Ames Sink Tracer Test – 2005

Interim report on the setup and results, comparison to the 2004 results, and interpretation of the controlling karst aquifer hydraulics

Woodville Karst Plain, North Florida

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1 INTRODUCTION

1.1. OVERVIEW

Groundwater quality in the Floridan aquifer is degrading particularly due to non-point source pollution. Declines in spring water quality, clarity, and the health of the ecosystems that springs support are some of the more noticeable consequences. One reason for the persistent decline in groundwater quality is the fundamental failing of standard hydrogeologic methods in characterizing the predominantly karstic nature of the Floridan aquifer. This failing, which is primarily manifest in a drastic under-prediction of groundwater velocities and groundwater-surface water interactions has facilitated land-uses that have nearly immediate and deleterious impacts on groundwater and spring water quality. If these impacts are allowed to persist unchecked, or worse increase through continued lack of understanding, the result will very likely be further widespread and significant reductions in the quality of groundwater in the Floridan aquifer and the loss or significant decline in Florida's spring water ecosystems.

Degrading groundwater quality, the resulting impacts to springs and springsheds, and to a lesser extent, the failing of the hydrogeologic profession to adequately address these problems, have become increasingly recognized over the past 15 years by the water resources community particularly the Florida Department of Environmental Protection (FDEP) and the Florida Geological Survey (FGS). To combat this problem, the FGS initiated an ongoing effort to characterize the hydrogeology and hydrology of the Woodville Karst Plain (WKP), located in north Florida, with the purpose of applying the knowledge gained through the endeavor to other basins throughout the karst region of Florida. The overarching purpose of this effort is to develop improved conceptual and numerical models of groundwater flow a single karst basin, and a methodology for their development, that can be applied to other such spring basins in Florida.

This report summarizes one component of that characterization effort in which Hazlett-Kincaid Inc. (HKI) was contracted through the Florida State University – Geophysical Fluid Dynamics Institute (FSU-GFDI) to conduct groundwater tracing experiments aimed at mapping karstic groundwater flow paths between Ames Sink and downgradient spring discharges. In summary, the results of those experiments demonstrated that:

1) runoff entering the Ames Slough from the Munson Slough cascades into three progressively higher swallets that take between 5 and 65 cfs;

2) the water from those swallets flows to Indian, Sally Ward, and Wakulla Springs within 14-22 days; and

3) breakthrough curves derived from quantitative tracer tests can be used in conjunction with hydrologic data to characterize the dynamics of flow from multiple inputs to spring discharges in the Floridan aquifer.

This work was jointly funded by the FGS Hydrogeology Program, the FDEP Springs Initiative Program, and the Florida Department of Natural Resources (FDNR).

1.2. WOODVILLE KARST PLAIN

The Woodville Karst Plain (WKP) is an extensively karstified topographic lowland (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 (*Figure 1*). Within this belt, the Floridan aquifer is unconfined, and therefore more vulnerable to contamination, because the clay-rich geologic formations usually overlying the limestone formations in much of the rest of Florida have been eroded away. The WKP constitutes the northwestern section of this karst belt and has been defined from its western boundary in the Apalachicola Coastal Lowlands to the Steinhatchee River in the east (Scott et al., 2001).

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. Within the WKP, the karstification is intensified by surface water that flows from north of the region, where the aquifer is confined or partially confined by clay-rich sediments. These sediments are in the Hawthorn Formation and parts of the Torreya, Chipola, Tamiami, Jackson Bulff, and Miccosukee Formations. Surface water flows onto the exposed carbonate rocks creating numerous dolines, sinkholes, karst windows, sinking streams and springs (Lane, 1986).

Recharge to the Floridan aquifer in the WKP occurs by: 1) sinking streams, 2) direct infiltration of precipitation through sinkholes, 3) infiltration through the variably thick sands and soils overlying the aquifer, and 4) groundwater flow into the WKP from the north. The Florida Department of Environmental Protection (FDEP) and Florida Geological Survey (FGS) are engaged in an effort to physically document all of the sinkholes and sinking streams within the WKP. To date, more than 400 sinkholes, ephemerally or perennially water filled, have been mapped in the northwestern quarter of the WKP by the FDEP. This suggests the presence of more than 1000 such features across the entire WKP. Of these 1000+ sinkholes, several are known to receive water, either perennially or ephemerally, from surface streams that drain upland regions, with flows ranging seasonally between 0.7 cfs to 3500 cfs. The five largest such streams are, in order of relative average flow: Lost Creek, Fisher Creek, Munson Slough, Black Creek and Jump Creek (*see Figure 1*).

Discharge from the Floridan aquifer under 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 380 cfs, is the largest inland 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 10 miles southeast to the St. Marks River and then to the Gulf of Mexico. Seasonal discharge from Wakulla Spring ranges from 25 cfs to 1900 cfs (Scott et al., 2002). This is the largest range of discharge recorded for any spring in Florida (Rupert, 1988). The Spring Creek group, which includes at least 14 underwater vents along the coast of Apalachee Bay in the Gulf of Mexico is listed as the largest spring in Florida and also displays a large range in discharge at between 300 and 2000 cfs (Scott et al., 2002). The variation in discharge at Wakulla Spring correlates closely with local rainfall, where spring hydrographs indicate that discharge responds to local storms in less than two days (Rosenau et al., 1977). The regional recharge area for these springs has been estimated to cover 965 mi^2, including parts of Leon, Wakulla, and Jefferson Counties and portions of five Georgia counties as far as 50 miles north of the Florida-Georgia border (Gerami, 1994; Davis, 1996).

In addition to the sinkholes and sinking streams, cave divers of the Woodville Karst Plain Project (WKPP) have mapped numerous underwater caves that trend for more than 10 miles across the basin from north to south at depths ranging from 50 to 300 ft below the water table (Werner, 2001). The five largest mapped caves in the WKP, ordered by length of mapped conduits, are: Leon Sinks Cave system (>14.9 miles), Wakulla Cave (>10 miles), Chip's Hole Cave (>4 miles), Indian Springs Cave (>2.2 miles), and Sally Ward Cave (>1.2 miles) – *Figure 1*. Conduit diameters within these caves range from less than 7 ft to greater than 100 ft and average approximately 30-50 ft (Kincaid, 1999; Werner, 2001).

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

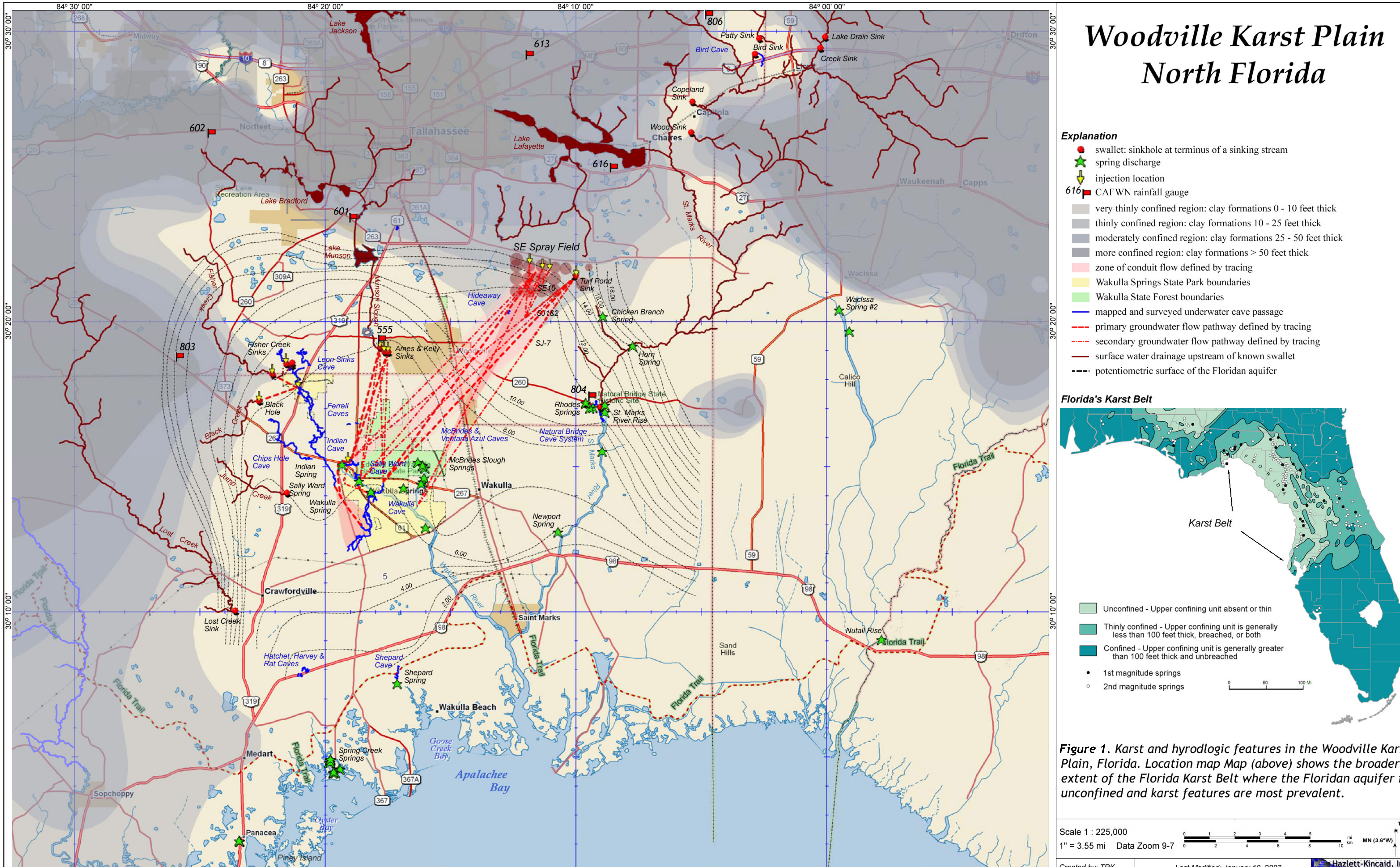


Figure 1. Karst and hyrodlogic features in the Woodville Karst Plain, Florida. Location map Map (above) shows the broader extent of the Florida Karst Belt where the Floridan aquifer is unconfined and karst features are most prevalent.

2 AMES SINK TRACER TEST ANALYSIS

Ames Sink is a swallet that receives flow from Munson Slough, which in turn, receives approximately 60% of the surface water runoff from the City of Tallahassee. The water flowing into Ames Sink disappears into the Floridan aquifer where it poses a threat to water quality in the aquifer and any down-gradient springs. HKI and CGW proposed and carried out two groundwater tracer tests in 2004 and 2005 for the FGS and FDEP that were designed to determine where the water disappearing in Ames Sink discharges, measure the travel-time between insurgence and discharge, and characterize the hydraulics of the flow path(s) in the aquifer. Both tests were successful and definitively showed that the water from Ames Sink flows primarily to Indian Spring within approximately two weeks and to Wakulla Spring within approximately three weeks.

Previous reports and publications (Hazlett-Kincaid, 2005; Kincaid et al, 2005) have described the design, execution, and results of each of the tests, and presented maps and discussions of the tracer-defined flow paths and travel times. As of 2006 however, an in depth analysis of the tracer recovery data had not been performed. The purpose of this task was therefore to develop such an analysis in comparison to available hydraulic data. Focus was directed on the 2005 tracer test because it was a broader test that addressed multiple flow paths and provided more complete tracer recovery curves at the sampling stations.

2.1 INFLOWS

Water flow into Ames Slough is partially controlled by a dam at Lake Munson, which is operated by Leon County. At present, Lake Munson is a flood control reservoir wherein the County aims to regulate flow out of the lake, such that flooding in the downstream Ames Slough and surroundings is prevented or minimized. However, medium to large rain events tend to overwhelm Lake Munson's storage capacity resulting in flood waves that travel from the dam through Munson Slough and Eight-mile Pond to Ames Slough and raise water levels at Ames Sink by several feet or more. Leon County and the NWFWMD operate a gauging station at Ames Sink to facilitate flood control through the balance of water levels in Lake Munson and Ames Slough. The station measures the water level in the sink and rainfall and is part of the CAFWN maintained by Leon County.

HKI conducted a set of field surveys in the Ames Sink region in 2005 to search for other potential swallets within or bordering Ames Slough and document surface water flow patterns during and after storm events. The field surveys revealed that Ames Slough is a broad lowland comprised of numerous shallow basins, deeper depressions, and sinkholes. Two additional swallets were discovered: a small feature internal to the slough that was named Ames2, and a larger feature, named Kelly Sink located on the southeast side of the slough. Figure 1 shows the location of each of the swallets and the network of streams and channels that drain into Lake Munson and Ames Slough. Figures 2 and 3 provide pictures of the swallets and Munson Slough during high and low flow periods.

