 2002).

The heterogeneous distribution of porosity and permeability in karst aquifers requires an understanding of the hydrologic relationship between matrix, fractures, and conduit systems. This is important when protecting and maintaining groundwater quality and, in particular, for determining the susceptibility of karst groundwater resources to surface contaminants. Large subsurface openings, such as conduits, allow surface water to travel long distances in a short amount of time with little or no filtration. When surface runoff containing contaminants flows only through conduits, karst springs will have high-amplitude, but relatively brief, periods of water-quality degradation (Smart and Hobbs, 1986; Ryan and Meiman, 1996). If, on the other hand, contaminated water infiltrates into the surrounding matrix porosity, contaminants may have longer residence times.

In aquifers where sinking streams or injections of stormwater runoff into sinkholes cause large fluctuations in head within the conduit system, exchange of water between conduits, fractures, and matrix should vary with time. When flow into the sinkholes is low, conduits are likely to act as a drain for the surrounding fractures and matrix (White, 1999). During times of high inflow into sinkholes, heads in the conduit system will rise, forcing water into the surrounding fractures and matrix. White (1999) speculated that storm response in wells within and outside of conduits potentially could be used to characterize coupling between the conduits and the matrix or fractures.

An important control on the exchange of water between the matrix and conduits is the hydraulic conductivity of the matrix. The majority of research on karst has been in regions where extensively recrystallized Paleozoic limestones form the matrix, resulting in little to no movement of water within the matrix (White, 1999). In contrast, the relatively young Cenozoic limestones of the Floridan aquifer, and other eogenetic karst aquifers (Vacher and Mylroie, 2002), have high primary porosity, producing hydraulic conductivity in the matrix up to four orders of magnitude greater than in Paleozoic limestones (Palmer, 2002).

Recession curves of karst spring hydrographs, in which the discharge declines with time during periods of no excess precipitation, have been used to estimate aquifer properties (e.g., Atkinson, 1977). Powers and Shevenell (2000) extended spring hydrograph analysis methods to study of recession curves for monitoring wells within karst aquifers. However, analysis of recession limbs to determine aquifer properties requires knowledge of the distance from the discharge point to the groundwater divide, which may be unknown, or, in the case of a conduit system linked to a sinking stream, may vary through time (Powers and Shevenell, 2000). Alternatively, if hydraulic heads through time are measured within the conduit and nearby wells, the aquifer parameters can be estimated based on the well response to changes in head within the conduit.

The Santa Fe River Sink and River Rise conduit system, and the surrounding unconfined Floridan aquifer, provides a study area where conceptual models of groundwater exchange can be tested and quantified. Practical considerations limit us to distinguishing between large conduit flow, as mapped by cave divers or inferred from rapid travel times (Screaton et al., 2004), and matrix flow, which may in reality include intergranular permeability, fractures, and small dissolution features. In this paper, we present the results from monitoring hydraulic head fluctuations in the conduits and matrix, and we compare the head differences between conduit and matrix to calculated rates of gains or losses of water as it flows through the conduit system from the River Sink to River Rise. Head and discharge measurements were also used in combination with analytical modeling to estimate matrix transmissivity and to describe the movement of water between the matrix and conduits.

STUDY AREA

The Santa Fe River Basin is a tributary to the Suwannee River (Fig. 1) and covers an area of ~3583 km^2 in north-central Florida (Hunn and Slack, 1983). Approximately 40 km from its headwaters at Lake Santa Fe, the Santa Fe River sinks and flows underground, reappearing intermittently before reemerging ~5 km from the Santa Fe River Sink at a spring called the Santa Fe River Rise (Fig. 1; Martin and Dean, 2001). This area of the Santa Fe River is within O'Leno and River Rise Preserve State Parks, and serves as the field area for the work presented here (Fig. 1).

Geologic Background

The Floridan aquifer covers an area of ~260,000 km^2, and underlies all of Florida and parts of Georgia, Alabama, and the southernmost part of South Carolina (Bush and Johnston, 1988). In the Santa Fe River Basin, the Floridan aquifer is composed of Oligocene and Eocene carbonate rocks (Fig. 2) that are between 90 and 240 m thick (Hunn and Slack, 1983). The Ocala Limestone is the uppermost unit in the unconfined portion of the Santa Fe River Basin and has an estimated thickness of ~46–76 m (Hisert, 1994). Surficial sediments of Pleistocene and Holocene age, composed of white to gray fine sand, ~3 m thick, cover most bedrock in the Santa Fe Basin. Where present, the Miocene Hawthorn Group, composed primarily of siliciclastic rocks, acts as a confining unit above the Floridan aquifer. The erosional edge of the Hawthorn Formation is known as the Cody Scarp and represents the physical division between the confined and unconfined Floridan aquifer (Fig. 1). To the northeast of the scarp, where the Hawthorn Group is present, the Floridan aquifer is confined, and surface water is abundant. Southwest of the scarp, where the Hawthorn Group has been removed by erosion, the Floridan aquifer is unconfined or semiconfined, and there are few surface streams. Instead, there are numerous karst features, such as sinkholes, springs, and disap-

