Conduit Flow Paths and Conduit/Matrix Interactions Defined by Quantitative Groundwater Tracing in the Floridan Aquifer

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ABSTRACT: Groundwater tracing and cave mapping conducted in the Woodville Karst Plain of north Florida have revealed an extensive dendritic network of saturated conduits, more than 70 km in total length, that convey water to Wakulla Spring from the northeast, north, northwest, and south. In some places, the conduits are known to connect to swallets and in others are known to extend up-gradient into the aquifer matrix. Two sets of tracer tests were performed in 2005 and 2006 to map groundwater flow pathways between the Ames Sink group of swallets, which receive approximately 60% of the City of Tallahassee's storm water runoff, and the City's wastewater spray field, and characterize groundwater velocities along those pathways. The results of these tests revealed that water flows rapidly from both locations to Wakulla Spring. Groundwater velocities through the swimmable portion of the conduit network range from ~1500 to >2000 m/day and velocities through the smaller conduit pathways range from 250 to >800 m/day.

We have also compared the shape and timing of the tracer concentration recovery curves to groundwater levels and swallet stage during the tested periods. The results indicate that the aquifer is composed of conduits with varying capacities to convey water and that those capacities establish controls on local hydraulic gradients in the aquifer. More broadly, the results of these tracer studies indicate that tracer recovery curves can reveal significant and potentially quantifiable insights about the hydraulic dynamics of the aquifer when interpreted relative to continuously measured hydraulic data such as heads and flows within the region being tested.

Citation

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note – address for lead author has been updated since 1st publication

INTRODUCTION

This paper presents the results of two sets of quantitative groundwater tracer tests performed in the Woodville Karst Plain (WKP) of north Florida for the Florida Geological Survey and the Florida Department of Environmental Protection. The purpose of the tests was to identify the location of discharge for water recharging the Floridan aquifer from two known sources of potential groundwater contamination and to quantify the travel-time of the water from those locations to the discharge points. One is Ames Sink, which receives ~60% of the City of Tallahassee's untreated storm water runoff. The other is the City of Tallahassee's treated waste water spray field, which receives water with significantly elevated levels of nitrate.

Fluorescent tracers were injected into multiple swallets and in three monitoring wells as part of the two sets of tests. Tracer concentration recovery curves were developed for several of the detection points and used to establish the primary flow paths from the swallets and wells and to define groundwater velocities along the pathways. The timing and shape of the recovery curves were then compared to water levels continuously measured at one of the swallet injection points and two of the wells where the tracers were recovered. Here, we provide examples of the tracer recovery curves and associated water level data, mapped delineations of the groundwater flow paths, the calculated groundwater velocities, and a conceptual model that ascribes variations in the shape and timing of the recovery curve peaks to local hydraulic gradients established by flooding in the swallets and the capacity of the conduits to which they connect to convey water.

Hydrogeologic Setting

***Woodville Karst Plain*:** The Wakulla-Leon Sinks Cave System is situated in an extensively karstified topographic lowland known as the Woodville Karst Plain (WKP) (Hendry and Sproul, 1966), which is part of a broader karst belt that extends around Florida's Big Bend from Ochlockonee Bay to Tampa Bay. The WKP is spatially defined by the Apalachee Bay to the south and the erosional boundary of the clay-rich sediments comprising the Hawthorn Formation and parts of the Torreya, Chipola, Tamiami, Jackson Bulff, and Miccosukee Formations to the north and west. The stratigraphy within the 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. The only significant surface drainage in the WKP s provided by the Wakulla, St. Marks, and Wacissa Rivers, all of which emanate from large springs in the northern part of the region. Extensive karstification is indicated by numerous dolines, sinkholes, karst windows, sinking streams and springs (Lane, 1986) and by numerous large underwater cave systems (Werner, 2001; WKPP, 2008; Figure 1).

Recharge to the Floridan aquifer in the WKP occurs by: 1) sinking streams, 2) point recharge of precipitation through sinkholes, and 3) diffuse infiltration through the unconsolidated overburden. More than 400 sinkholes, ephemerally or perennially water filled, have been mapped in the northwestern quarter of the WKP suggesting at least 1000 such features across the entire region (FLDEP, 2008; Benoit et al, 1992). At least twelve of these sinkholes act as swallets for intermittent and perennial streams draining the impermeable uplands with flows ranging seasonally between 0.02 and 100 m^3/sec. The five largest such streams are: Lost Creek, Fisher Creek, Munson Slough, Black Creek and Jump Creek (Figure 1).