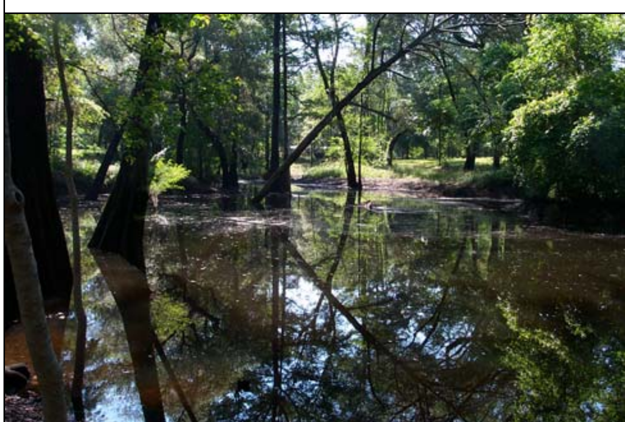
The timing of both the tracer injections and the field surveys were coordinated with a storm event and with a water release from the Lake Munson Dam performed by Leon County such that inflows to each of the three swallets could be measured as Ames Slough flooded and drained. Discharge measurements were performed immediately upstream of Kelly and Ames2 Sinks as the slough flooded and overflowed the various internal depressions and sinks. The discharge into Ames and Kelly Sinks had also been measured during the 2004 tracer test. The intake capacity of each of the three swallets was constrained by recording the discharge into each swallet prior to overflow. Table 1 provides a listing of the discharge measurements and the estimated intake capacities for each of the swallets. Figure 4 shows the position of the three swallets relative to an estimated boundary of the water flowing into Ames Slough at low, medium, and high water levels. Figures 5, 6, and 7 provide hydrographs for Ames Sink and mark the timing of the swallet activations and their inflows.

Southern Munson Slough near Ames Sink looking north toward the bridge on Oak Ridge Road – dry period

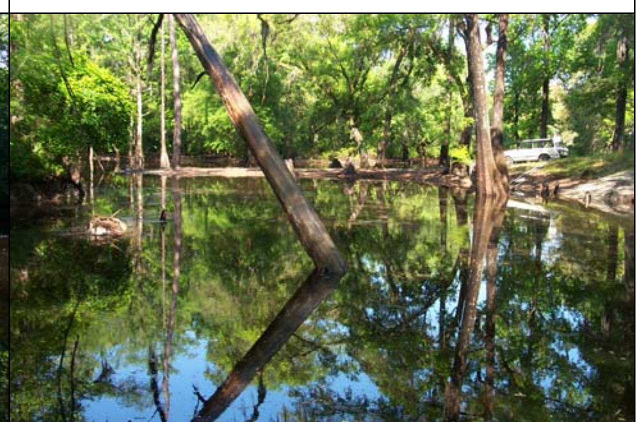
Flow over the spillway on Lake Munson Dam into the upper Munson Slough following a large storm event

View to the northwest across Ames Sink during a low water period

View to the east looking into Ames Sink during a low water period



View to the east looking across Ames Sink during a high water period



View to the west looking across Ames Sink during a high water period

Figure 2. Pictures of the channel through Munson Slough and Ames Sink at low and high water stages.

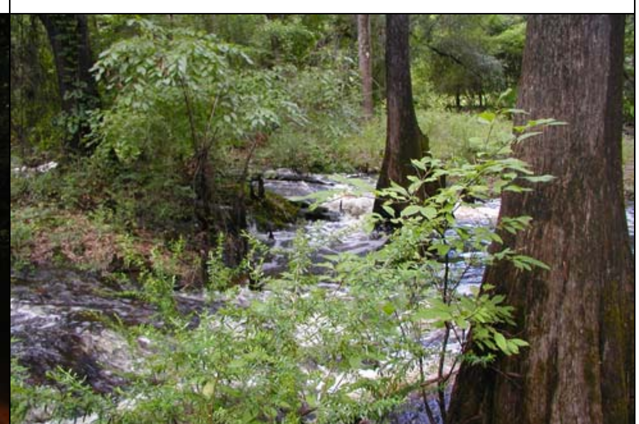
Water flow into Ames2 Sink during a rising stage in Ames Slough

High water level in Ames Slough at Ames2 Sink

Divers preparing to carry sampling tube into Kelly Sink at a low water level.

High water level in Kelly Sink with water flow entering the sink from left to right

Water flowing from right to left across Ranchero Road into Kelly Sink during a high water period



Rapid water flow into Kelly Sink during a high water period

Figure 3. Pictures of Ames2 and Kelly Sinks at low and high water stages.

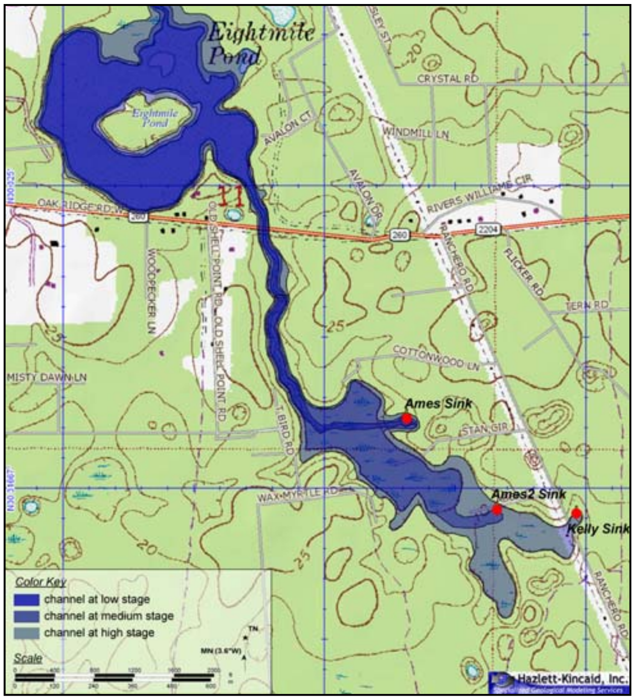


Table 1. Discharge and stage at the three swallets in Ames Slough during the 2004 and 2005 Ames Sink groundwater tracing experiments.

Location	Date	Time	Flow (CFS)	Stage Condition
Ames	8/11/04	19:30	6.52	Rising
Kelly	8/23/04	17:50	64.25	Constant
Ames2	4/29/05	17:35	5.03	Constant
Kelly	4/30/05	9:00	0.00	Constant
Kelly	4/30/05	12:00	3.77	Rising
Kelly	4/30/05	18:45	15.39	Constant
Kelly	5/1/05	12:00	24.29	Constant
Kelly	5/2/05	10:58	0.00	Falling

Figure 4. Location of the three swallets in Ames Slough south of Tallahassee, Florida relative to the estimated boundary of water flowing through the slough during low, medium, and high water levels.

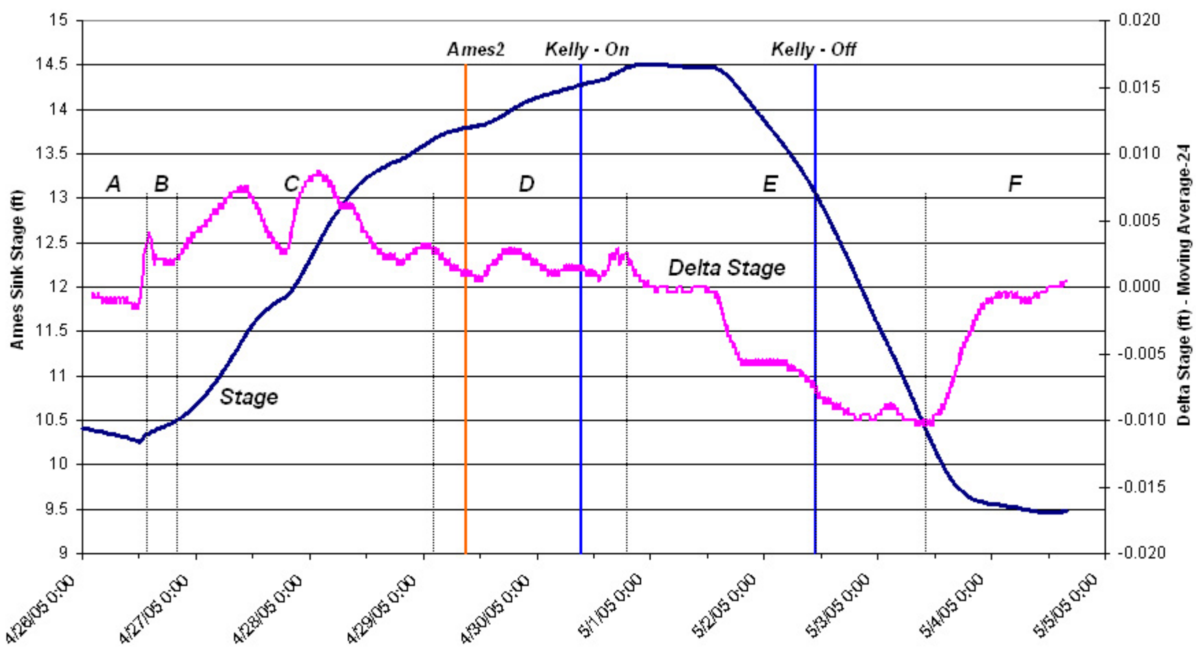


Figure 5. Water level measured in Ames Sink as reported by the Capitol Area Flood Warning Network (CAFWN), Leon County Florida relative to the approximate times when two higher swallets within Ames Slough became active. Letters mark time periods wherein the fluctuating rate of change in stage appears to be related to flow into and out of progressively higher basins and swallets. (A) Ames Sink began to fill. (B) Ames Sink filled and then overflowed into Ames Slough. (C) Water overflowed into progressively higher depressions and sinks within the slough. (D) Ames2 began receiving water but eventually overflowed. (E) Kelly Sink began receiving water. (F) All flow returns to Ames Sink.

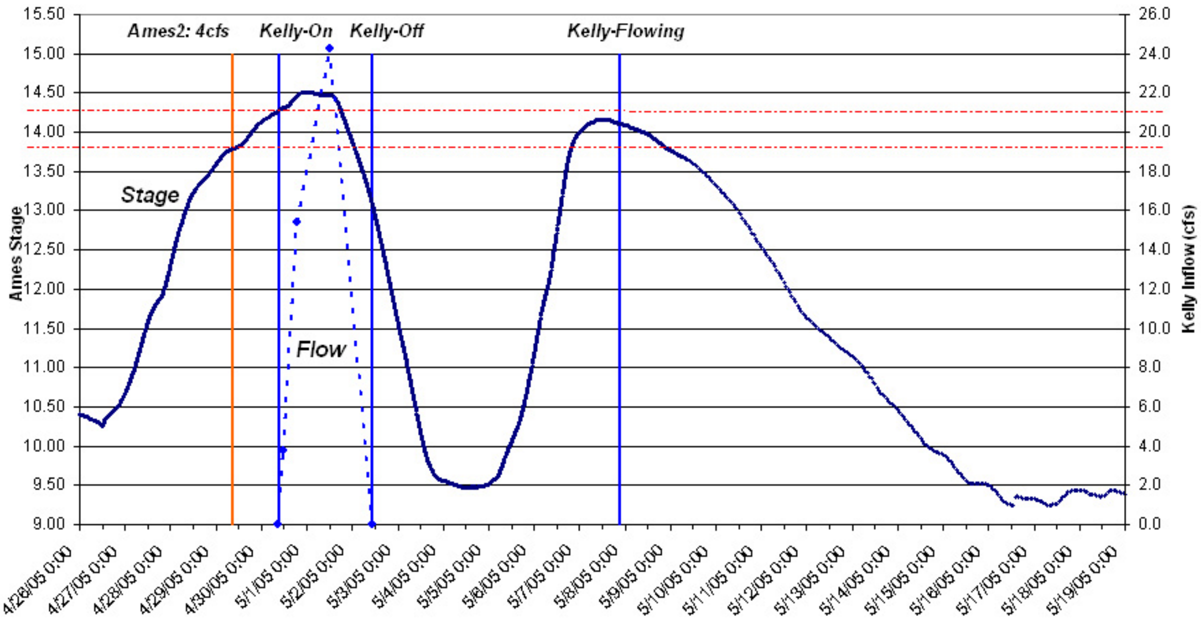


Figure 6. Water level measured in Ames Sink over two flooding periods as reported by the Capitol Area Flood Warning Network (CAFWN), Leon County Florida relative to the approximate times when two higher swallets within Ames Slough became active. The first flooding event was caused by a large storm. The second event was caused by a water release from the Lake Munson Dam by Leon County. The differently shaped hydrographs indicate that local rainfall during the first hydrograph caused depressions and sinks within the slough to take more water and at different rates than during the flood wave that generated the second hydrograph. In both cases, the slough responded to the flood by filling Ames Sink first and then overflowing into the progressively higher swallets.