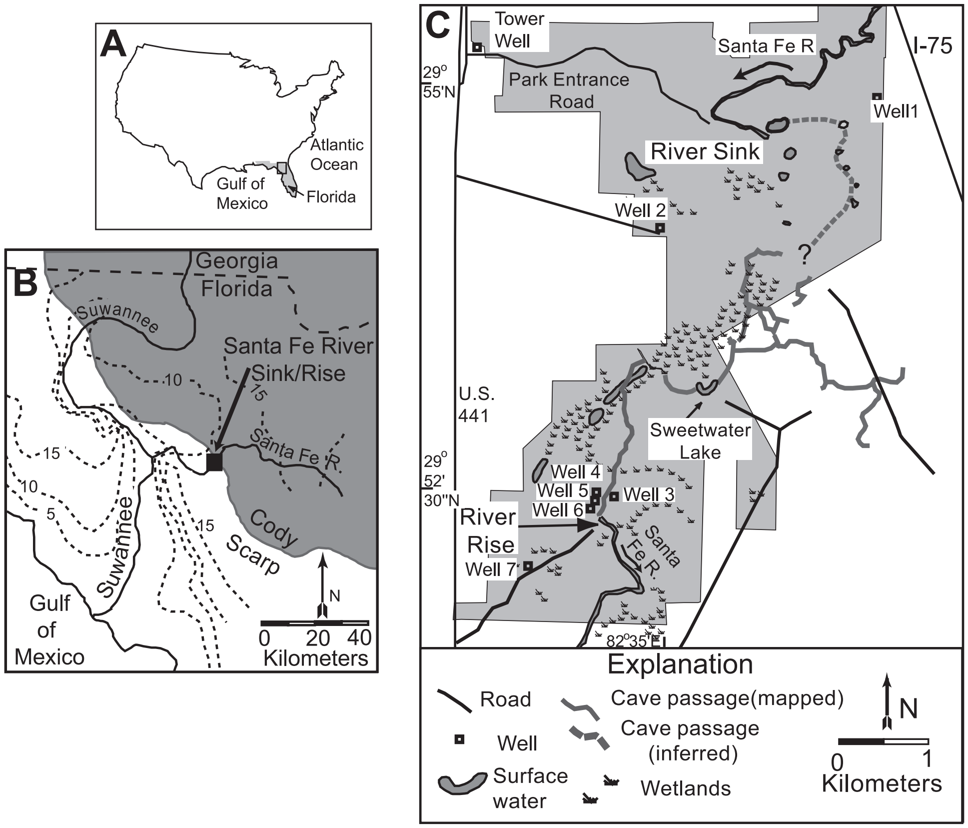

Figure 1. Location and schematic map of the study area. (A) Location of Florida (shaded) within the United States. Box shows location of B. (B) General setting of the Santa Fe River Sink and River Rise. The Cody Scarp marks the erosional boundary of the Miocene Hawthorn Group. West and south of the Cody Scarp, the Hawthorn Group has been eroded away, and the Floridan aquifer is unconfined. Shading north and east of the Cody Scarp indicates the Floridan aquifer is confined. Dashed lines show generalized potentiometric surface contours based on information for May 2002 from the Suwannee River Water Management District. Contour interval is 5 m. (C) Details of the study area including the locations of the Santa Fe River Sink and River Rise, monitoring wells, and mapped and inferred conduits. The shaded area indicates the combined extent of the O'Leno and River Rise Preserve State Parks.

pearing streams. At the edge of the scarp, streams flowing to the southwest either flow into sinkholes, as does the Santa Fe River, or become losing streams. Groundwater flow in the unconfined Floridan aquifer is generally to the Gulf of Mexico and the major rivers and springs (Fig. 1B). An extended drought beginning in 1999 led to very low groundwater levels prior to this study (Fig. 1B).

Previous Investigations in the Santa Fe River Sink and River Rise System

The subsurface conduit system between the Santa Fe River Sink and River Rise has been inferred using natural and introduced tracers, and has also been partially mapped by cave divers. Hisert (1994) used SF_6 as a tracer to connect Santa Fe River Sink and Sweetwater Lake, and, in a second test, to connect Sweetwater Lake and River Rise (Fig. 1). Dean (1999) and Martin and Dean (1999) used temperature as a high-resolution natural tracer and calculated flow rates of 1300–9000 m/d, suggestive of conduits, between the Santa Fe River Sink, Sweetwater Lake, and River Rise. Since 1995, cave divers have explored conduits within the Santa Fe Sink and Rise system (Fig. 1). Upstream of Sweetwater Lake, divers have found connections to surface openings located to the east of O'Leno State Park (Fig. 1). Cave divers have estimated the average dimensions of the passages upstream of River Rise to range in width from 18 to 24 m and in height from 12 to 18 m. Depths of the flow of the conduit typically range from 30 to 40 m below the water table (Poucher, 2001).

In a recent study, Screaton et al. (2004) used temperature signals to connect flow and determine velocities between additional surface-water features, not yet connected by cave divers. Connecting these surface-water features helped to infer a conduit path between the Santa Fe River Sink and Sweetwater

Series	Stratigraphic Unit	Hydrogeologic Unit	Lithologic Description
Holocene Pleistocene	Undifferentiated sediments	Surficial aquifer	Poorly indurated quartz sands with minor amounts of clay.
Pleistocene to Miocene	Alachua Formation	Intermediate aquifer/Upper confining unit	Reddish -white sands with clays, sandy clays, and phosphate pebbles
Middle to Lower Miocene	Hawthorn Group		Phosphatic clayey sand sandy clay with varying amounts of Fullers Earth and carbonate
Oligocene	Suwannee Limestone	Upper Floridan aquifer	Very pale yellow, moderately indurated, porous, fossil-rich calcarenite
Eocene	Ocala Limestone		Very permeable white to yellow bioclastic limestone
	Avon Park Formation	Semi-confining Unit	
	Oldsmar Formation	Lower Floridan aquifer	Dolomitic limestone & dolomite
Late Paleocene	Cedar Keys Formation	Sub-Floridan confining unit	Dolomitic limestone, some evaporites and clay

Figure 2. Lithostratigraphic and hydrostratigraphic units of the Santa Fe Basin based on Hunn and Slack (1983).