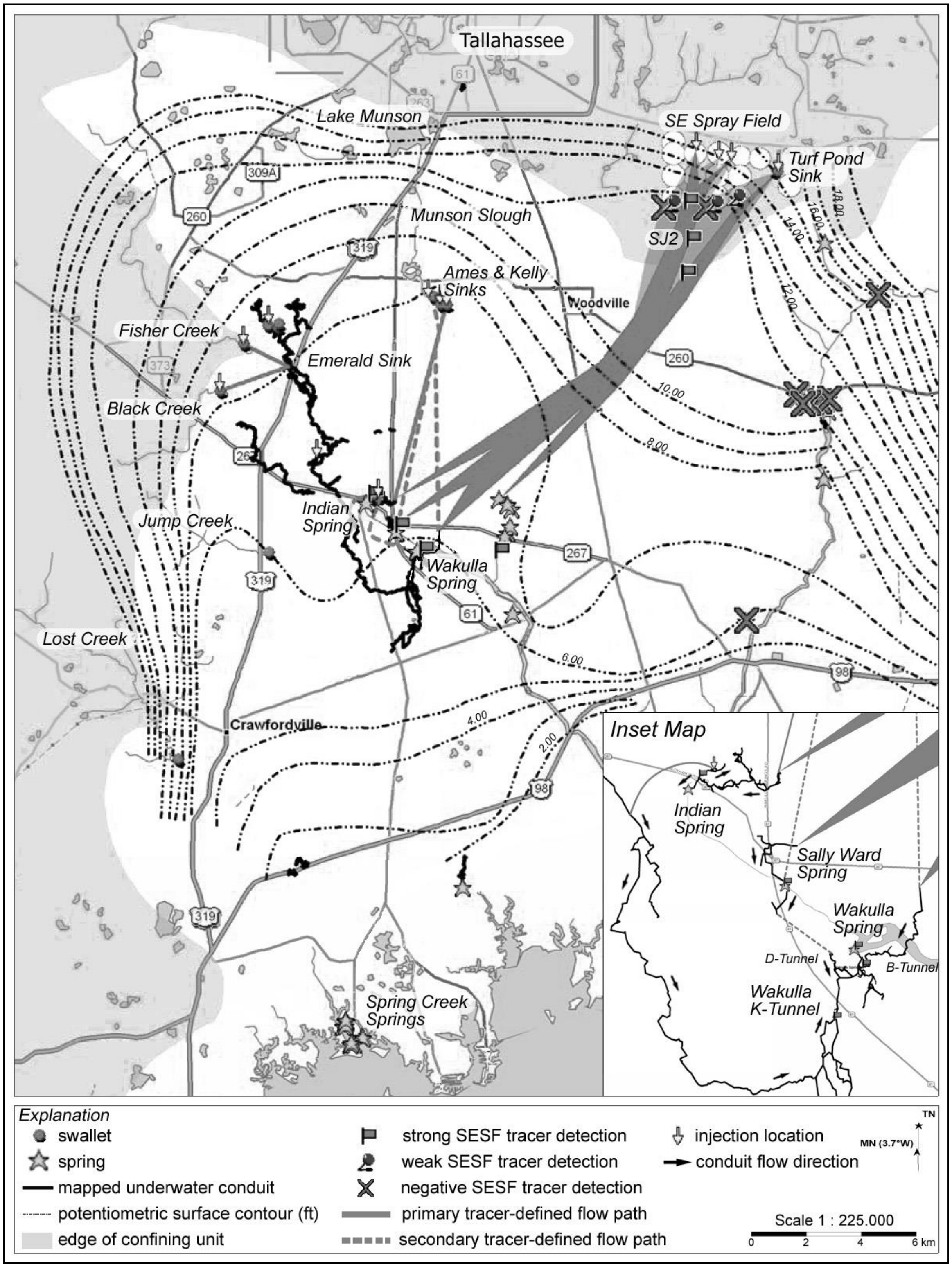

FIG. 1. Map of the Woodville Karst Plain, north Florida showing the locations of key karst and hydrologic features, tracer injection and detection points, and inferred tracer-defined conduit flow paths.

Discharge from the Floridan aquifer in the WKP is predominantly through springs in the southern part of the region and submarine springs in the Gulf of Mexico. Wakulla Spring, with an average discharge of 10.8 m^3/sec, is the largest spring in the WKP and one of the five largest springs in Florida. Wakulla Spring is the headwater of the Wakulla River, which flows for approximately 16 km southeast to the St. Marks River and then to the Gulf of Mexico. Seasonal discharge from Wakulla Spring ranges from 0.7 to 54 m^3/sec (Scott et al., 2002), which is the largest range recorded for any spring in Florida (Rupert, 1988). The Spring Creek group, which includes at least 14 underwater vents along the coast of the Gulf of Mexico also displays a large range in discharge at between 8.5 and 56.6 m^3/sec (Scott et al., 2002). The discharge at both springs correlates closely with local rainfall, with a response time of less than two days (FGS, 2008). The baseflow recharge area for these springs extends into the confined regions of the aquifer to include 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, 1984; Davis, 1996).

Accessible parts of the underwater conduit network in the WKP have been explored and mapped by cave divers of the Woodville Karst Plain Project (WKPP). Conduit depths range between 45m and 90m below the water table (Werner, 2001). Conduit diameters range from less than 2 m to greater than 30 m and are typically between 9-15 m (Kincaid, 1999; Werner, 2001). Water clarity in the conduits varies both temporally on the scale of days and spatially on the scale of individual conduits (McKinlay, 2008).

The largest continuously accessible portion of the conduit network extends both up-gradient and down-gradient from Wakulla Spring (Figure 1) and is thought to connect to conduits leading up-gradient from Spring Creek springs (Loper et al., 2005; McKinlay, 2008). The northernmost section of this group of conduits and the two tunnels leading north from near Wakulla Spring (B-Tunnel and D-Tunnel on the Figure 1 Inset) contain clear water year-round; whereas the remaining sections of the conduit network contain water that becomes dark tea-colored throughout the rainy season and shortly after any large rain events. Groundwater tracing has confirmed that the tea-colored water originates as discrete recharge through swallets that enters the cave system within hours to days of sinking (Kincaid et al, 2005; 2007[a]; 2007[b]).