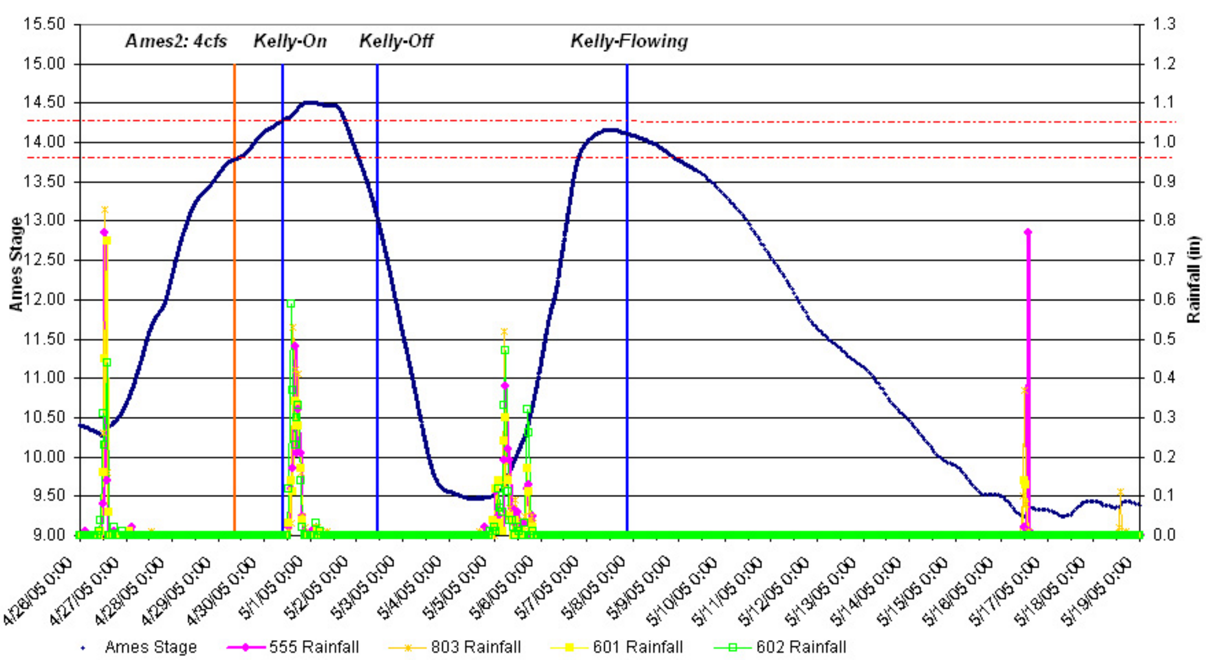


Figure 7. Water level in Ames Sink over two flooding periods relative to rainfall at Ames Sink and three regional stations. Gauges 601 and 602 are in the Lake Munson / Ames Slough surface water basin. Gauge 803 is downgradient of Ames Sink. The left peak in the hydrograph was primarily generated by rainfall whereas the later peak was driven by a planned release from Lake Munson.

The discharge measurements show that Ames Sink is not the primary insurgence in Ames Slough and therefore not the primary receptor of storm water runoff from the City of Tallahassee. The maximum inflow that Ames Sink can convey into the Floridan aquifer is less than 6.52 cfs because the stage in the sink was rising at the time that discharge was measured. Similarly, the inflow capacity at Ames2 Sink is probably close to 5 cfs, however the inflow capacity at Kelly Sink is greater than or equal to 64.25 cfs because the stage in the sink was holding constant when that discharge was measured.

After observing how the three sinkholes become progressively activated as water flows into and overflows each sink, a closer inspection of the Ames Sink hydrograph reveals the cascading pattern of flow through Ames Slough. The fluctuating rate of change in stage at Ames Sink (Figure 5) is likely caused by flow into and out of progressively higher basins and sinks within Ames Slough. The pattern is not, however, identical between the two flood periods measured in 2005. Figures 6 and 7 show that the flood driven by a dam release at Lake Munson produced a significantly smoother leading edge to the hydrograph than the flood driven by a storm. The difference could be related to repeated rainfall events within the Ames watershed (Figure 7), however it could indicate that the controlled release caused water to move more quickly and directly through the slough to the progressively higher swallets. The locations of the rainfall gauges shown in Figure 7 are marked on Figure 1. The data used to construct the plots is provided electronically as Appendix I.

In either case, these data clearly show that swallets identified during low flow periods may not be the primary insurgence points for disappearing stream flow during higher flow periods. The observation and documentation of overflow into progressively higher swallets in Ames Slough is consistent with observations made by this group in the Fisher Creek basin (Hazlett-Kincaid, 2004) and probably holds true for all of the sinking streams in the WKP. Furthermore, there might be additional smaller swallets within the slough and additional ones beyond the observed extent of the slough that are only activated during very high flow periods if Kelly Sink overflows.

2.2 TRACER TEST ANALYSIS

The 2004 tracer test was conducted between August and September. Approximately 7.5 kg of Uranine (AY73) were injected into Ames Sink at the leading edge of a flood associated with Hurricane Bonnie. The 2005 tracer test was conducted between May and July and was broader in scope than the previous test. Three injections were performed: the first at Kelly Sink (approximately 12 kg Eosin – AR87), the second at Ames Sink (approximately 12 kg Uranine – AY73), and the third at Indian Spring (approximately 5 kg Phloxine-B – AR92). Both the Kelly Sink and Ames Sink injections were performed by releasing the dye directly into the stream flow as it entered the sink at the leading edge of a flood. The Indian Spring injection was conducted by having divers from the WKPP release the dye into a siphoning conduit approximately 500 ft into the cave from the spring discharge after both of the floods had subsided. Figure 8 provides pictures of the three swallet injections.

For both tests, regular sampling for the tracers was conducted at Wakulla, Sally Ward, Indian, and McBrides Springs and the St. Marks River Rise. During the 2004 test, several sinkholes located along the projected flow path between Ames and the down-gradient discharges were also sampled. During the 2005 test, K, D, and B-Tunnels in Wakulla Cave were sampled. In both tests, the strongest detection of the tracers injected at Ames and Kelly Sinks occurred at Indian Spring. The tracer(s) were also detected at all of the Wakulla stations as well as Sally Ward Spring. None of the tracers were recovered from the St. Marks River Rise, McBrides Spring, or the intermediate sinkholes. The tracer recovery data for the 2005 test is provided in Appendix II.

All four of the tracer tests were successful in that the injected tracers were detected at one or more of the sampling locations (Figure 9). Moreover, though the sampling period for the first test was not long enough to obtain complete recovery curves, those that were obtained compare favorably with the more complete curves obtained during the 2005 test (Figure 10). The favorable comparison indicates that the results adequately described the hydraulics (velocity and dispersion) of flow between the sinks and springs and that the flow hydraulics along the pathways were similar during both tests. Based on this comparison, we assume that a detailed analysis of the 2005 data will describe the hydraulics of flow along the traced paths under conditions similar to those encountered during the 2004 and 2005 tests – i.e. moderate rainfall occurring over short duration storms.

Uranine dye flowing into Ames Sink – August 11, 2004

Uranine dye flowing into Ames Sink – August 11, 2004

Eosin dye being released into stream immediately above Kelly Sink – April 30, 2005

Eosin dye flowing into Kelly Sink – April 30, 2005

Uranine dye being gravity drained into Ames Sink during a rain storm – May 5, 2005

Uranine dye being gravity drained into Ames Sink during a rain storm – May 5, 2005

Figure 8. Pictures of tracer injections at Ames and Kelly Sinks during the 2004 and 2005 Ames Sink groundwater tracer tests, Woodville Karst Plain, Florida.

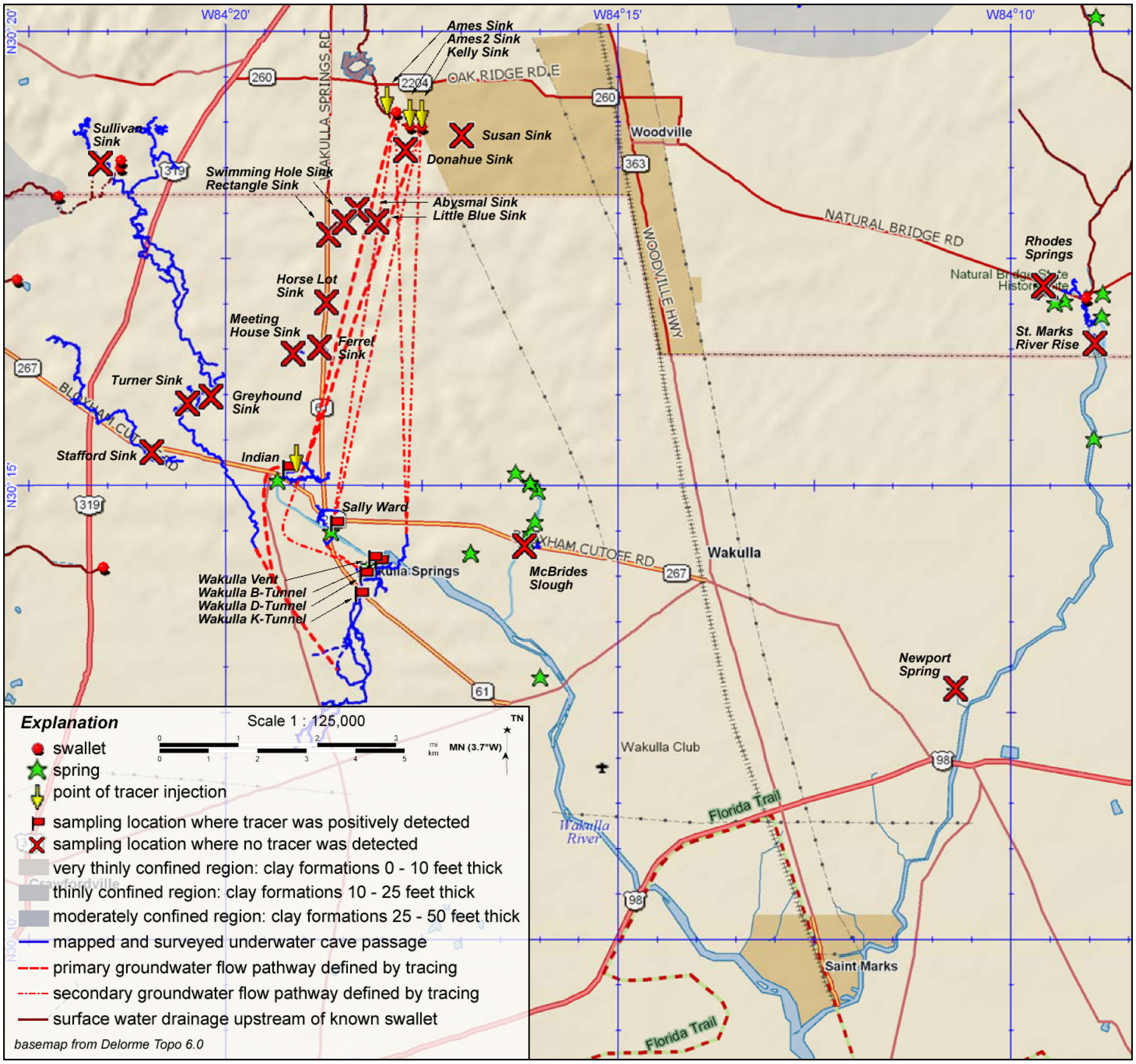


Figure 9. Map of part of the Woodville Karst Plain, north Florida showing the tracer injection locations, traced groundwater flow paths, and the locations of sampling stations marked by positive or negative detections pertaining to the 2004 and 2005 Ames Sink tracer tests. Note that the primary flow path was determined to connect Ames and Kelly Sinks to Indian Cave and then to Wakulla Spring. The Indian to Wakulla connection is inferred to be via the Leon Sinks Cave System and traced connection to Wakulla Cave because of the positive detection at Wakulla K-Tunnel. The inferred pathway between Wakulla D-Tunnel and Indian Cave rather than Sally Ward Cave was based on tracer travel times. The pathway to Wakulla B-Tunnel was marked by very low tracer concentrations, too low to record a tracer recovery curve. None of the injected tracers were detected at the St. Marks River Rise, Rhodes Springs, Newport Spring, or McBrides Slough during the sampling periods.

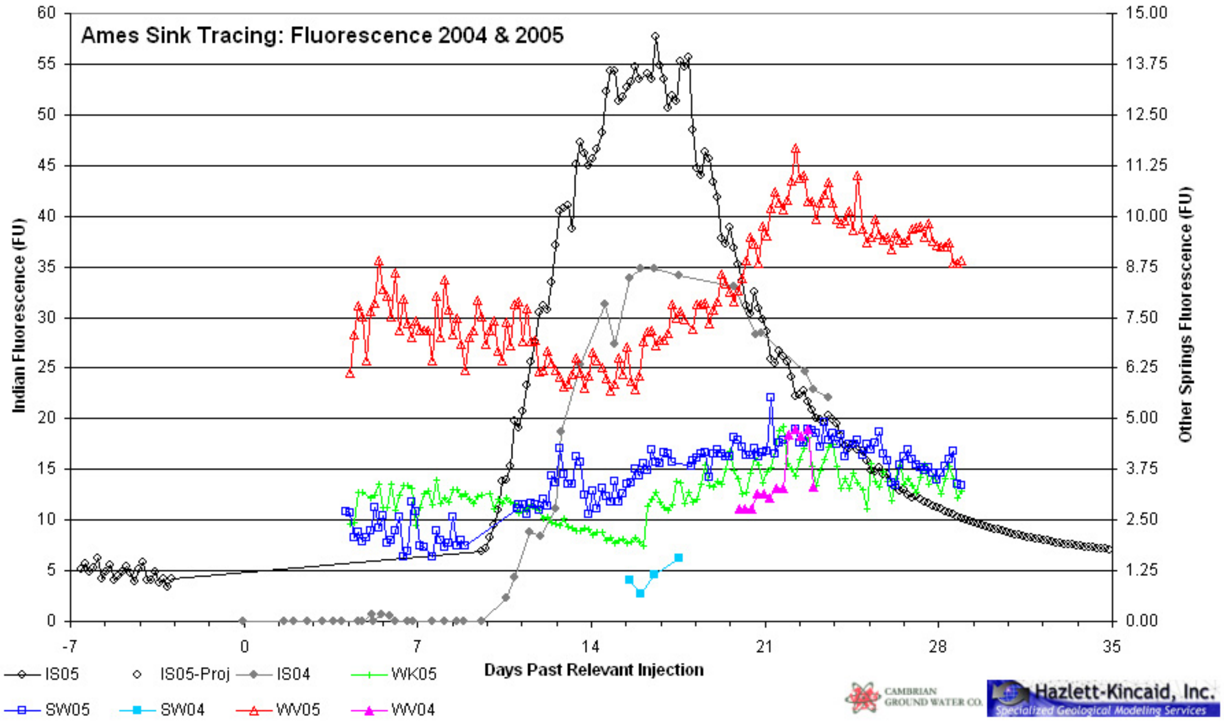


Figure 10. Uranine recovery curves at Indian Spring (IS), Wakulla K-Tunnel (WK), Sally Ward Spring (SW), and the Wakulla Spring Vent (WV) for the 2004 (04) and 2005 (05) Ames Sink tracer tests. The position of the approximate peaks (roughly the highest part of each curve) correlate to within less than one day at Indian and Wakulla Springs. Few samples were obtained from Sally Ward during the 2004 test, however the small curve appears to mimic the rising limb of the 2005 recovery curve. The tailing edge of the IS05 curve was extrapolated using an exponential curve fitted to the tailing edge data.