Lake (Fig. 1). In addition, Screaton et al. (2004) compared estimated inflow rates of the Santa Fe River into the River Sink with outflow rates from the conduit system, as determined from the discharge of the Santa Fe River immediately downstream of River Rise. Results suggest that the conduit system gains water during times when input into the Santa Fe River Sink is low, and loses water during times of high flow into the Santa Fe River Sink. These results are consistent with previous studies of water chemistry at the River Sink and Rise, which indicated groundwater contributions from the matrix to the conduit system under low-flow conditions (Skirvin, 1962; Martin and Dean, 2001), and chemical changes at a well near the conduit system, which suggested loss of conduit water to the matrix following a flood event (Martin and Dean, 2001). However, Screaton et al. (2004) could not evaluate how gains or losses from the conduits were related to flow out of or into the aquifer matrix because of a lack of monitoring wells outside of the conduits during their investigation.

METHODS

Santa Fe River Sink and River Rise Discharge

Discharge rates of the Santa Fe River entering the River Sink were calculated by converting water levels to discharge using a rating curve developed by the Suwannee River Water Management District (SRWMD, Rating No. 3 for Station Number 02321898, Santa Fe River at O'Leno State Park). River Rise discharge rates were calculated using a relationship between water-level elevations and unpublished discharge data from SRWMD. The rating curve was constructed by Screaton et al. (2004) by plotting recorded discharge measurements for a variety of water levels. Using the best-fit curve of the data points, it was possible to infer discharges for all water levels within the range of measured values.

Monitoring Wells

During early 2003, seven monitoring wells were installed at various distances from mapped or inferred subsurface conduits (Fig. 1). The monitoring wells were constructed of 2-in (0.05 m)-diameter PVC set in a 6-in (0.15 m)-diameter borehole and were ~30 m deep each. Each well had a 20 ft (6.1 m) screened interval. The annular space around the screened interval was filled with sand up to ~1 m above the screened interval. The sand pack was topped with bentonite, and the remaining annular space was filled with grout. Well development was performed by surging the well and pumping out water to remove fines. An existing well, Tower Well, located near the main entrance to O'Leno State Park, was also monitored. The total depth of Tower Well is 26 m, and the casing depth is not known.

Water Levels

Water levels were monitored at the Santa Fe River Sink and River Rise to represent conduit hydraulic heads. Water levels at monitoring wells were assumed to represent hydraulic head in the matrix. Observations during drilling of wells 1 through 7 did not indicate any penetration of large conduits (e.g., there were no significant bit drops). Tower Well was assumed to represent matrix due to its significant distance from any mapped or inferred conduits. As noted already, our categorization of matrix may include thin conduits and fractures as well as intergranular porosity.

Water levels were monitored by one of three types of recording instruments (Global Water WL14 Water Level Logger with an accuracy of ±0.01 m, Van Essen Diver with an accuracy of ±0.005 m, or Van Essen CTD Diver with an accuracy of ±0.03 m) or were measured using an electronic probe. The water-level loggers located at the River Sink and River Rise were installed within 2-in (0.05 m)-diameter, slotted PVC pipes fixed to trees on the shore. The water-level loggers at monitoring wells were attached to the well cap by a plastic-coated stainless steel wire. Water levels were generally recorded at 10 min intervals. Data were downloaded from the loggers every four to five weeks. For each recording interval, water pressures from the Van Essen Divers and CTD Divers were corrected using the ambient barometric pressure recorded by a Van Essen Baro Diver© (with an accuracy of ±0.0045 m) and then referenced to the water elevation surveyed at the time the data were downloaded or measured in the wells.

Reference elevations at the Santa Fe River Sink and River Rise were surveyed by personnel from the Department of Geological Sciences, University of Florida, using a Sokkia Automatic Level Model B21. These surveys were tied to nearby U.S. Army Corp of Engineers bench marks. Temporary bench marks (nails in trees) were established at each monitoring location, and water levels were measured monthly relative to the temporary bench marks. The monitoring wells were surveyed by commercial surveyors.

Water-level discrepancies at the Santa Fe River Sink and River Rise were examined by comparing consistency of recorded values with manual water-level readings taken at the beginning and end of a recording interval. Observed discrepancies were typically <±0.03 m, and likely reflect movement of the logger or instrument drift. Total estimated errors were calculated by summing the observed discrepancies, instrument error, and survey errors, and were estimated to be <±0.07 m and <±0.08 m for the River Sink and River Rise, respectively. Water-level errors at the monitoring wells are expected to be lower than at the karst windows because pressure transducer movement, a suspected source of error at the surface-water sites due to human or natural disturbance of the PVC, is likely to be minimal within the monitoring wells. Summation of survey error, water-level reading error, and instrument error suggests total errors at the monitoring wells of ±0.02 m for manual readings and ±0.03 m for automated readings.

Matrix Transmissivity

Accurate estimates of transmissivity are necessary to predict aquifer response to various hydrologic stresses (Pinder et al., 1969) and can be used to estimate hydraulic conductivity by dividing transmissivity by aquifer thickness. Transmissivity is difficult to determine through pumping tests in karst aquifers due to the very high rates of pumping necessary to create a significant drawdown of the potentiometric surface during aquifer tests. Passive monitoring uses naturally occurring events to determine aquifer properties, and can provide an inexpensive and more representative alternative to pumping tests (Powers and Shevenell, 2000).