Diver's observations that the flows are substantial enough to significantly impair their ability to swim or travel with underwater propulsion vehicles but that the velocities are spatially and temporally variable and can be oriented to the south away from Wakulla Spring in the southernmost sections of the cave system (McKinlay, 2008). Data to support those flow observations was provided in the form of responses to extreme tidal fluctuations that occurred as Hurricanes Francis and Ivan passed over the WKP in 2004 wherein abnormally low tide was associated with a nearly immediate and precipitous drop in flow at Wakulla Spring whereas an abnormally high tide was associated with the opposite (Loper et al, 2005).

Tracer Testing Results: Previous groundwater traces conducted by this group have consistently revealed that recharge through swallets to the northwest of Wakulla Spring flows rapidly into the mapped part of the conduit network and then very rapidly to Wakulla Spring (Kincaid et al, 2005; Table 1). In each of those traces, injections were performed either at swallets located relatively close to mapped conduits or directly into points within the conduit network. This paper presents the results of two sets of tracer tests performed from swallets and wells distant from the mapped conduits and compares the resulting velocities to those calculated from the previous tests and to local hydraulic conditions that were measured during the tracer tests (Kincaid et al., 2007[a], 2007[b]). Distances and velocities reported for all of the traces have been calculated using conduit pathways defined by exploration and mapping conducted by the WKPP in 2007 (Figure 1).

Table 1. Summary of tracer-defined flow paths in the WKP.

Trace	Distance (m)	Travel Time (days)	Velocity (m/day)
Fisher Creek – Emerald	2,680	2.4	820
Black Creek – Emerald	2,576	3.2	810
Emerald – Wakulla Spg.	16,550	7.1	2,337
Ames – Indian Spg.	8,400	17.2	506
Kelly – Indian Spg.	8,400	13.5	622
Indian Spg. – Wakulla Spg.	8,790	5.9	1,490
SESF Wells1 – B-Tunnel	16,800	66.5	252
SESF Wells2 – B-Tunnel	16,800	56	300
Turf Pond – B-Tunnel	17,500	56	312

Notes: 1) Points are shown on Figure 1.
2) Distance from wells calculated from estimated down-gradient flow convergence point.

Ames Sink Tracer Test: Ames Sink is one of three swallets (Ames, Ames 2, and Kelly Sinks) that receive flow from Munson Slough, which in turn, receives approximately 60% of the surface water runoff from the City of Tallahassee (Figure 1). Water flow into Munson Slough is controlled by a dam at Lake Munson that regulates flow outflow to minimize flooding in and around Munson Slough. However, medium to large rain events tend to overwhelm Lake Munson's storage capacity resulting in flood waves that raise water levels at Ames Sink by several meters or more. Leon County and the Northwest Florida Water Management District operate a gauging station at Ames Sink to monitor water levels and facilitate flood control by balancing water levels in Lake Munson and Ames Sink.

The intake capacity of each of the three swallets was measured by recording the discharge into each swallet prior to overflow. The results showed that Kelly Sink is capable of recharging more than 10 times the flow of either Ames or Ames 2; ≥1.80 m^3/sec for Kelly Sink compared to <0.18 and <0.14 m^3/sec for Ames and Ames 2 respectively (Kincaid et al, 2007[a]). Ames 2 and Kelly Sink only receive water when the inflow capacity of Ames is exceeded and water levels in the slough rise sufficiently to flood into the other swallets. Kelly Sink is the highest of the two overflow sinks and its recharge capacity has never been observed.

A series of groundwater tracer tests were performed in 2005 to map groundwater flow patterns from Ames and Kelly Sinks. A different fluorescent dye was injected at different times separated by approximately 5 days, in the two sinks where each injection was performed by releasing 12.0 kg of the tracer directly into the stream flow as it entered the swallet at the leading edge of a short-duration flood. The first injection was performed at Kelly Sink (*the largest capacity swallet*) by releasing the fluorescent dye eosin (AR87) into the stream immediately upstream of the swallet. All of the injected tracer was entrained in the swallet basin and disappeared underground in a matter of a few hours. As it is the highest swallet in the chain, there was no overflow from Kelly Sink during or after the injection.

The second injection was performed at Ames Sink using uranine (AY73) in the same manner as the Kelly Sink injection. The tracer was completely entrained in the Ames Sink swallet basin but the flood pulse that followed the injection raised water levels in the slough sufficiently to flood both Ames 2 and Kelly Sinks for a short period of time before the tracer disappeared from the Ames Sink swallet.

A third injection was performed by releasing 5.0 kg of phloxine-B (AR92) at a point in the conduit network connected to Indian Spring where flow was observed to be away from the spring into a small siphoning conduit and approximately 200 m down-gradient of the Indian Spring sampling point (Figure 1 Inset). The tracer was released into the flow and carried down-gradient away from Indian Spring.

Both the uranine and eosin tracers were detected at several down-gradient springs including Wakulla Spring but, in both cases, the primary detection point was at point in the conduit network approximately 300 m up-gradient of Indian Spring at a junction between a conduit trending up-gradient and two conduits leading down-gradient, one to the spring and one into a siphon leading away from the spring (Figure 1 Inset). The primary detection points for the phloxine-B tracer were Wakulla K-Tunnel and the Wakulla Spring vent approximately 10 m inside the conduit network (Figure 1 Inset).