An analysis of the recovery curves from Indian Spring provides for an evaluation of 1) the relative groundwater velocities along the pathways connecting Ames and Kelly Sinks to Indian Spring; 2) the hydraulic relationship between the two sinks; and 3) the relationship between data derived from laboratory analysis of water samples on a scanning spectrofluorophotometer (*spectrometer*) and fluorescence data measured by an insitu filter fluorometer (IFF), in this case deployed in a sealed container at the surface that received continuous flow from the sampling station.

2.3 Relative Groundwater Velocities

Figure 4-11 shows the eosin recovery curve from the Kelly Sink injection and the uranine recovery curve from the Ames Sink injection relative to the hydrograph at Ames Sink spanning the duration of the test and the timing of the three 2005 injections. Neither curve returns to the pre-injection fluorescence levels (thus they are incomplete) however both show significant portions of the tailing edge of the curve. The higher uranine fluorescence was expected because uranine is approximately 20 times more fluorescent than eosin and equal masses of the tracers were injected. The broader eosin curve is attributed to higher flow rates into Kelly Sink producing more dispersion.

The eosin peak arrived at Indian Spring on May 14, 2005 or approximately 14 days after the injection. The uranine peak arrived at the same station on May 22, 2005 or approximately 17 days after the injection. The travel times equate to average groundwater velocities (assuming a straight-line path between injection and sampling locations) of approximately 2000 and 1600 ft/day (610 and 490 m/day) respectively (Table 2). The different velocities directly correlate with the respective intake capacities for each swallet, <= 6.5 cfs for Ames Sink and >=64.25 cfs for Kelly Sink (Table 1). The recovery curves therefore demonstrate that the pathway between Kelly Sink and Indian Spring can be characterized by a larger diameter conduit(s) the pathway between Ames Sink and Indian Spring.

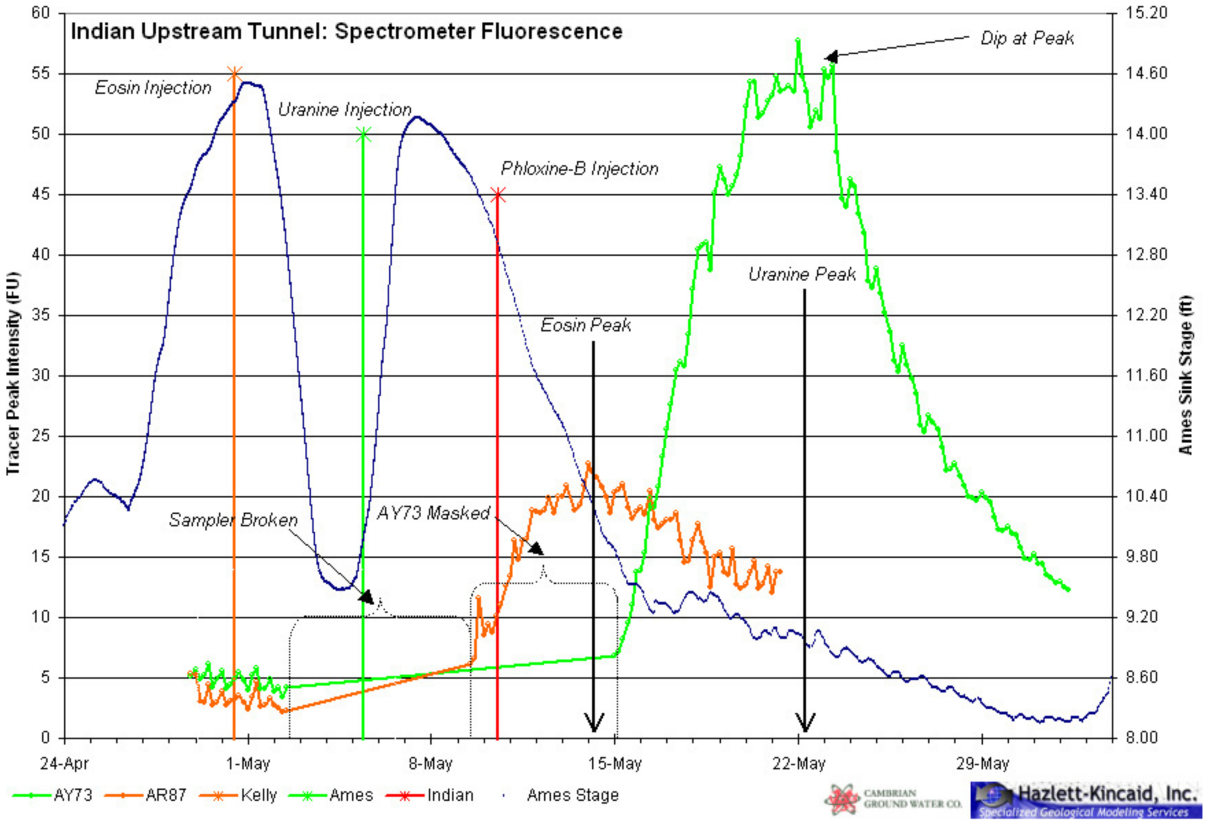


Figure 11. Tracer recovery curves recorded at the Indian Spring sampling station during the 2005 Ames Sink tracer test, Woodville Karst Plain Florida. Both the eosin and uranine injections occurred immediately prior to a flood in the respective swallets. The phloxine-B injections at Indian Cave coincidently occurred as the eosin tracer was beginning to pass the sampling station and presumably enter the same siphoning conduit. The eosin curve is broader and lower than the uranine curve. The breadth is attributed to higher flow rates into the swallet at the time of injection. The magnitude of the fluorescence would have been similarly affected but is attributed primarily to the fact that eosin is approximately 20 times less fluorescent than uranine.

Figures 12 and 13 show the tracer recovery curves at the Indian, Wakulla K-Tunnel, Wakulla-Vent, and Sally Ward sampling stations. All of the curves are plotted against the time past injection and are normalized to the maximum recorded fluorescence to facilitate a comparison of the travel times for the peak values. The plots indicate that there are at least two active pathways between Ames and Kelly Sinks and Wakulla Spring. The primary pathway connects to Indian Cave and from there to Wakulla Spring through the southern part of Wakulla Cave, most likely via the Leon Sinks Cave System and A2-Tunnel (Figure 9). This pathway was confirmed by all three tracers. The Leon Sinks to Wakulla Cave connection via K-Tunnel was previously established by tracing (Hazlett-Kincaid, 2004).

A second pathway must connect to Sally Ward Spring (then to Wakulla Spring via the spring channel) because both uranine and eosin were recovered but phloxine-B was not. It is, however impossible to determine if it is an independent pathway or if the Ames/Kelly to Indian pathway bifurcates somewhere upstream of the siphon tunnel in Indian Cave where the phloxine-B was injected.

Table 2 and Figure 14 show the distances between the documented pathways, the peak travel times, and the calculated groundwater velocities. The Indian to Wakulla path assumes a connection through the Leon Sinks Cave System as described above. Groundwater velocities are calculated from the peak travel times on the recovery curves. Very low tracer concentrations rendered the peaks for uranine and particularly eosin difficult to confidently define at the Wakulla and Sally Ward sampling stations therefore the error in velocity calculations is higher for those paths and tracers.

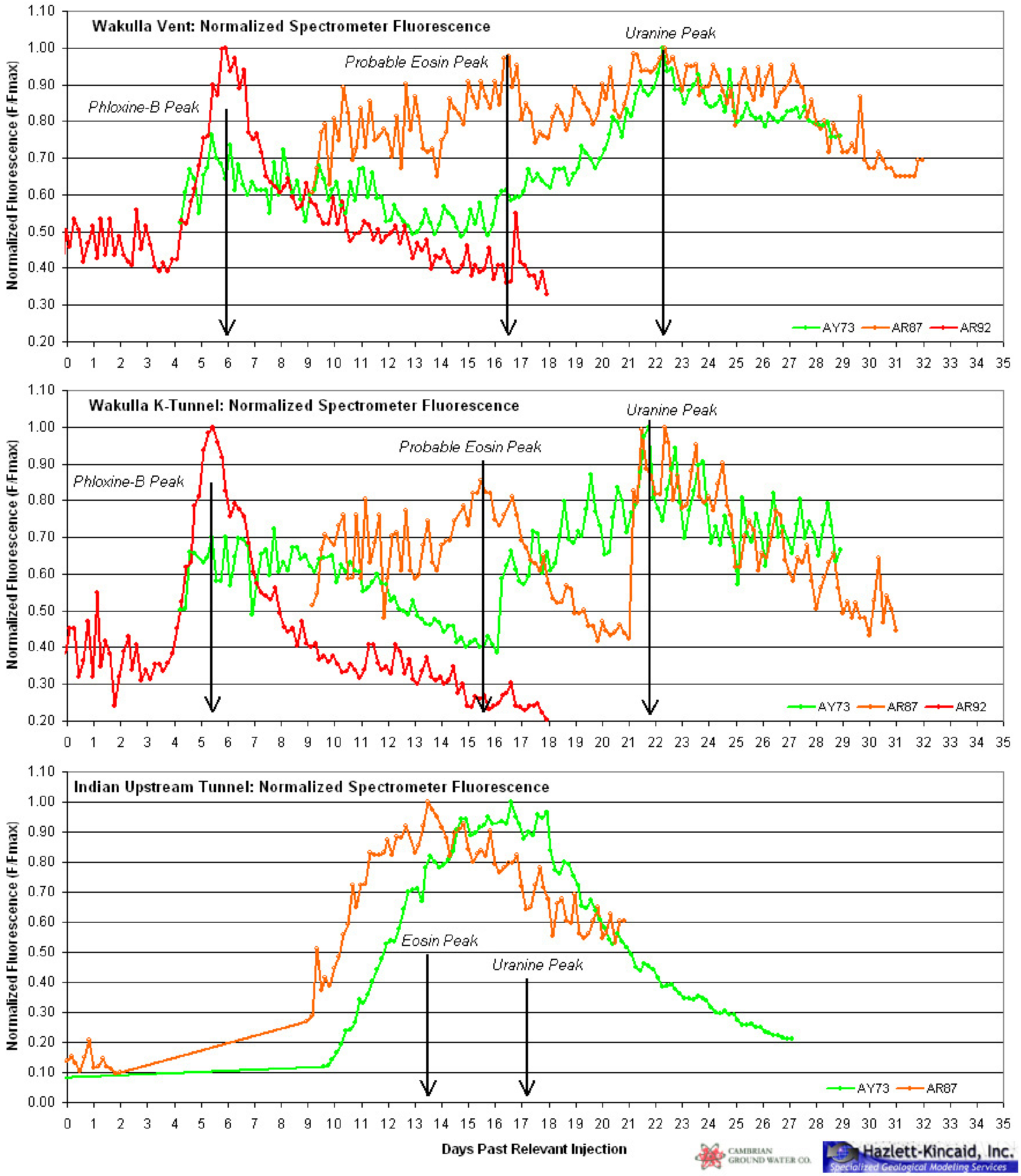


Figure 12. Tracer recovery curves recorded at the Indian, Wakulla K-Tunnel, and Wakulla-Vent sampling stations during the 2005 Ames Sink groundwater tracer test, Woodville Karst Plain, Florida. All of the plots are normalized to the maximum recorded fluorescence and plotted against the days past the relevant injection to facilitate comparison. Groundwater velocities were calculated from the peak arrival times and the distance between stations. Straight-line flow paths were assumed between all stations except Indian to Wakulla K-Tunnel, which was assumed to connect through the Leon Sinks Cave System. The uranine and eosin peaks are difficult to confidently define at K-Tunnel and the Vent stations because of the very low tracer concentrations detected. Eosin was particularly problematic

because it becomes masked when the uranine becomes detectable. However, under background conditions, the eosin should plot beneath uranine therefore the eosin peak is most probably reflected by the maximum positive deviation between the eosin and uranine curves.