Methods have been developed to determine aquifer properties using response to tidal fluctuations (e.g., Ferris, 1963). It has been suggested that these methods could be applied to a single event, such as a storm pulse in a stream (Ferris, 1963). Cooper and Rorabaugh (1963) derived solutions for the change in groundwater head to changes in river stage, approximated by a sinusoidal hydrograph. Pinder et al. (1969) developed a method that expanded analysis of the transmissivity of aquifers surrounding streams to allow use of non-sinusoidal hydrographs. In this study, we apply the method of Pinder et al. (1969) to determine aquifer properties surrounding the Santa Fe River Sink and River Rise conduit system. One difficulty with applying this method to a conduit system is that the exact locations of the conduits are often not known. For the Santa Fe River Sink and River Rise system, conduit pathways have been mapped by cave divers (Fig. 1) and inferred from previous studies of temperature transmission between the River Sink, karst windows, and the River Rise (Martin and Dean, 2001; Screaton et al., 2004). However, additional conduits that have not yet been mapped are likely to exist throughout the region.

The method of Pinder et al. (1969) assumes that the aquifer is homogeneous and of uniform thickness, and that the stream fully penetrates the entire thickness of the aquifer. It should be noted that these assumptions are not strictly met in this analysis. The aquifer is probably heterogeneous, and the conduits and monitoring wells do not penetrate the full thickness of the Floridan aquifer. Estimates of conduit dimensions by cave divers suggest heights ranging from 12 to 18 m, while the total thickness of the Floridan aquifer is estimated to be 90–240 m. Thus, vertical flow effects are likely, especially for wells close to the conduit. The analysis also does not account for head changes at the wells due to diffuse recharge. However, the methods used in this study provide a first approximation of the hydrologic properties of the system.

Because the Floridan aquifer system in the Santa Fe River Basin is not known to be laterally bounded by impermeable materials, an equation for a semi-infinite aquifer was used (Pinder et al., 1969). The input signal, which is the conduit hydraulic head, is broken into increments, and then the incremental change in head is calculated:

$$\Delta h_m = \Delta H_m \operatorname{erfc}\left(\frac{x}{2\sqrt{tT/S}}\right), \quad (1)$$

where Δh_m is the incremental change in head at the well in the mth time step, ΔH_m is the incremental change in head at the conduit in the mth time step, x is the distance between the well and the conduit (m), T is the transmissivity (m^2/d), S is the storativity (dimensionless), erfc is the complementary error function, and t is the time-step size (d). The total change in head at the well at any time is calculated by summing the increments of head change resulting from all prior changes in the input signal.

For the unconfined Floridan aquifer, the appropriate storage parameter (S) would be specific yield. A value of 0.20 was chosen as a reasonable estimate of the storage parameter, based on reported porosity values ranging from 0.1 to 0.45 (Palmer, 2002). Distances from the wells to the conduits were estimated based on the closest mapped or inferred conduit location, and thus should be considered a maximum value.

RESULTS

Santa Fe River Sink and River Rise Discharge

Plotting the flow into the Santa Fe River Sink and the outflow from River Rise (Fig. 3) illustrates the gains or losses from this reach of the conduit system. Prior to 17 November 2002, both the inflow to the Santa Fe River Sink and the outflow from River Rise were negligible due to drought conditions. During most of the study period in which there was flow, the discharge out of Santa Fe River Rise exceeded the flow rate into Santa Fe River Sink. In contrast, the inflow into the Santa Fe River Sink exceeded the discharge out of River Rise during the two time intervals marked by shading on Figure 3.

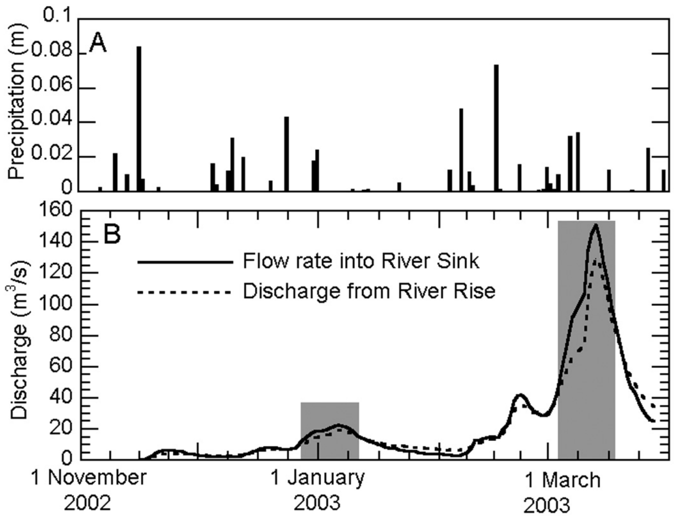

Figure 3. Precipitation and Santa Fe River discharge data for November 2002 to March 2003. (A) Daily precipitation recorded at O'Leno State Park. (B) Inflow rates into Santa Fe River Sink and discharge rates from River Rise. Shaded areas show time intervals when output from the River Rise exceeded input to the River Sink.