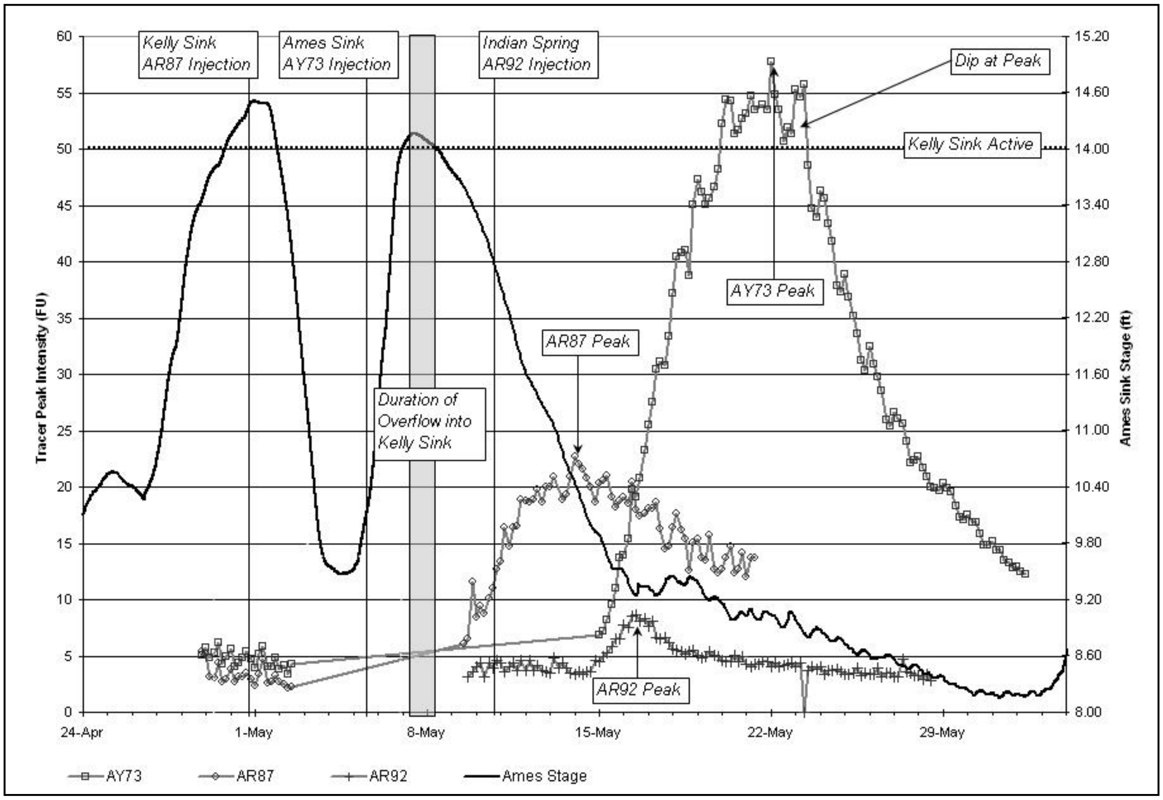

FIG. 2. Stage in Ames Sink during the 2005 Ames Sink groundwater tracer test and the associated tracer recovery curves measured at Indian and Wakulla Springs.

Figure 2 shows the three injections and their respective recovery curves at the Indian Spring and Wakulla Spring sampling points relative to the stage at Ames Sink. The recovery curves for both tracers have well defined leading and tailing limbs about broad peaks with an apparent regular short-period variation (marked by 2-3 points) particularly across the peak and tailing limbs. The AY73 recovery curve, however, contains a more evident depression in the peak that is marked by 7 points.

Figure 3 shows an expanded view of the AY73 recovery relative to green and blue fluorescence curves marked by fluorescence measured at 15 minute intervals by an insitu detection device (IDD) from the Indian Spring sampling point. The rise in the green fluorescence curve corresponds to the AY73 tracer passing the sampling point and correlates closely with the AY73 recovery curve. The blue fluorescence trend marks variation in natural fluorescence created by tannins in the water. The green fluorescence curve contains an evident depression that corresponds with the depression in the AY73 recovery curve and a depression in blue fluorescence.