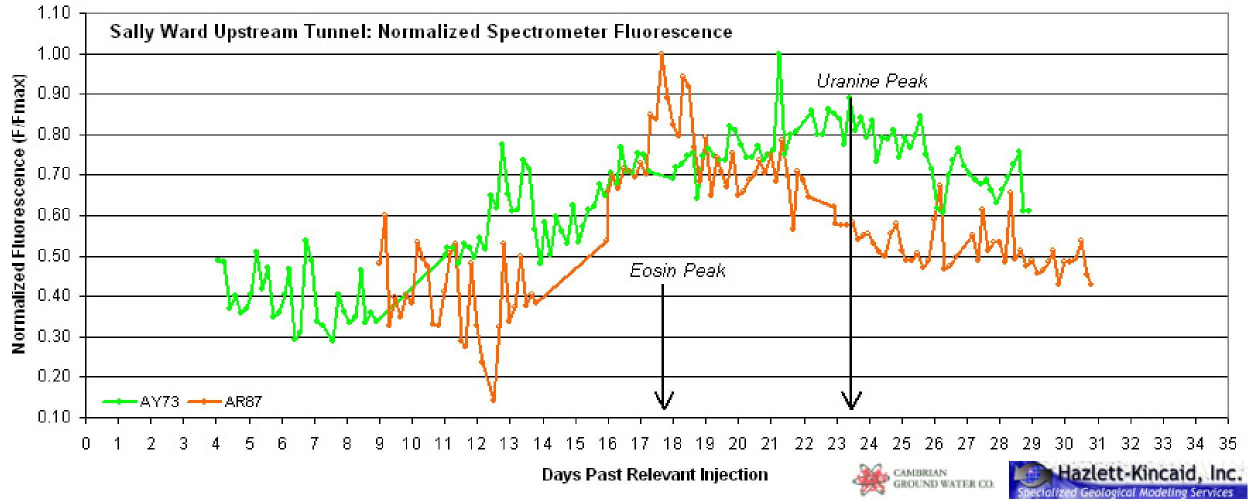


Figure 13. Tracer recovery curves recorded at the Sally Ward sampling station during the 2005 Ames Sink groundwater tracer test, Woodville Karst Plain, Florida. The travel times for both the apparent peaks are approximately one day longer than the travel times recorded for the same tracers at the Wakulla Spring Vent. The slower travel times indicate that the Sally Ward pathway is less prominent than the pathway to Indian Cave and then to Wakulla Spring via K-Tunnel.

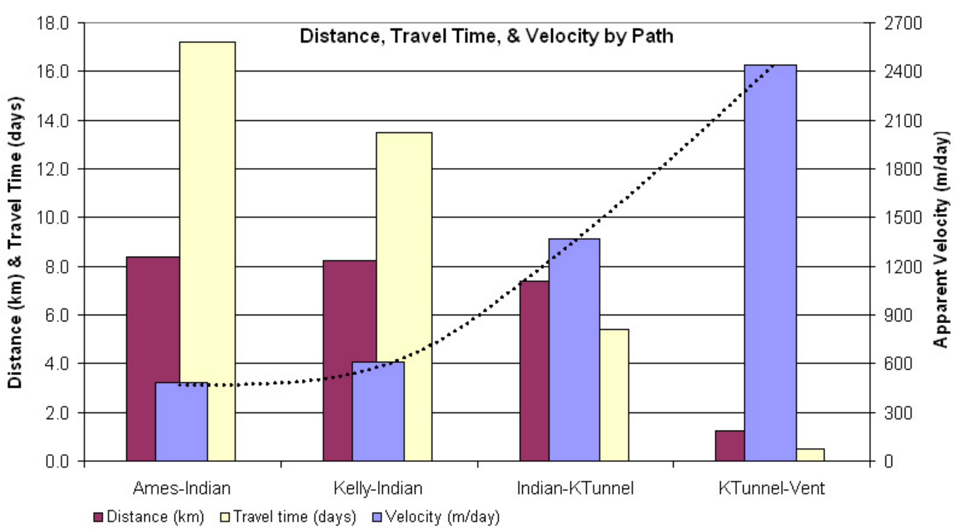


Figure 14. Comparison of distance, travel time, and calculated groundwater velocity for variations or segments of the observed flow pats between Ames and Kelly Sinks and Wakulla Spring in the Woodville Karst Plain, north Florida. There is an apparent exponential increase in groundwater velocity as the tracer approaches Wakulla Spring, presumably because the conduits in the aquifer become larger and carry more water as they approach the spring discharge.

3 AQUIFER HYDRAULICS

Table 2. Travel times and velocities measured during the 2005 Ames Sink Tracer Test.

Pathway	Distance (km)	Travel Time (days)	Groundwater Velocity (m/day)
Ames – Indian	8.4	17.2	487
Kelly – Indian	8.4	13.5	608
Indian – K-Tunnel	7.4	5.4	1371
K-Tunnel - Vent	1.2	0.5	2438

Figure 15 shows the uranine recovery curve relative to the hydrograph at Ames Sink spanning the duration of the test, and the timing of the Ames Sink injection relative to the hydrograph. The plot shows a correlation between a measured depression in uranine fluorescence at the top of the recovery curve that produces two obvious peaks, and the duration of flooding into Kelly Sink from Ames Slough following the injection. The correlation suggests that the flow paths from Ames and Kelly sinks to Indian Spring merge somewhere close to the swallets, and that the depression is caused by dilution of the tracer from storm water that entered the flow path from Kelly Sink after a large part of the dye had already passed the junction.

It follows from the intake capacities of the respective sinks (Table 1) and the tracer travel-times (Table 2) that the Ames section of the flow path is more restrictive than the Kelly section, $C_{KS} >> C_{AS}$ where C is the conveyance capacity of the Kelly Sink (KS) and Ames Sink (AS) sections of the flow path. Under constant head and flow conditions, the width of the recovery curve would not only reflect longitudinal dispersion along the flow path, but also the $C_{KS} : C_{AS}$ contrast. Figure 16 presents a diagrammatic sketch of the probable hydraulic head configuration around Ames and Kelly Sinks and a series of hypothetical tracer recovery curves that would be produced by 1) independent tracer injections when only Ames Sink is receiving water, and 2) an injection into Ames Sink followed by a flood of tracer-free water into Kelly Sink at various times relative to the transport of the tracer mass.

In addition to the relationship between the conveyance capacity of the respective flow paths, the model presented in Figure 16 assumes that: 1) the pathway between Kelly Sink and Indian Spring is the primary groundwater flow path during low flow conditions; 2) flow along the Ames Sink section of the flow path is driven only by surface water runoff into the Ames Sink swallet; and 3) that surface water runoff into Kelly Sink only occurs as a result of flooding in Ames Slough that first overflows Ames Sink. All of these assumptions are supported by field observations. Flow into Kelly Sink has only been observed as a result of flooding in Ames Slough. During low flow periods, surface water stops flowing into Ames Sink and the water remains deeply tea-colored. During the same low flow periods, water clarity in Kelly Sink increases significantly to the point where the WKPP divers have explored the basin and a small connected cave and reported visibility similar to that observed in down-gradient springs. Moreover, their explorations have revealed that Kelly Sink is actually a karst window. They reported the conduit to be several feet in diameter; that it trends in both up-gradient and down-gradient directions for 100 or more feet; and that there was perceptible flow through the cave during their exploration.

The models show that, under the assumed conditions, a tracer recovery curve associated with a Kelly Sink injection should be taller and narrower than a tracer recovery curve associated with an Ames Sink injection due to a faster travel-time. The expected recovery curve from an Ames Sink injection, is complicated by the $C_{KS} : C_{AS}$ contrast in that once in the Ames flow path, the tracer massed would be released into the Kelly flow path at a rate slower than the velocity of the tracer once in enters the Kelly flow path. The resulting recovery curve should be nearly flat on top resulting from the slow continuous flux of tracer from the Ames flow path into to higher conveyance Kelly flow path, where the width of the curve at the flat part of the peak would be a function of primarily the $C_{KS} : C_{AS}$ contrast. A short duration flood of tracer-free water into Kelly Sink at any point during the transit of the tracer would result in a depression in the tracer recovery curve where the width of the depression is related to the duration of the inflow and the height of the depression is related to the magnitude.

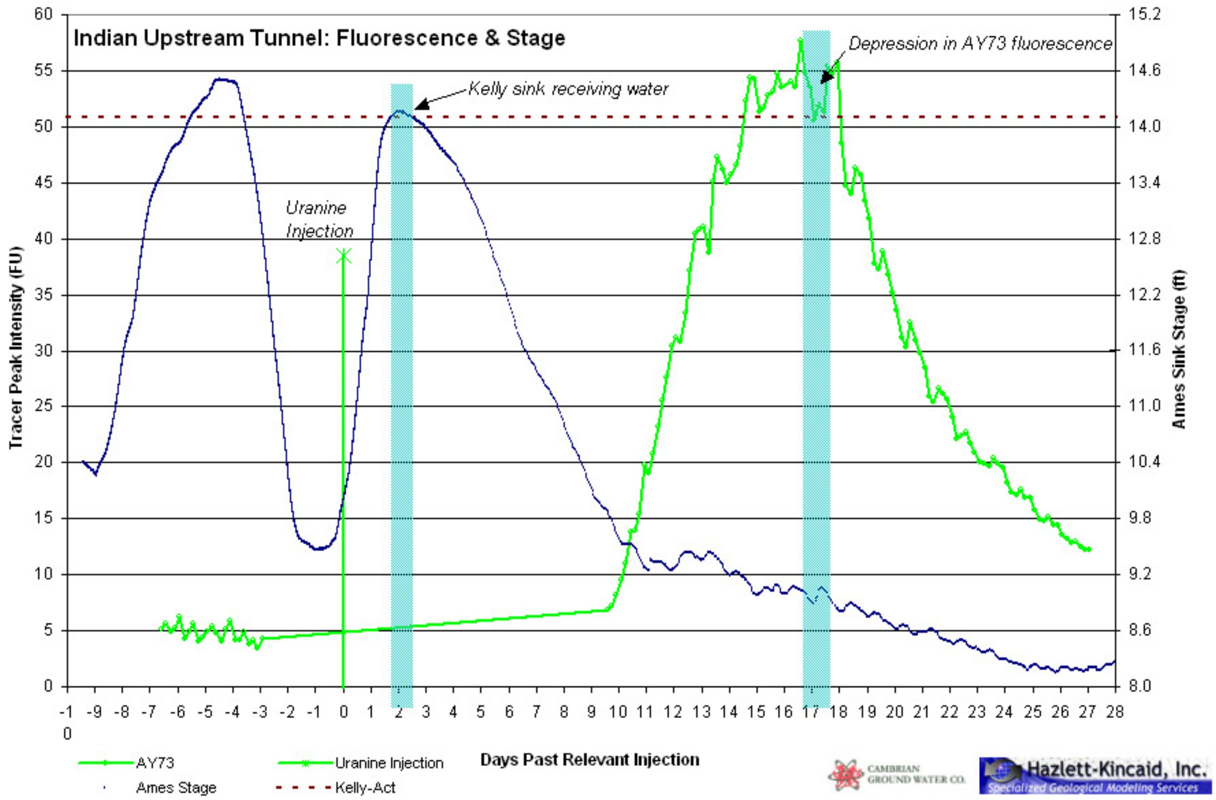


Figure 15. Tracer recovery curve for uranine recorded at the Indian Spring sampling station during the 2005 Ames Sink tracer test, Woodville Karst Plain Florida relative to the hydrograph at Ames sink spanning the period of the test. The uranine was injected immediately prior to a flood in Ames Sink that overflowed into Kelly Sink from Ames Slough approximately 2 days after the injection. The uranine recovery curve contains two distinct peaks wherein the depression between the peaks approximately correlates in timing and duration to the duration of flow into Kelly Sink. We therefore interpret the depression as dilution in tracer concentration resulting from a short duration flood of tracer-free water into the combined Ames/Kelly – Indian flow path at about the time that the tracer mass was passing the junction between the Ames and Kelly components of the pathway.