Matrix Water Levels

Water levels in monitoring wells and at Santa Fe River Sink are shown in Figure 4. During the monitoring period, there was high inflow into Santa Fe River Sink (Fig. 3), resulting in high water levels, which we compare with the matrix water levels from the monitoring wells (Fig. 4). Water-level fluctuations in the matrix were too large to be explained by diffuse recharge alone. For example, the water level at well 4 fluctuated ~2 m between 8 February 2003 and 17 March 2003, but during this period, total rainfall recorded at O'Leno State Park was only 0.27 m (Fig. 3). The change in head at the wells appears to be transmitted from the conduit system. Furthermore, water-level maxima in the wells lag the water-level maximum in the Santa Fe River Sink. The time lag is a reflection of the distance, transmissivity, and specific yield between the conduit and each well and was used to calculate transmissivity of the Floridan aquifer matrix.

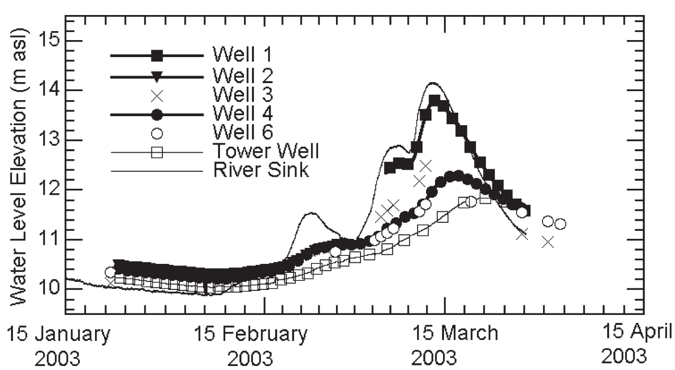

Figure 4. Water levels measured at the River Sink and monitoring wells January to March 2003. Continuous records (every 10 min) were available from Tower Well and well 4. Water levels are reported in m above sea level (asl; 1927 North American Datum). The data record from well 1 is continuous except for missing data between 13 February and 5 March 2003, while the record from well 2 is missing data after 26 February 2003. Wells 3 and 6 have only intermittent probe measurements, and data from well 7 were insufficient to plot. Well 5 installation was not completed until after the storm event.

Transmissivity

Observed hydrographs at Tower Well, well 1, and well 4 were compared to changes in head calculated using the method of Pinder et al. (1969). Transmissivity was adjusted until the calculated curves matched the measured hydrographs (Fig. 5). Matching the curves was done visually. Curve matching could not be performed for well 2 due to lack of data during the peak

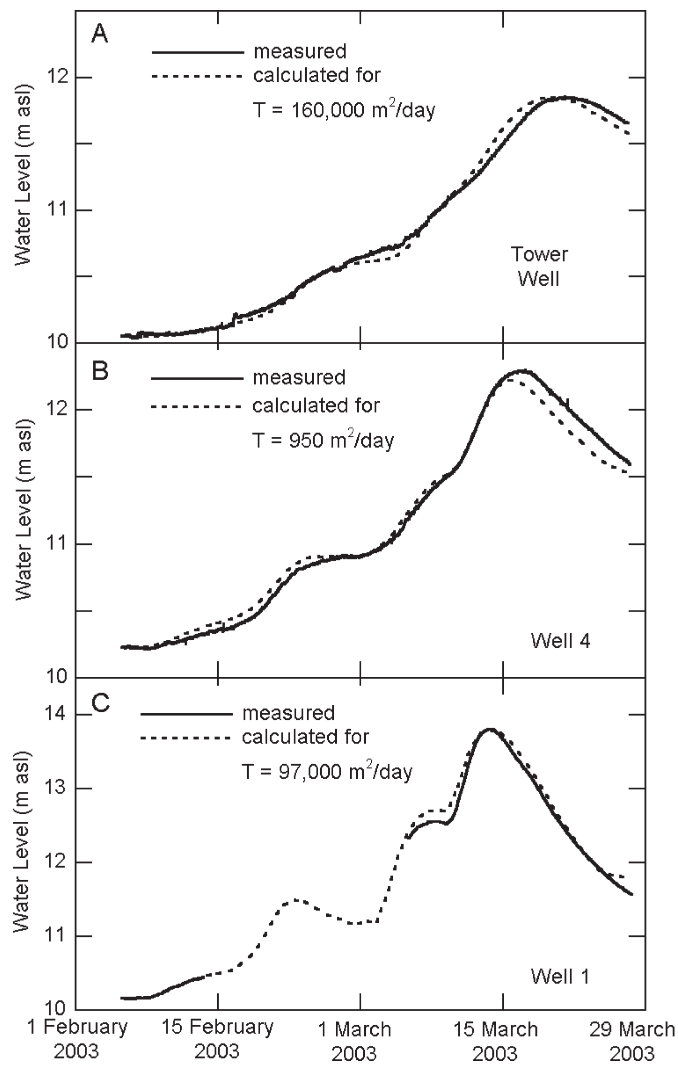

Figure 5. Comparison of measured and calculated water levels for (A) Tower Well, (B) well 4, and (C) well 1. T—transmissivity.

of the storm response. Matching of limited data at wells 3 and 6 suggests that these wells were also responding to conduit head changes (Martin, 2003), but data were too limited to confidently assess transmissivity.

The conduit head during a time step (H_m) was assumed equal to the measured water level at the Santa Fe River Sink for matching of Tower Well and well 1 hydrographs, and to the measured water levels of River Rise for analysis of the well 4 hydrograph. It was assumed that the magnitude of head changes after 6 February 2003 (up to 0.63 m/d) was large enough to disregard any effects of head changes prior to the start of the analysis (<0.01 m/d). Loss of River Sink and River Rise data prevented continuation of the analysis beyond 27 March 2003.