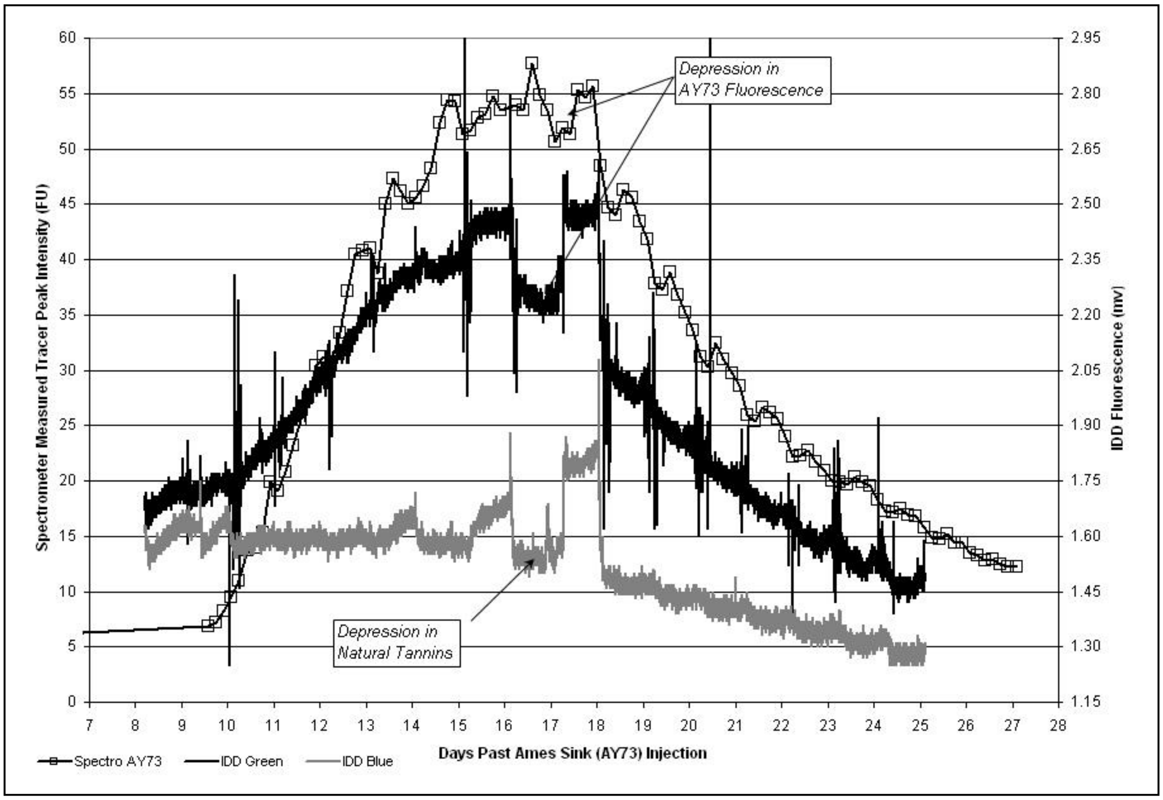

FIG. 3. AY73 recovery curve and green and blue fluorescence recorded at the Indian Spring sampling point.

The results confirmed a groundwater flow path between Ames and Kelly Sinks and Wakulla Spring via unmapped conduits connecting to Indian Spring and then through mapped conduits to Wakulla Spring. Table 1 shows the groundwater velocities calculated from the peak concentrations recorded on the tracer recovery curves. The pathway from Kelly Sink conveyed the tracer more quickly than the pathway from Ames, which was also indicated by the higher measured intake capacity at Kelly Sink. From Indian Spring, the groundwater velocity increased by 2-3 times by entering the larger mapped conduits.

Tallahassee Southeast Spray Field: The Tallahassee Southeast Spray Field (SESF) is a wastewater disposal facility that disperses secondarily treated wastewater onto the land surface via center-pivot irrigators at an average rate of 64,500 m^3/day over an area of approximately 8.7 km^2, which equates to an application rate of approximately 7.4 mm/day (City of Tallahassee, 2007). Nitrate levels in SESF groundwater monitoring wells increased precipitously after it became operational, rising from ~0.5 mg/L in 1980 to as much as 10 mg/L in the 1990's and stabilizing at ~6 mg/L by 2000 (Chelette et al, 2002). During the same period nitrate levels measured at Wakulla Spring rose from ~0.2-0.3 mg/L between 1971 and 1976, to >1.0 mg/L in the late 1980's, to ~0.7-0.8 mg/L between 1998 and 2000 (Chelette et al, 2002). The apparent correlation between nitrate increases in Wakulla Spring and SESF groundwater focused considerable attention on the SESF as a likely source of nitrate contamination to the spring.

A series of groundwater tracer tests involving multiple injections of multiple tracers were performed at the SESF in 2006 to identify the discharge locations for groundwater flowing under the SESF (Kincaid et al, 2007[b]). The first set of injections was performed in January when 5 kg of the fluorescent tracer phloxine-B (AR92) were injected into the middle of the open interval of three monitoring wells located across the up-gradient side of the SESF. The same tracer was injected into each well and the injections were performed sequentially such that all three were completed within approximately 4.5 hours of the first injection start time.

The second set of injections was performed in March using two different tracers at the same three wells and the Turf Pond swallet. The Turf Pond injection was performed first wherein 60 kg of eosin (AR87) was injected into the swallet located on the eastern side of the SESF that was receiving water at the time of the injection. The well injections were then performed sequentially wherein 20 kg of uranine (AY73) was injected into the three wells in the same manner as described for the January injections. All four of these injections were performed sequentially such that all of the tracers were fully injected into the aquifer within about 6.25 hours of the first injection start time.

Both of the tracers injected into the wells were detected at the same three of ten sampled down-gradient wells and the same four of eight sampled down-gradient springs (Figure 1). The tracer injected into Turf Pond swallet was detected at three of the eight sampled down-gradient wells, one of which was a different well than any of those that received the well-injected tracers, and the same four of the eight sampled down-gradient springs (Figure 1). For the well-injected tracers, the primary well detection point (well with the most distinct and highest concentration recovery curve) was monitoring well SJ-2. The primary spring detection point for all of the injected tracers was Wakulla B-Tunnel.