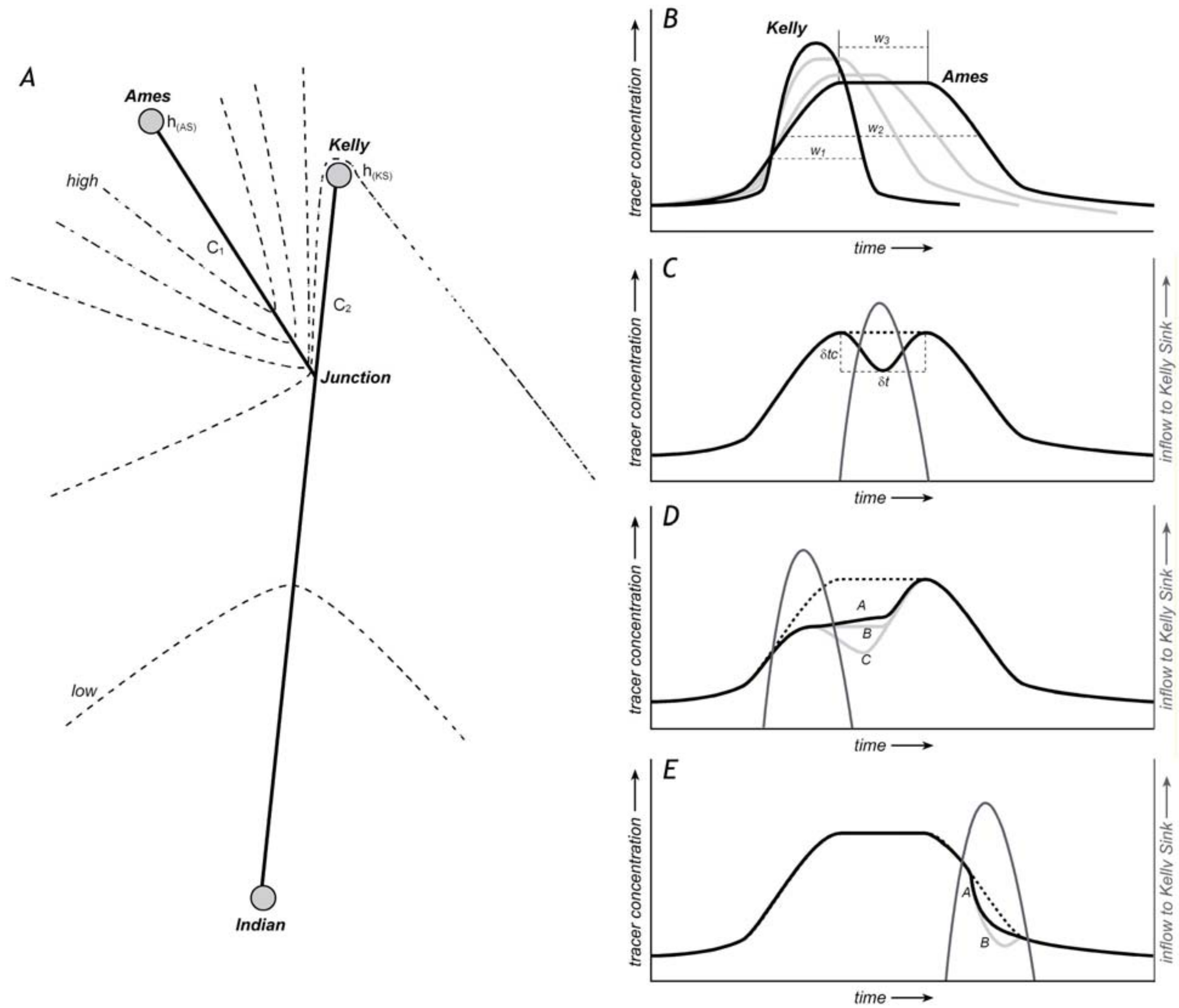


Figure 16. A) Diagrammatic model of the Ames/Kelly Sink to Indian Spring flow path and the probable hydraulic head configuration (dashed lines) associated with a constant flux of runoff into the Ames Sink swallet but no runoff into the Kelly Sink swallet. C_1 and C_2 denote the relative conveyance capacities of the Ames and Kelly sections of the flow path. B) Hypothetical tracer recovery curves (black lines) associated with independent injections into Kelly and Ames Sinks under the hydraulic conditions described for (A). The gray lines mark the influence of the C_1:C_2 contrast on the height and width of the Ames Sink recovery curve. C-E) The effect of a short duration flood of tracer-free water into Kelly Sink at various times relative to the transit of the tracer center of mass past the junction between the two flow paths. C) The flood into Kelly Sink occurs as the tracer center of mass is entering the Kelly section of the flow path where the height of the depression in measured tracer concentration is controlled by the magnitude of the flux into Kelly Sink and the width is controlled by the duration. D) The flood into Kelly Sink occurs before the tracer center of mass enters the Kelly section of the flow path where the shape of the leading edge of the recovery curve (A, B, C) is controlled by the magnitude and duration of the flood into Kelly Sink. E) The flood into Kelly Sink occurs after the tracer center of mass enters the Kelly section of the flow path where the shape of the tailing edge of the recovery curve (A, B) is controlled by the magnitude and duration of the flood into Kelly Sink.

4 SPECTROMETER AND IFF COMPARISON

In 2005, we recommended that the FGS purchase an insitu filter fluorometer (IFF) that could be deployed in the field and used to automatically collect real time fluorescence measurements without the need for water sampling and laboratory analysis. Few such devices exist and most of those in existence are designed to measure one range of fluorescence, typically meaning one tracer. Such devices have limited utility because our research has grown to depend on the simultaneous injection and measurement of multiple tracers.

We did however identify one device, the Schnegg downhole fluorometer (Schnegg and Kennedy, 1998), which permits the simultaneous measurement of three fluorescence ranges and turbidity. The design specifications indicated that the device should be able to efficiently measure green (uranine) and red (phloxine-B) fluorescence and that we may be able to calculate eosin fluorescence based on its cross-fluorescence into the green and red ranges. The device also measures blue fluorescence, which effectively tracks the fluorescence of natural tannins and turbidity, which can be an effective marker for surface water flow.

Based on these specifications, we purchased two devices and deployed them during the 2005 Ames Sink tracer test. The purpose of the deployment was to 1) test the devices and compare the resulting data against analytical data obtained from water samples for which we have a high level of confidence; and 2) determine if the devices could be confidently used alone or nearly alone in future tracer tests, specifically the Southeast Spray Field test that was proposed for 2006.

The purpose of this section is to provide a comparison of the spectrometer and IFF data obtained from the Ames sink test. Two IFFs were deployed, one at the Indian sampling station, and one at the Wakulla Vent sampling station. Though the IFFs are designed to be deployed underwater and are rated to depths well beyond those in the WKP, the location of the sampling stations well within Indian and Wakulla Caves precluded actual deployment of the devices at the stations. Instead, IFFs were deployed into a light-sealed container on the land surface that received a continuous flow of water from the same sampling tubes that were used to collect the spectrometer water samples. Unfortunately, the Wakulla IFF was found to not be functioning correctly and had to be sent back to the manufacturer for repair. Thus, the Indian station provided the only data with which to perform the comparison.

The IFF measures fluorescence by transmitting light in filtered excitation ranges for blue, green, and red bands of wavelength and then measures the resulting emitted filtered light in the respective filtered emission ranges. The IFF converts the collected light in the three separate ranges into voltage responses that are recorded in separate channels on a datalogger. The plots in Figures 17 – 21 show the voltage response as a measure of fluorescence. The IFF deployed at the Indian sampling station was programmed to record fluorescence every two minutes and operated continuously from May 13, 2005 at 9:06 PM to May 30, 2005 at 6:48 PM. Figure 17 provides a plot of the three fluorescence ranges and turbidity measured by the IFF. The data is provided electronically in Appendix III.

The IFF data shows that the only signal that displayed a significant change in trend during the sampling period was the green fluorescence. There is a clearly defined rise and fall in green fluorescence that mimics the shape of the uranine recovery curve obtained from the spectrometer data, contains the same twin peaks observed in the spectrometer data, and shows that the estimated peak passed the sampling station approximately 17 days after the Ames Sink injection, which matches the uranine travel-time measured by the spectrometer data. The twin peak signal is also evident in the blue fluorescence. The pattern shows a slow rise, pronounced fall, pronounced rise, and pronounced fall in natural fluorescence, that indicates an addition of tannin-rich water into the flow path that was diluted over a relatively short-duration time period.

One benefit of the IFF data is that it consistently measures both blue fluorescence and turbidity, which can both be used to measure changes in the source water entering the flow path. Both can therefore provide a proxy for changes in the background fluorescence in the green and red ranges, which can easily be filtered by subtracting the blue fluorescence or turbidity from the green or red readings. Afterward, the resulting green or red fluorescence curves should provide a cleaner and truer measure of fluorescence changes resulting from the presence of the injected tracers.

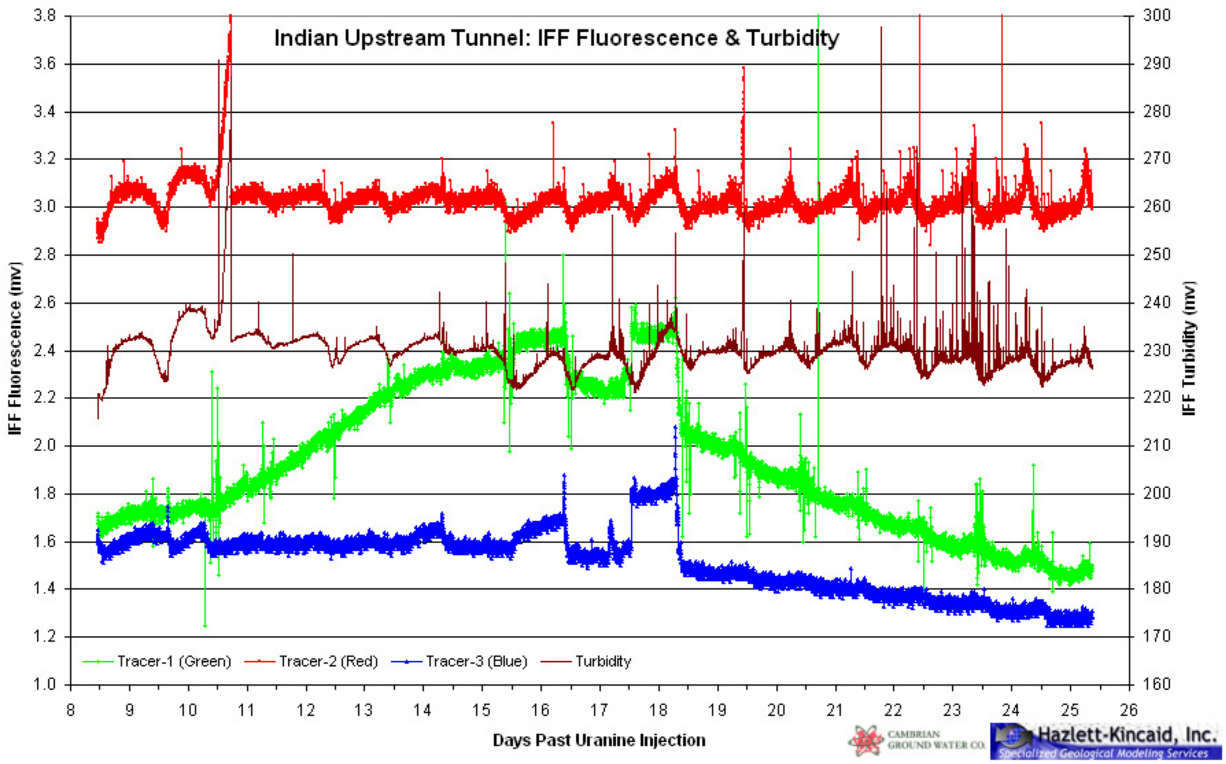


Figure 17. Fluorescence and turbidity measured by the insitu filter fluorometer (IFF) deployed at the Indian sampling station during the 2005 Ames Sink tracer test, Woodville Karst Plain Florida. The data shows a clear rise in the green fluorescence (a measure of uranine), that contains two distinct peaks at the top of the curve. The center of the two peaks was measured at approximately 17 days after the injection, which correlates to the arrival of the uranine peak measured by the spectrometer data (Figure 12) at the same station.

Figure 18 shows a plot of the green-blue fluorescence relative to the uranine data measured by the spectrometer. Figure 19 shows a plot of spectrometer vs. IFF fluorescence and shows the correlation coefficients for the whole curve and the leading and tailing sections of the curve independently. The plots show that the two data sets are very well correlated, where the leading and tailing sections of the curve show higher correlation coefficients than the curves as a whole. The slight deviation is therefore primarily restricted to the region around the peak where the timing and magnitude of the twin peaks evident in the both the uranine data (Figure 15) and the raw IFF data for green fluorescence (Figure 17) have been attenuated.

The presence of the twin peaks and apparent dilution in the green and blue fluorescence data and their attenuation after blue was subtracted from the green signal provides further evidence that the source of the dilution was the overflow into Kelly Sink described in *Section 2*. It follows that the rise in blue fluorescence reflects the flood into Ames Slough where the runoff water has sufficient residence time to incorporate tannins; that the depression in blue fluorescence reflects the overflow into Kelly Sink wherein runoff was flowing rapidly through the slough and into the Floridan aquifer before it could incorporate tannins; and that the subsequent rise in blue fluorescence marks the cessation of flow into Kelly Sink when the flood was subsiding and all recharge from the slough was again restricted to the lower capacity swallets (Ames and Ames2 Sinks). The presence of the twin peaks in the uranine data indicates that the spectrometer data reflects both the fluorescent signal generated by the uranine and that generated by the tannins.

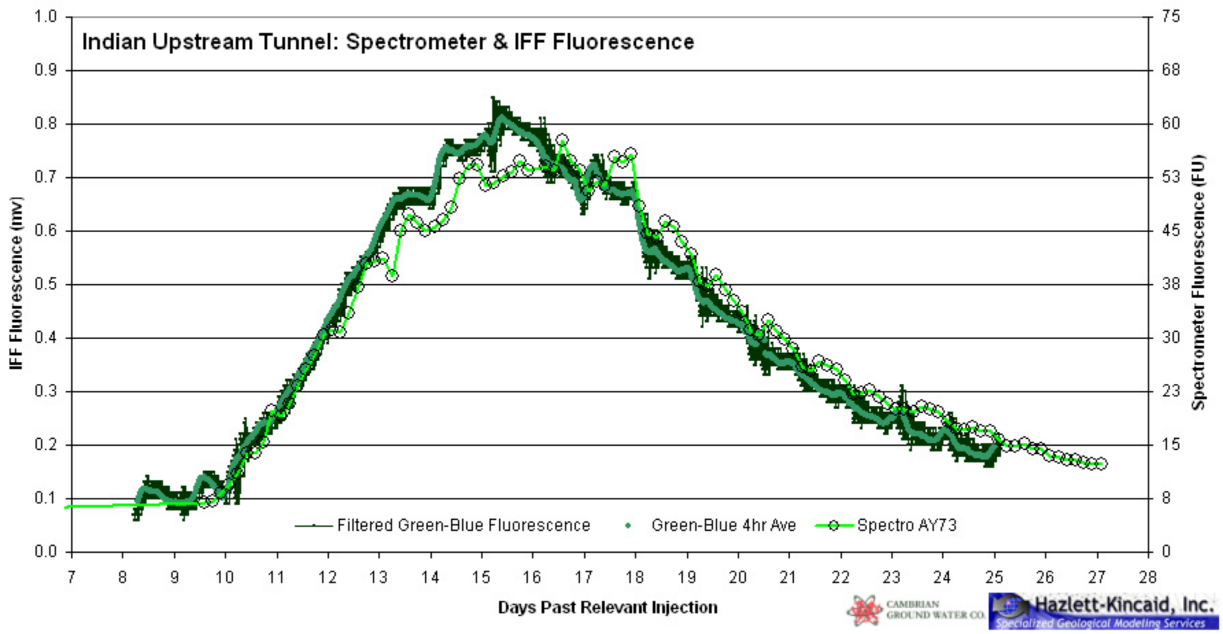


Figure 18. Comparison of the Spectrometer and IFF data measured in Indian Cave during the 2005 Ames Sink tracer test, Woodville Karst Plain, Florida. The IFF plot shows the green minus blue fluorescence filtered to remove all points that deviate from a 4-hour moving average by more than 1 σ calculated over the same section of data; and the 4-hour moving average of the resulting dataset.