Calculated transmissivity ranged from 950 to 160,000 m^2/d (Table 1). Equation 1 indicates that if higher or lower values of specific yield were used for the curve matching, the optimal transmissivity would change proportionally. Thus, transmissivity may be ~0.5–2 times the calculated values, if specific yield were as low as 0.10 or as high as 0.40. If the actual distance to the nearest conduit is less than the value used to calculate transmissivity, the transmissivity will decrease. For example, if the distance to the nearest conduit were half of the estimated value, optimal transmissivity would be four times smaller than estimated.

DISCUSSION

Transmissivity Values

Averaging numerous small-scale tests of transmissivity in a karst aquifer yields lower values than the results of large-scale tests in the same area (Bradbury and Muldoon, 1990; Rovey and Cherkauer, 1995). This scaling effect stems from the likelihood that large-scale tests will include preferential paths through the matrix, and these preferential pathways will dominate a larger percentage of groundwater flow, thus increasing average transmissivity (Rovey, 1994). In karstic carbonates, such as the Floridan aquifer, transmissivity increases with the amount of dissolution within the aquifer (Rovey, 1994). In addition to the possible effects of the partial penetration of the conduit, scale effects are a likely reason that the transmissivity calculated for well 4 (a distance of 115 m from the conduit) is two orders of magnitude smaller than transmissivity calculated at well 1 and Tower Well, with distances of 475 and 3750 m from the conduit, respectively. At a smaller scale, slug tests performed on wells 3, 4, 5, 6, and 7 yielded transmissivity ranging from 270 m^2/d to 550 m^2/d (Hamilton, 2003, personal commun.), which is lower than that calculated from the storm response for well 4. At a regional scale, Bush and Johnston (1988) estimated a transmissivity of 93,000 m^2/d for the area containing the Santa Fe River Sink and River Rise System, based on calibration of a finite-difference model with a cell size of 165 km^2. This large-scale result is similar in magnitude to transmissivity calculated for well 1 and Tower Well (Table 1) using the method of Pinder et al. (1969).

TABLE 1. TRANSMISSIVITY RESULTS

Monitoring well	Estimated distance from conduit (m)	Transmissivity (m^2/d)
Tower Well	3750	160,000
Well 1	475	97,000
Well 4	115	950

Mixing of Conduit and Matrix Water

Differences between the rate of water entering the Santa Fe River Sink and emerging from the River Rise indicate that water enters or leaves the conduit system along the reach between the River Sink and River Rise (Fig. 3). Although there is a conduit entering the main conduit from the east (Fig. 1) and probably other unmapped conduits, there are no obvious surface-water sources supplying water to these systems. Thus, at low-flow conditions, the conduit system appears be recharged by groundwater from the surrounding matrix. Previous observations of the chemical composition and temperature of River Rise water are consistent with this interpretation (Martin and Dean, 2001). In contrast, when inflow into the Santa Fe River Sink exceeds the outflow from River Rise, the conduit system must be losing water, possibly into the matrix porosity of the surrounding aquifer.

To further explore the relationship between the conduit system and the surrounding aquifer, the difference between inflow into the Santa Fe River Sink and discharge out of River Rise was plotted versus the corresponding head difference between a well and the nearest conduit measuring point (Fig. 6). Tower Well, well 4, and well 1 were analyzed because of the high number of data points collected from each location. Well 2, estimated to be ~1000 m from the conduit system, had less data, but showed similar results. The analyses indicate that when the conduit system gains water, the head measured in the observation wells is higher than within the conduit system. Conversely, when the conduit system loses water, the head measured in the monitoring wells is lower than within the conduit system. Ideally, the best-fit line should cross the origin, which is the point where the conduit is neither gaining nor losing water and the head difference is zero. Summation of the errors of the water-level measurements at the Santa Fe River Sink or River Rise and the wells suggests a total error of ±0.09–0.11 m. Results for wells 1 and 2 appear within the range of errors. Well 4 head is 0.21 m greater than the conduit (Fig. 6B) when there is no net conduit gain or loss, which is slightly larger than the estimated error. Tower Well (Fig. 6A) head is 0.38 less than the conduit when there is no net conduit gain or loss, which is greater than could be attributed to water-level measurement error. One possibility for this discrepancy is that the conduit may not be gaining or losing water uniformly along its length. This explanation could be tested through measurements made at a smaller scale than the current study.