Figure 4 shows the recovery curves for all three tracers at the two primary detection points. The traced pathways for the SESF tests are represented on Figure 1 as shaded polygons to reflect both the tracer-defined connections and the probable width of the conduit zone in the aquifer based on the pattern of tracer detections and non-detections. At both detection points, variation in tracer concentration was higher for phloxine-B than for the other two tracers, which we equate to smaller quantity of tracer used for the test.

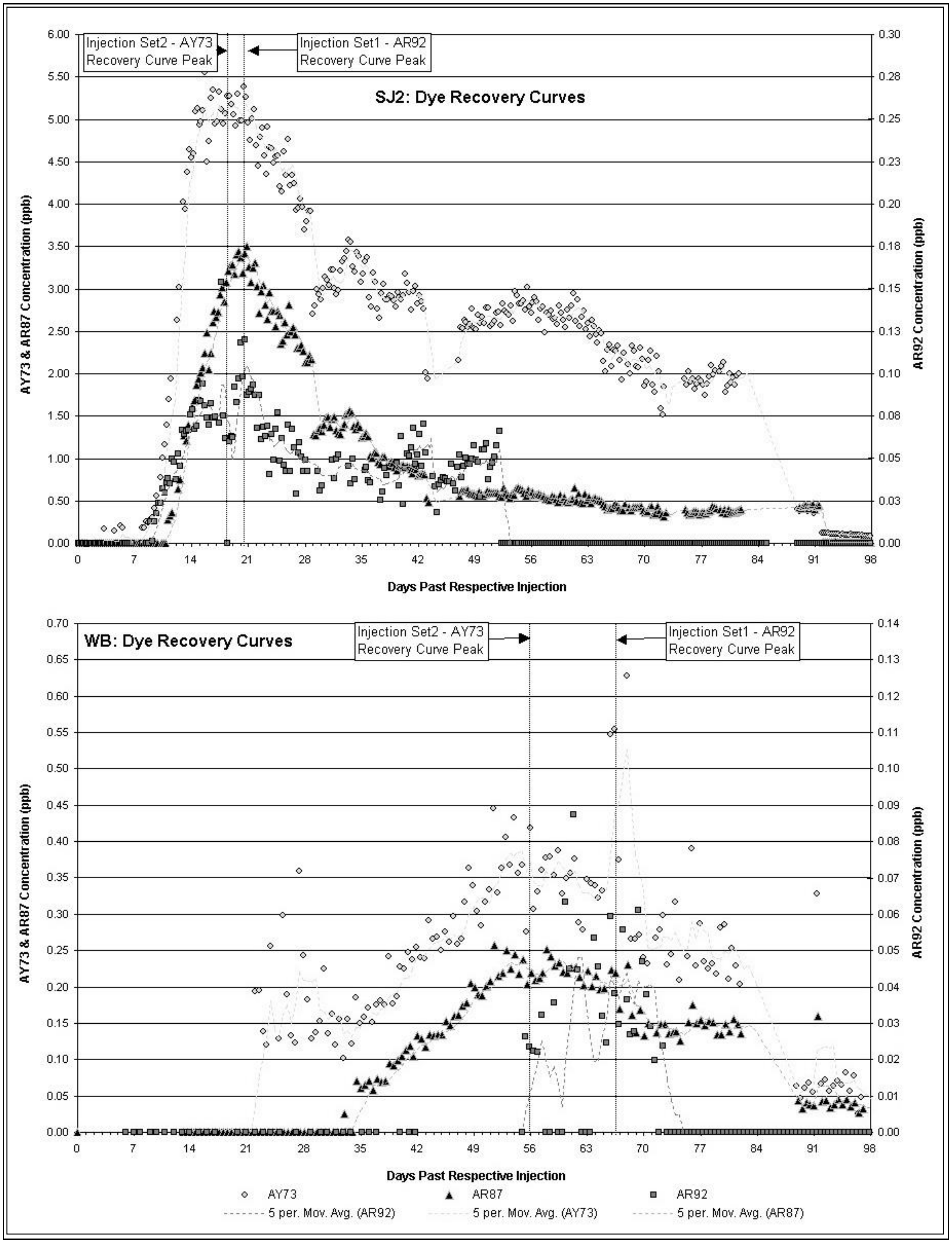

FIG 4. Tracer concentration recovery curves recorded at monitoring well SJ2 (top) and Wakulla Spring B-Tunnel (bottom) during the 2006 City of Tallahassee Spray Field groundwater tracer test showing that the tracer from the first set of well injections traveled slower than the tracer from the second set of well injections.

The uranine and phloxine-B curves were marked by broader peaks than the eosin curve, which we equate to the injection locations, wells for uranine and phloxine-B and a swallet for eosin. Uranine and phloxine-B were both detected at some, but not all, of the other sampled wells (Figure 1) later than the detection of the peaks at well SJ-2.

The travel-times used for velocity calculations were marked at the estimated center of the peak on the recovery curves rather than the point of highest concentration to account for the variation. Table 1 shows the estimated travel-times to Wakulla B-Tunnel and the corresponding calculated groundwater velocities for the three tests. Travel times and velocities were very similar for the second set of well injections and the swallet injection but were slower for the first set of well injections 66.5 verses 56 days and 252 m/day verses 300 m/day respectively.