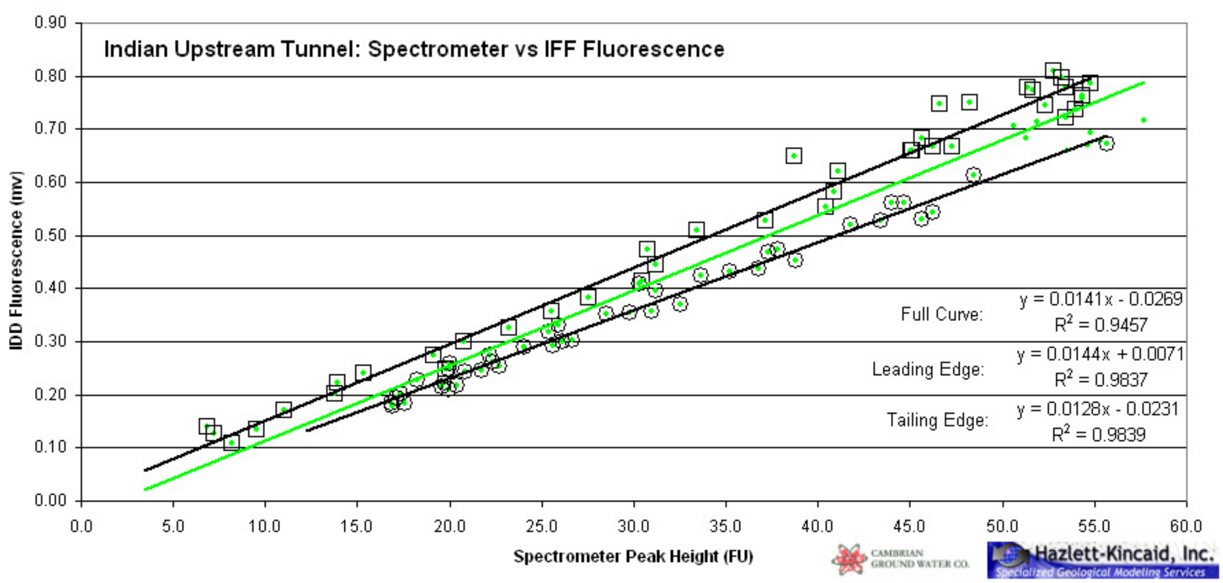


Figure 19. Spectrometer vs IFF data measured in Indian Cave during the 2005 Ames Sink tracer test, Woodville Karst Plain, Florida. Correlation coefficients are shown for the bulk curves, and the leading and tailing sections of the curves. Both the leading and tailing sections of the curves are almost identically correlated meaning that the deviation is restricted to the region around the peak where the twin peaks evident in the uranine data have been attenuated in the green minus blue fluorescence data.

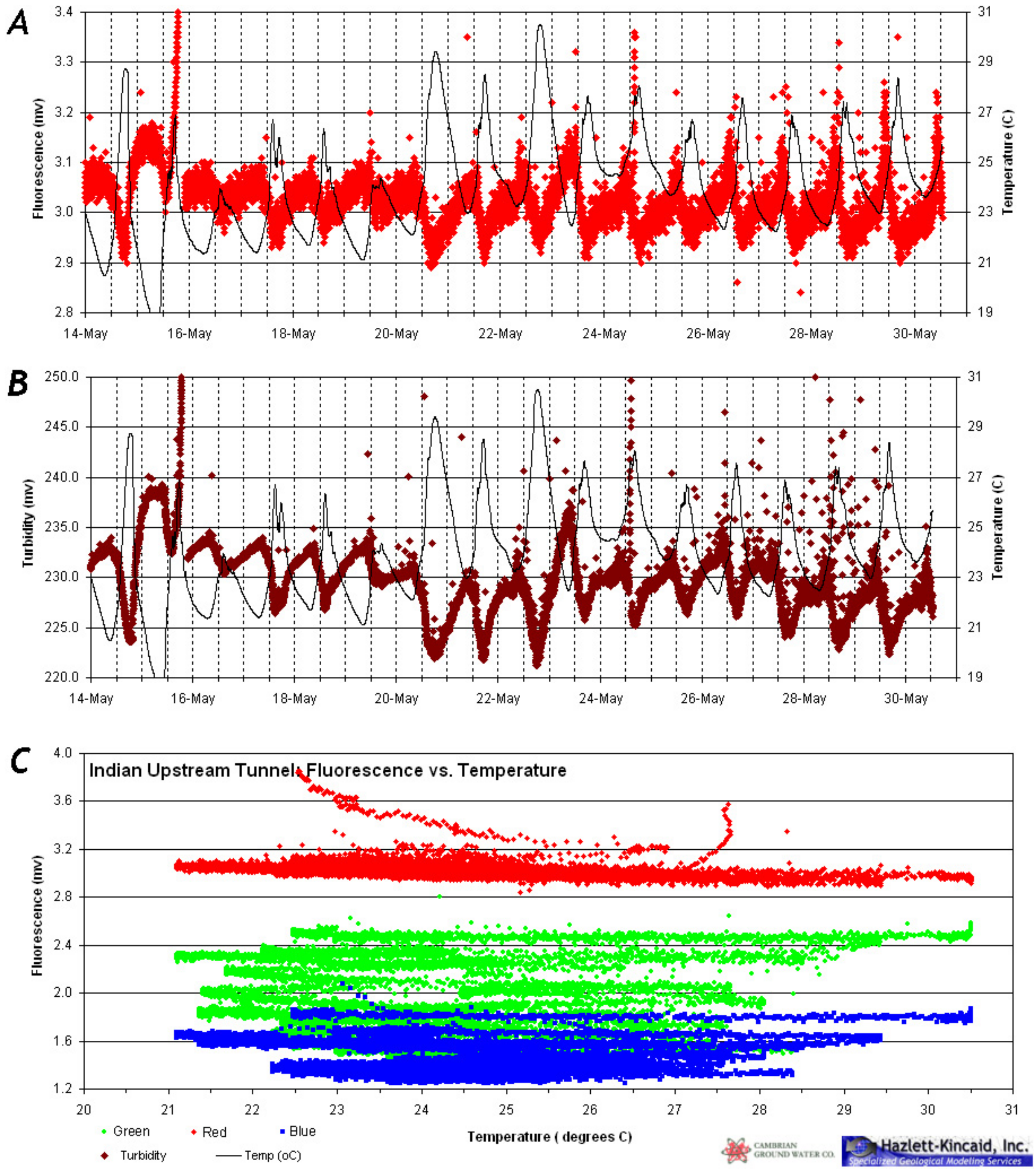


Figure 20. Fluorescence and turbidity relative to temperature measured by the insitu filter fluorometer (IFF) deployed at the Indian sampling station during the 2005 Ames Sink tracer test, Woodville Karst Plain Florida. The data shows a consistent negative correlation between (A) red fluorescence and temperature and B) turbidity and temperature. C) The correlation does not appear to hold for green and blue fluorescence.

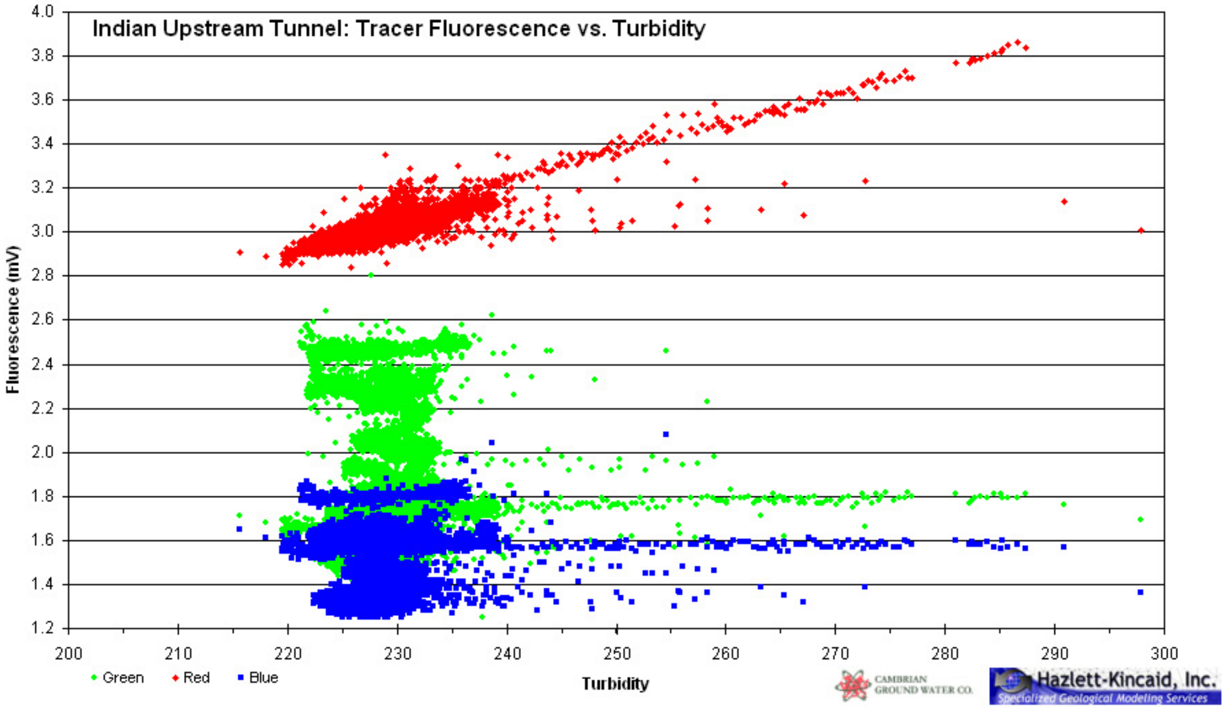


Figure 21. Fluorescence relative to turbidity measured by the insitu filter fluorometer (IFF) deployed at the Indian sampling station during the 2005 Ames Sink tracer test, Woodville Karst Plain Florida. The data shows a positive correlation between red fluorescence and turbidity but no apparent correlation between green or red fluorescence and turbidity.

Neither the red fluorescence or turbidity show any obvious pattern that could be attributed to the inflow from Ames or Kelly Sinks, however both display an obvious diurnal signal that is negatively correlated to temperature (Figures 20). We attribute this correlation to the daily rise and fall of temperature in the sampling container at the land surface where the maximum temperature is recorded at approximately 6:00 PM and the minimum temperature at approximately 6:00 AM. The correlation between red fluorescence and temperature indicates that the design of the sampling station should be modified such that the temperature of the sampling reservoir is held more constant and preferably close to the temperature of the formation water. Figure 21 shows that the red fluorescence also correlates to turbidity, which indicates that red dyes can be more easily masked by background signals in tannin stained turbid stream water than green dyes.

5 MASS RECOVERIES

Tracer concentrations were calculated for all water samples collected during the Ames Sink tracer test by calibrating measured peak heights on the spectrometer against known concentrations for standards prepared from each of the respective fluorescent dyes (Figure 22). Dye concentrations in the collected water samples were then calculated from the following equation:

$$C_T = ((PH_T - BG_T) \times CS_T) + CI_T \;;$$

where: C_T = tracer concentration,

PH_T = tracer peak height measured on the spectrometer (FU),

BG_T = average of peak heights measured prior to tracer arrival, i.e. background signal (FU),

CS_T = slope of the calibration curve for the respective tracer standards, and

CI_T = intercept of the calibration curve for the respective tracer standards *(set to zero)*.

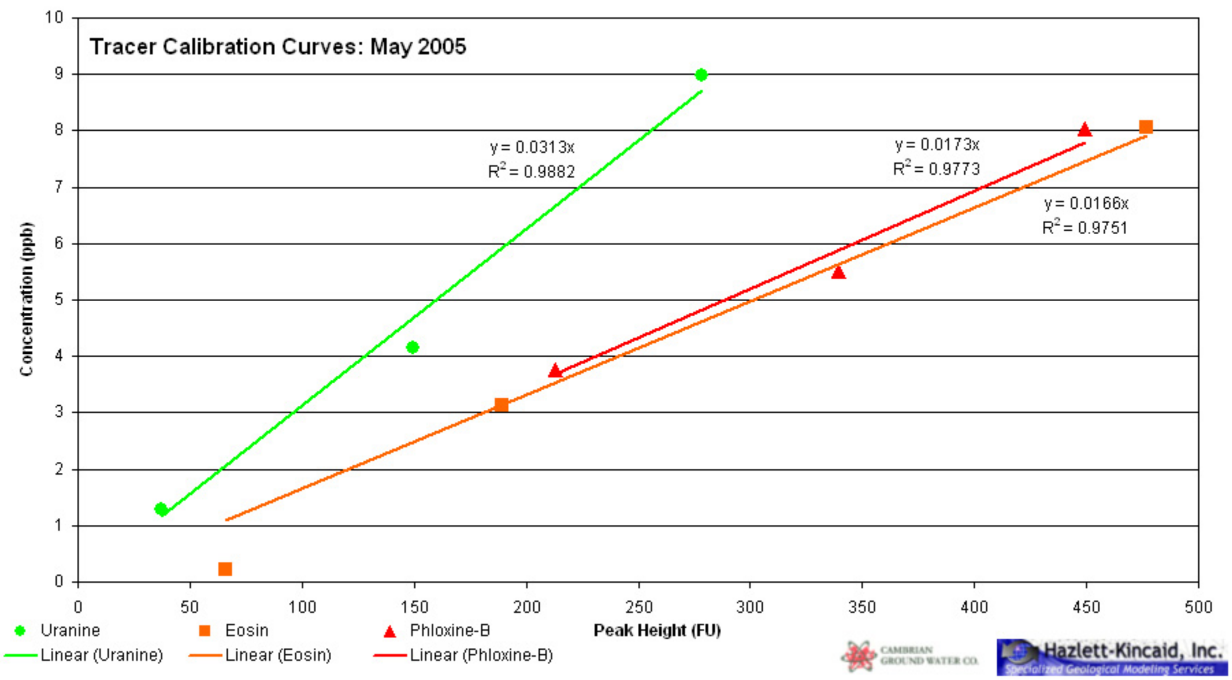


Figure 22. Calibration curves for uranine, eosin, and phloxine-B plotted from standards calculated in May 2005 during the Ames Sink tracer test, Woodville Karst Plain Florida. The slope for each trend is shown next to the respective line along with the correlation coefficient R^2.