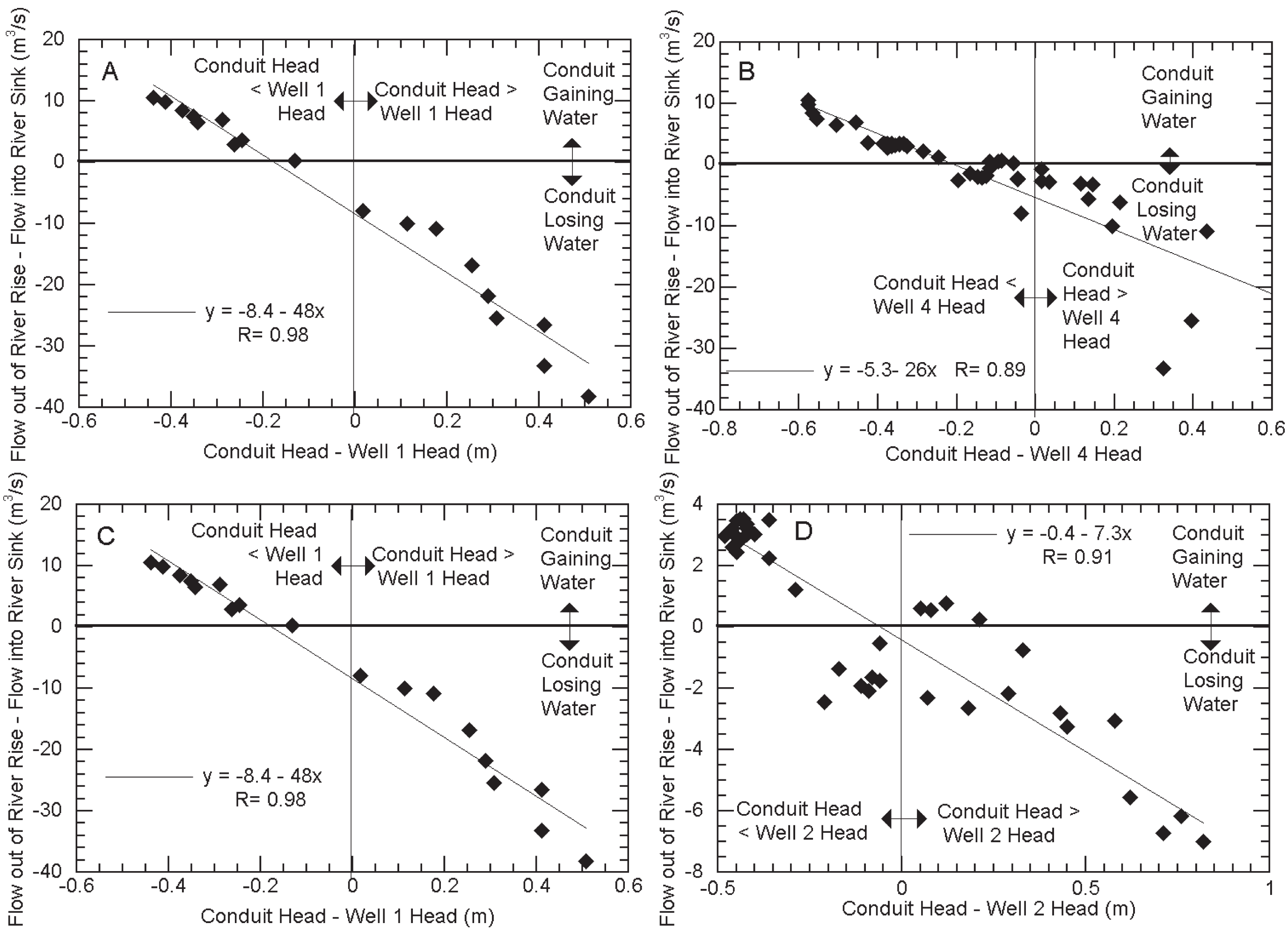

Figure 6. Relationship between change in conduit gains and losses and head differences for (A) Tower Well, (B) well 4, (C) well 1, and (D) well 2.

Although the data show some scatter, the plots also indicate a linear relationship between head differences and the net gain or loss of water from the conduit system for all the wells (Fig. 6), suggesting that flow may be Darcian between the conduits and wells. Further interpretation of the slopes in Figure 6 is limited by not knowing the portion of the total net gain or loss between Santa Fe River Sink and River Rise that is represented by the measurements at each well. Due to heterogeneity, a greater percentage of the net flow into or out of the conduit would be expected in areas of high transmissivity and less inflow or outflow in areas of low transmissivity.

SUMMARY

Karst aquifers are a significant source of drinking water for millions of people, but because of their high permeability and connection to surface-water sources, they are especially vulnerable to contamination by surface water. Understanding the relationship between the exchange of matrix and conduit water will help in determining the best way to protect this valuable resource. Surface water entering the matrix will also have significant effects on karstification within the Floridan aquifer because of the differences in the chemical composition of the surface and groundwater.

Floridan aquifer transmissivity over several distances between conduits and monitoring wells was quantified using the passive monitoring method of Pinder et al. (1969). Calculated values are between 950 and 160,000 m^2/d. The variability in transmissivity with distance from the conduit is consistent with previous observations (Bradbury and Muldoon, 1990; Rovey and Cherkauer, 1995; Rovey, 1994), which showed that measured transmissivity in karst regions increases with increasing scale. Comparison of conduit and monitoring-well hydraulic head allowed tracking of the changes in hydraulic gradient as a storm peak passed through the conduit. Our results confirm the suggestion by White (1999) that storm response in wells within and outside of conduits could potentially be used to characterize coupling between conduits and matrix or fractures.

ACKNOWLEDGMENTS

Acknowledgment is given to the Florida Department of Environmental Protection and the staff of O'Leno State Park for their cooperation. Reviews by Kevin Cunningham and Andy Long improved this manuscript. The research was funded by the National Science Foundation grants EAR-003360 and EAR-0510054.

REFERENCES CITED

Atkinson, T.C., 1977, Diffuse and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain): Journal of Hydrology, v. 35, p. 93–110, doi: 10.1016/0022-1694(77)90079-8.

Bradbury, K.R., and Muldoon, M.A., 1990, Hydraulic conductivity determinations in unlithified glacial and fluvial materials, *in* Nielson, D.M., and Johnson, A.I., eds., Hydraulic conductivity and waste contaminant transport in soils: Philadelphia, American Society for Testing and Materials, v. 1142, p. 138–151.