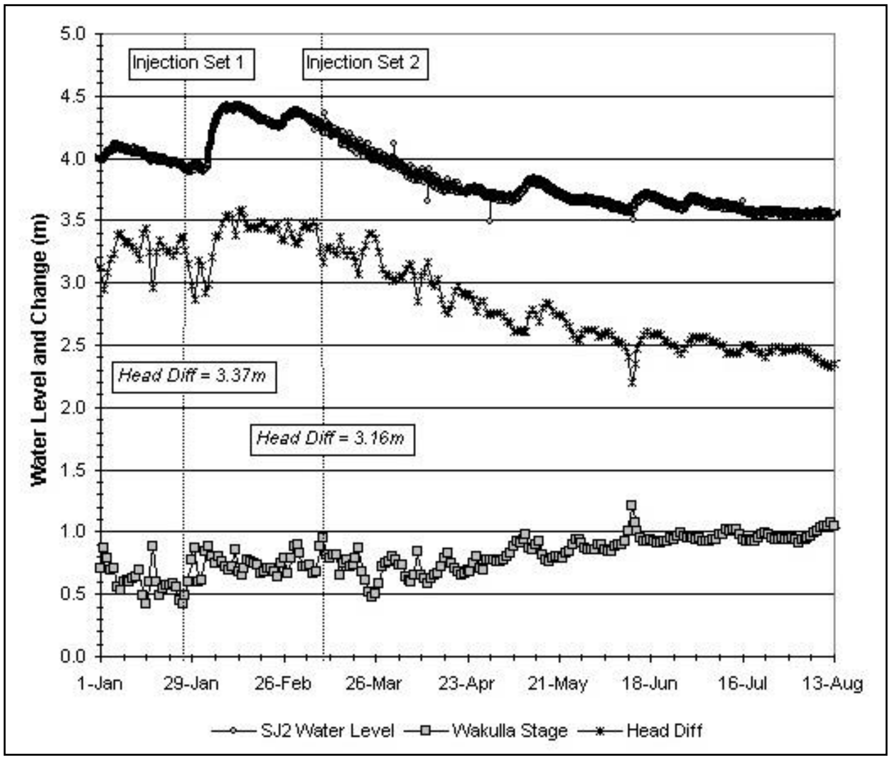

FIG. 5. Water level in monitoring well SJ2, stage in the Wakulla River, and the head difference between the two during the 2006 SESF groundwater tracer test.

Figure 5 shows that the first set of well injections was performed a few days prior to the rising limb of an increase in groundwater levels due to rainfall that activated (flooded) all of the regional swallets including Turf Pond swallet. The second set of injections was performed on the falling limb of that event, which marked the transition into the summer drought. Shortly after those injections all of the region’s swallets, including Turf Pond swallet, stopped receiving surface water inflow.

DISCUSSION

Travel Times & Velocities: Travel times and velocities from both the Ames Sink and SESF tracer tests reveal conduit-dominated flow paths throughout the northern and northeastern sections of the WKP despite the lack of mapped conduits in those regions. The recorded velocities from all the traces performed in the WKP reveal a pattern of increasing velocity with respect to proximity to the mapped conduit network and/or Wakulla Spring regardless of rather the injection was performed in wells or swallets. The slowest recorded velocities (252 – 312 m/day) were recorded for the longest such flow paths, ~14,000 – 15,000 m between well and swallet injection points at the SESF and the intersection with a mapped conduit (B-Tunnel, Figure-1 Inset). For the Ames Sink pathways, which were approximately ½ the length (~8,000 m), the recorded velocities were approximately two times faster (506 – 622 m/day). Within the conduit network, velocities increased by 2 – 3+ times again (1,490 – 2,337 m/day).

These results have challenged previously accepted suppositions about groundwater flow patterns, velocities, and ages derived from aquifer performance and/or borehole hydraulic conductivity tests, porous media groundwater flow modeling, and isotopic age dating of spring waters. By comparison, aquifer pumping tests have revealed values for aquifer transmissivity in the region that range from 90,000 – 180,000 m^2/day (Bush and Johnston, 1988), which using gradients calculated from Figure 1 ($1.26E^{-4}$ from SESF to Wakulla Spring and $3.16E^{-5}$ from Ames Sink to Wakulla Spring) and an average thickness for the upper Floridan aquifer in the region of 100 m, equate to groundwater velocities of 0.03 – 0.23 m/day. Transmissivities derived from regional groundwater model calibration range from 90,000 – 930,000 m^2/day (Davis, 1996), which using the same values for gradient and aquifer thickness, equate to groundwater velocities of 0.03 – 1.17 m/day. Finally, geochemical age dating has identified the age of the Wakulla Spring discharge at between 20 and 40 years old (Chanton, 2002; Katz et al, 2004), which even assuming that 100% of the recharge is derived from the northernmost extent of the estimated Wakulla springshed of approximately 110 km (Gerami, 1984; Davis, 1996), equates to groundwater velocities of 7.5 to 15 m/day. In all cases, the estimated velocities are between 1 and 4 orders of magnitude slower than the slowest observed velocities in the tracer tests and as much as 5 orders of magnitude slower than the fastest velocities.

Discrepancies with the values derived from aquifer testing and modeling are likely due to an inability of aquifer testing methods to measure head changes along the conduit pathways and to modeling techniques that either distribute observed spring discharges along broadly defined river reaches for modeling expedience or simply fail to calibrate to those discharges. Rectifying those problems will only come through modeling practices that incorporate very high velocity pathways and calibrate to point sources of discharge.

Discrepancies with the age dating derived velocities are likely due to mixing of very old and very recent recharge such as a combination of recharge through the variably thick sequence of clays that confine the Floridan aquifer over large parts of the recharge area and swallet recharge in the unconfined regions. That problem is not and likely cannot be adequately addressed by any revision to the age-dating of spring waters independently but will likely have to incorporate detailed water budget analyses and independent age-dating of the identified discharge components.

Tracer Test Inferred Aquifer Properties: The tracer recovery curves obtained at the Indian Spring and the SJ-2 and Wakulla B-Tunnel sampling stations from the Ames Sink and SESF tests respectively contain interesting variations that can be interpreted as indications of hydraulic dynamics occurring in the aquifer during the tests.

The primary pathway for tracers injected into both the Ames Sink and Kelly Sink swallets was to the conduit junction approximately 300 m up-gradient of Indian Spring. Flow measurements and the tracer-defined travel-times indicate that the Kelly Sink flow path can convey significantly more water than the Ames Sink flow path. During the Ames Sink injection, water levels in Munson Slough that drains to the sinks rose sufficiently to permit tracer-free water to flow into Kelly Sink for a duration of approximately 34 hours (Figure 2) while the tracer was entrained in and slowly recharging through the Ames Sink basin. The associated tracer recovery curves (Figures 2 and 3) display a distinct trough in the peaks that exceeds the variation displayed anywhere else along the curves or in the curve derived from the Kelly Sink test that was conducted one week prior and under nearly identical hydraulic conditions.

Given these observations, a reasonable hypothesis that explains the observed depression in the recovery curve stems from the relative capacities of the swallets to recharge water into the conduit network and the temporary activation of the higher capacity swallet during the injection. If the flow paths from Ames Sink and Kelly Sink to Indian Spring merge somewhere close to the swallets, then the depression could be caused by dilution of the tracer from tracer-free storm water that entered Kelly Sink after a large part of the dye had already passed the conduit junction. The recorded tracer intensity would have dipped during the flood and then recovered afterward as flow through the conduit became dominated again by recharge from Ames Sink. The similar response in blue fluorescence (Figure 3) would likewise reflect a rise in background as the storm water recharge through Ames Sink dissolved more tannins from the vegetation in the flooded slough; a decrease after a direct flow path became established through the slough to Kelly Sink; and then a subsequent rise after Kelly Sink's intake shut off and the flood water slowly subsided due to recharge through the lower capacity Ames Sink. If this hypothesis could be substantiated, then the important implication is that the tracer breakthrough curves can be used to quantify the relative capacities of the respective flow paths to convey water, which could then be used to define aquifer properties for modeling studies.

In a similar manner, the timing of tracer recoveries from the SESF test can be interpreted to result from hydraulic interactions between conduits and the aquifer matrix controlled by different recharge driven hydraulic gradients active during the respective two sets of tracer tests. The first test consisted solely of well injections and was initiated shortly prior to a wet period that flooded the area swallets and appreciably raised groundwater levels (Figure 5). The second test consisted of well and swallet injections and was initiated during the recession of groundwater levels to drought conditions (Figure 5). The timing of the respective tracer arrival at both the primary well and spring detection points was markedly slower for the first injected tracer than for the second.

While it is impossible to definitely define the cause of the apparent discrepancy between the travel-times, one explanation stems from the likely change in local gradients due to flooding into the swallets. Such flooding equates to point-source recharge that creates water table mounds in the vicinity of the swallets and raises the head in the conduits to which they are connected relative to the head in the surrounding aquifer matrix. Under such conditions, the gradient from the aquifer matrix into the conduits is reduced and tracers injected into wells not directly connected to the conduit network and outside of the mounding area will travel more slowly. Once the flooding subsides and the swallets drain, head in the conduits falls with respect to the surrounding aquifer matrix. Local gradients between the matrix and the conduits increases and tracers injected into the same wells would travel faster.

CONCLUSIONS

The results of several groundwater tracer tests performed in the WKP relative to the mapped extent of underwater conduits indicates that the permeability structure of the upper Floridan aquifer in this region is dominated by conduits and these conduits convey water from the northern end of the WKP (Apalachicola National Forest on the west to the SESF on the east) to Wakulla Spring at rates on the order of hundreds to thousands of meters per day. The rapid velocities hold for both swallet and matrix recharge within the region. Conduit sizes and therefore their capacities to convey water are not homogeneous. Inflow to swallets can exceed a conduit's capacity to convey water and when those capacities are exceeded, the conduits will develop a mound that will propagate (along with swallet recharge) into the aquifer matrix. Such mounding will persist as long as the conduit head exceeds the matrix head where the spatial extent of the mounding will be controlled by the hydraulic gradient between the conduits connecting to the swallet and surrounding aquifer water levels, which are controlled by the hydraulic conductivity of the aquifer matrix, duration of the mounding, and the distribution and magnitude of matrix recharge. More broadly, the results of these tracer studies indicate that tracer recovery curves can reveal significant and potentially quantifiable insights about the hydraulic dynamics of the aquifer when interpreted relative to continuously measured hydraulic data such as heads and flows within the region being tested. Given these, we believe that the use of quantitative tracing should be expanded in the WKP and throughout the unconfined section of the Floridan aquifer system and methodologies for equating the results into hydraulic parameters that can be used for quantitative and predictive studies.

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