Bush, P.W., and Johnston, R.H., 1988, Ground-water hydraulics, regional flow, and ground-water development of the Floridan aquifer system in Florida and in parts of Georgia, South Carolina, and Alabama: U.S. Geological Survey Professional Paper 1403-C, 80 p.

Cooper, H.H., and Rorabaugh, M.J., 1963, Groundwater movements and bank storage due to flood stages in surface streams: U.S. Geological Survey Water-Supply Paper 1536-J, 23 p.

Dean, R.W., 1999, Surface and groundwater mixing in a karst aquifer: An example from the Floridan aquifer [M.S. thesis]: Gainesville, University of Florida, 74 p.

Ferris, J.G., 1963, Cyclic water-level fluctuations as a basis for determining aquifer transmissibility, *in* Bentall, R., ed., Methods of determining permeability, transmissibility and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 305–323.

Hisert, R.A., 1994, A multiple tracer approach to determine the ground and surface water relationships in the western Santa Fe River, Columbia County, Florida [Ph.D. thesis]: Gainesville, University of Florida, 212 p.

Hunn, J.D., and Slack, L.J., 1983, Water resources of the Santa Fe River Basin, Florida: U.S. Geological Survey Water-Resources Investigations Report 83-4075, 105 p.

Martin, J.B., and Dean, R.W., 1999, Temperature as a natural tracer of short residence times for ground water in karst aquifer, *in* Palmer, A.N., Palmer, M.V., and Sasowsky, I.D., eds., Karst modeling: Charlestown, West Virginia, Karst Waters Institute, p. 236–242.

Martin, J.B., and Dean, R.W., 2001, Exchange of water between conduits and matrix in the Floridan aquifer: Chemical Geology, v. 179, p. 145–165, doi: 10.1016/S0009-2541(01)00320-5.

Martin, J.M., 2003, Quantification of matrix hydraulic conductivity in the Santa Fe River Sink/Rise system with implications for the exchange of water between the matrix and conduits [M.S. thesis]: Gainesville, University of Florida, 80 p. Online at http://etd.fcla.edu/UF/UFE0002882/martin_j.pdf.

Palmer, A.N., 2002, Karst in Paleozoic rocks: How does it differ from Florida?, *in* Martin, J.B., Wicks, C.M., and Sasowsky, I.D., eds., Hydrogeology and biology of post-Paleozoic carbonate aquifers: Charlestown, West Virginia, Karst Water Institute, p. 185–191.

Pinder, G.F., Bredehoeft, J.D., and Cooper, H.H., Jr., 1969, Determination of aquifer diffusivity from aquifer response to fluctuations in river stage: Water Resources Research, v. 5, p. 850–855.

Poucher, M., 2001, Cave exploration at River Rise and Sweetwater Lake, project update September 1, 2001: http://cavesurvey.com/sept_1,_2000.htm (accessed 16 January 2003).

Powers, J.G., and Shevenell, L., 2000, Transmissivity estimates from well hydrographs in karst and fractured aquifers: Ground Water, v. 38, p. 361–369, doi: 10.1111/j.1745-6584.2000.tb00221.x.

Quinlan, J.F., and Ewers, R.O., 1989, Subsurface drainage in the Mammoth Cave area, *in* White, W.B., and White, E.L., eds., Karst hydrology: Concepts from the Mammoth Cave area: New York, Van Nostrand Reinhold, p. 65–103.

Rovey, C.W., II, 1994, Assessing flow systems in carbonate aquifers using scale effects in hydraulic conductivity: Environmental Geology, v. 24, p. 244–253, doi: 10.1007/BF00767085.

Rovey, C.W., II, and Cherkauer, D.S., 1995, Scale dependency of hydraulic conductivity measurements: Ground Water, v. 33, p. 769–780, doi: 10.1111/j.1745-6584.1995.tb00023.x.

Ryan, M., and Meiman, J., 1996, An examination of short-term variations in water quality at a karst spring in Kentucky: Ground Water, v. 34, p. 23–30, doi: 10.1111/j.1745-6584.1996.tb01861.x.

Screaton, E., Martin, J.B., Ginn, B., and Smith, L., 2004, Conduit properties and karstification in the Santa Fe River Sink-Rise system of the Floridan aquifer: Ground Water, v. 42, p. 338–346, doi: 10.1111/j.1745-6584.2004.tb02682.x.

Skirvin, R.T., 1962, The underground course of the Santa Fe River near High Springs, Florida [M.S. thesis]: Gainesville, University of Florida, 52 p.

Smart, P.L., and Hobbs, S.L., 1986. Characterization of carbonate aquifers: A conceptual base, *in* Environmental Problems in Karst Terranes and Their Solutions Conference, Bowling Green, Kentucky, United States, October 28–30, 1986: Dublin, Ohio, National Water Well Association, p. 1–14.

Vacher, H.L., and Mylroie, J.E., 2002, Eogenetic karst from the perspective of an equivalent porous medium: Carbonates and Evaporites, v. 17, p. 182–196.

White, W.B., 1999, Conceptual models for karstic aquifers, *in* Palmer, A.N., Palmer, M.V., and Sasowsky, I.D., eds., Karst modeling: Charlestown, West Virginia, Karst Waters Institute, p. 11–16.

White, W.B., 2002, Karst hydrology: Recent developments and open questions: Engineering Geology, v. 65, p. 85–105, doi: 10.1016/S0013-7952(01)00116-8.

Manuscript Accepted by the Society 22 September 2005