The total mass of tracer recovered at each sampling station can then be determined from the calculated concentration in each sample, flow at the sampling station between samples, and the time lag between samples as follows:

$$MR_T = \sum_{i=1}^{n} Q_i \times (t_i - t_{i-1}) \times (C_{Ti} / 1E9);$$

where: MR_T = total mass of tracer recovered at sampling station (g),

Q_i = flow past the sampling station at sample i (cms),

t = time past tracer injection (seconds), and

C_T = calculated tracer concentration in sample i (ppb).

In order to accurately determine the mass of tracer recovered at each sampling station the following criteria must therefore be fulfilled.

- The tracer must be conservative, i.e. there can be no loss of tracer along the flow path due to adsorption/absorption, chemical reaction with the water or matrix, or biological degradation.
- The full tracer recovery curve must be measured.
- The water flow past the sampling station must be known when each sample is collected.
- The background fluorescence must be calculated for each sample.
- Sufficient tracer must be present in the sample to be measurable above the background fluorescence in the sample.

Figures 23 and 24 show the tracer recovery curves (in ppb) for the tracers detected at the Indian and Wakulla Vent sampling stations. Unfortunately none of the latter four criteria above were completely met at the sampling stations during the tracer test. Figures 12 and 13 show that the sampling periods were not long enough to record complete recovery curves for either uranine or eosin at any of the sampling stations. Complete recovery curves for phloxine-B were apparently measured at both K-Tunnel and the Wakulla Spring Vent though there are insufficient samples to confidently identify the background fluorescence levels at the end of the curves (Figure 12). Mass recoveries therefore reflect only the measured extent of the recovery curves except for the uranine curve measured at the Indian sampling station, which included a sufficiently well constrained tailing edge to extrapolate concentrations back to background levels (Figure 13). In each case however, it was impossible to be sure that some quantity of the tracers was not sequestered along the flow paths and therefore not measured in the recovery curves.

Flow measurements were also problematic. The sampling stations were located in conduits, often deep within the cave systems. Flow across the sampling stations could not therefore be measured or estimated directly. Falmouth hydraulic meters were installed at the Wakulla Spring Vent and Wakulla K-Tunnel during the tracer test, however the K-Tunnel meter was not functioning. A replacement meter was obtained but could not be deployed by the WKPP divers during the test due to poor water clarity conditions in Wakulla Cave. It was temporarily deployed at the Indian sampling station for a period of approximately two months immediately following the tracer test. The tracer recovery calculations shown in Figures 23 and 24 were based on an average of the flow measured during or as near to the tracer test as possible by the Falmouth meters installed at the Wakulla Spring Vent and Indian sampling station.

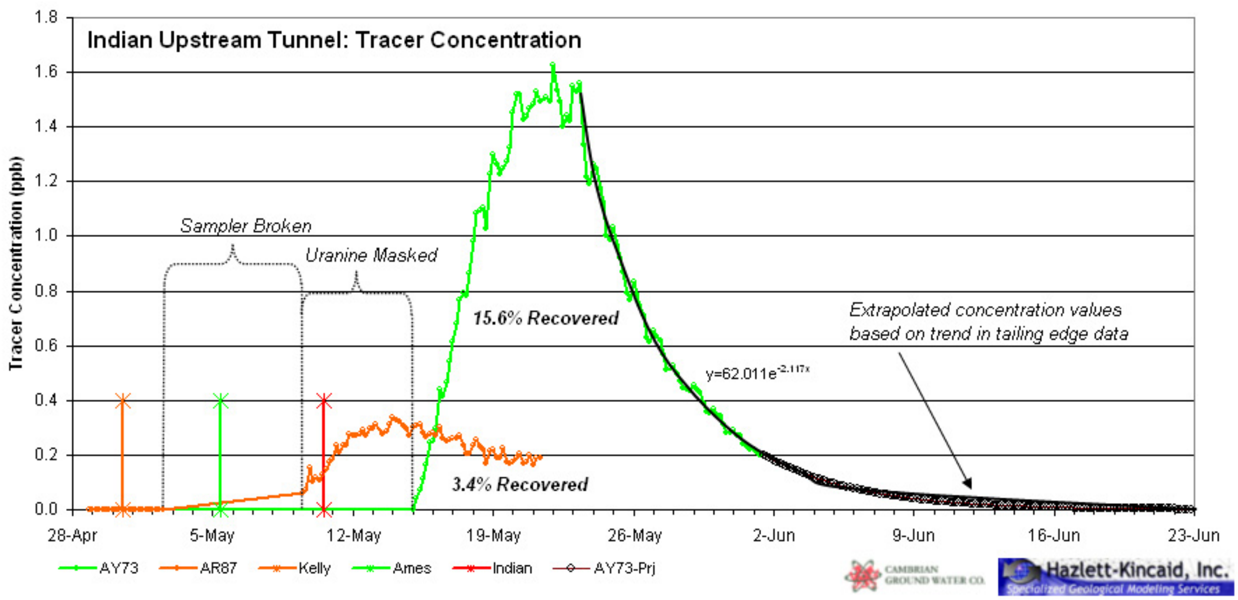


Figure 23. Uranine and eosin concentration recovery curves measured at the Indian sampling station during the 2005 Ames Sink tracer test, Woodville Karst Plain Florida showing the calculated percent of the injected tracers recovered at the station during the test. The uranine mass recovery incorporated an extrapolation of concentrations on the tailing edge of the curve to background levels based on an exponential curve fitted to the tailing edge of the recovery curve. The leading edge of the eosin curve was not measured due to a broken sampler. Both the leading edge of the uranine curve and the tailing edge of the eosin curve were masked by the presence of the other tracer in the water samples and thus concentrations were not calculated for those periods. The tailing edge of the eosin curve was not extrapolated because there were insufficient points on the tailing edge of the curve to yield a confident trend. Note that the phloxine-B was injected as the leading edge of the eosin curve was passing the sampling station indicating that the two tracers traveled nearly together down-gradient.

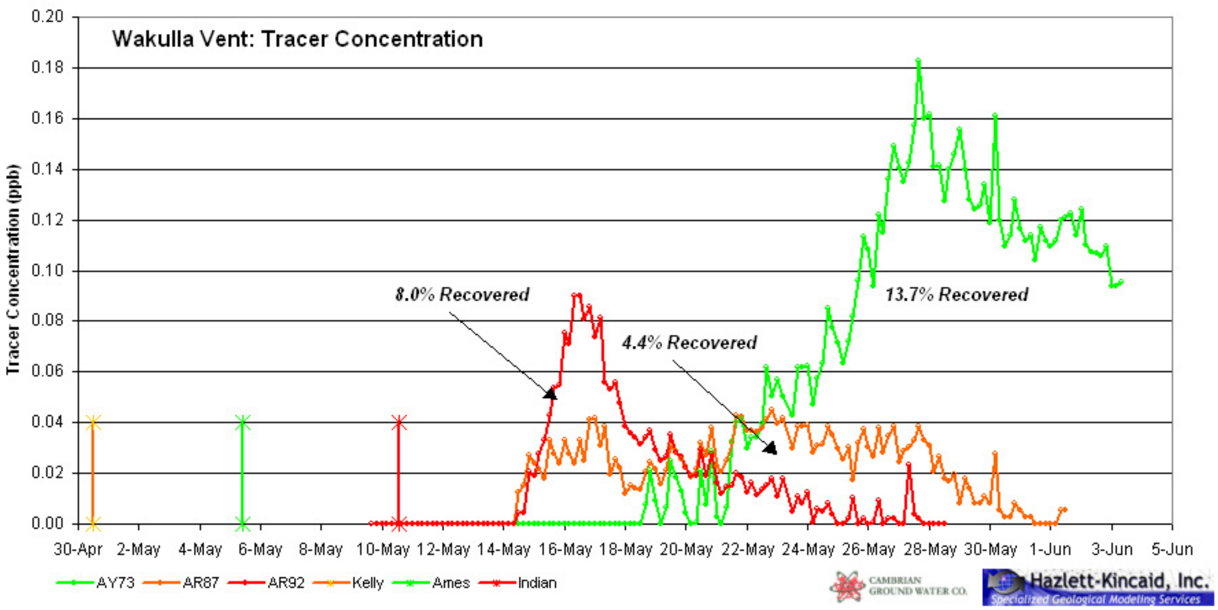


Figure 24. Uranine, eosin, and phloxine-B concentration recovery curves measured at the Wakulla Spring Vent sampling station during the 2005 Ames Sink tracer test, Woodville Karst Plain Florida showing the calculated percent of the injected tracers recovered at the station during the test. The magnitude of the eosin curve is likely attenuated due to masking by both phloxine-B, which traveled simultaneously with the eosin, and uranine, which arrived slightly after the eosin but overlapped the recovery curve significantly.

The background fluorescence levels were not measured specifically for each sample. Rather, the background levels for the mass recovery calculations were assumed to remain constant throughout the test and were assigned the estimated average fluorescence level measured for each tracer prior to the first arrival of the tracers at the sampling stations (Figure 12 and 13 and Appendix II). We believe that this assumption resulted in an under estimation of the total mass recovered because the background fluorescence apparently declined during the course of the test (*see the blue fluorescence trend in Figure 17*).

The recovery plots and calculations show that a relatively small amount of the injected tracers was recovered at the sampling stations. There are at least four possible explanations for the relative low recoveries.

1. A relatively large quantity of the tracers was carried by the groundwater to discharge points that were not sampled. The only reasonably possible such discharge would be Spring Creek springs as all of the other large magnitude springs in the basin were sampled. We believe that Spring Creek and Wakulla are hydraulically connected, probably by one or more conduits and that a groundwater divide crosses the conduit(s) somewhere between the southern part of Wakulla Cave and Spring Creek Springs (Werner, 1998; Kincaid, 1999; Loper, et al., 2005). It is therefore possible that some portion of the water from Ames Sink could be flowing to Spring Creek Springs. Based on the lack of tracer detections in the Leon Sinks Cave System or McBrides Slough (Figure 9) however, such a diversion must occur south of Indian Cave and most likely within the southern part of Wakulla Cave. Further testing will have to be performed to evaluate the probability of a diversion to Spring Creek.
2. A large part of the tracers could have been sequestered in the conduits for a period longer than the sampling period minus the travel time from that point. Though we have observed sequestration in karst windows connected to the conduit flow paths and in large chambers within the conduits, such an occurrence should be evident in the tailing edge of the recovery curve, which it is not in any of the measured curves.

3. A large part of the tracers could have passed the sampling stations at levels below the spectrometer detection limit, however, the mass recovery calculated from the measured and extrapolated tracer concentrations at the Indian sampling station indicate that this is unlikely.
4. A large part of the tracers could have adsorbed onto or absorbed into the conduit walls and/or aqueous organic compounds in the conduit flow. We believe this to be the most probable mechanism responsible for the low observed tracer recoveries supported as follows.

Figure 25 provides a plot of the tracer concentration recovery curves calculated for the tracer test between Emerald Sink in the Leon Sinks Cave System and Wakulla Spring conducted by HKI and CGW in 2004 (Hazlett-Kincaid, 2004). For the purpose of this analysis, it is assumed that the recovery curve at Upper River Sink measured 100% of the injected tracer. The resulting flow at that location is 118.2 cfs (3.3 cms), which correlates to the approximate average flow measured at Turner Sink by a Falmouth hydraulic meter installed there for two weeks in December 2003.

Mass recoveries calculated at Turner Sink, and Wakulla K-Tunnel and AK-Tunnel are based on an assumption of constant flow between Upper River Sink and those locations whereas the calculation at the Wakulla Spring Vent is based on the flow measured at that location during the tracer test by a Falmouth hydraulic meter. The assumption of constant flow between Upper River and Turner Sinks is reasonable based on the lack of mapped inflowing conduits between those two points in the Leon Sinks Cave System. The constant flow assumption between Turner Sink and Wakulla K-Tunnel may be underestimating flow by 30-50 cfs (1-1.5 cms) based on the traced connection between Indian Cave and Wakulla Spring (Figure 9) and the flow measured by a Falmouth hydraulic meter in at the Indian Cave sampling station in July 2005.

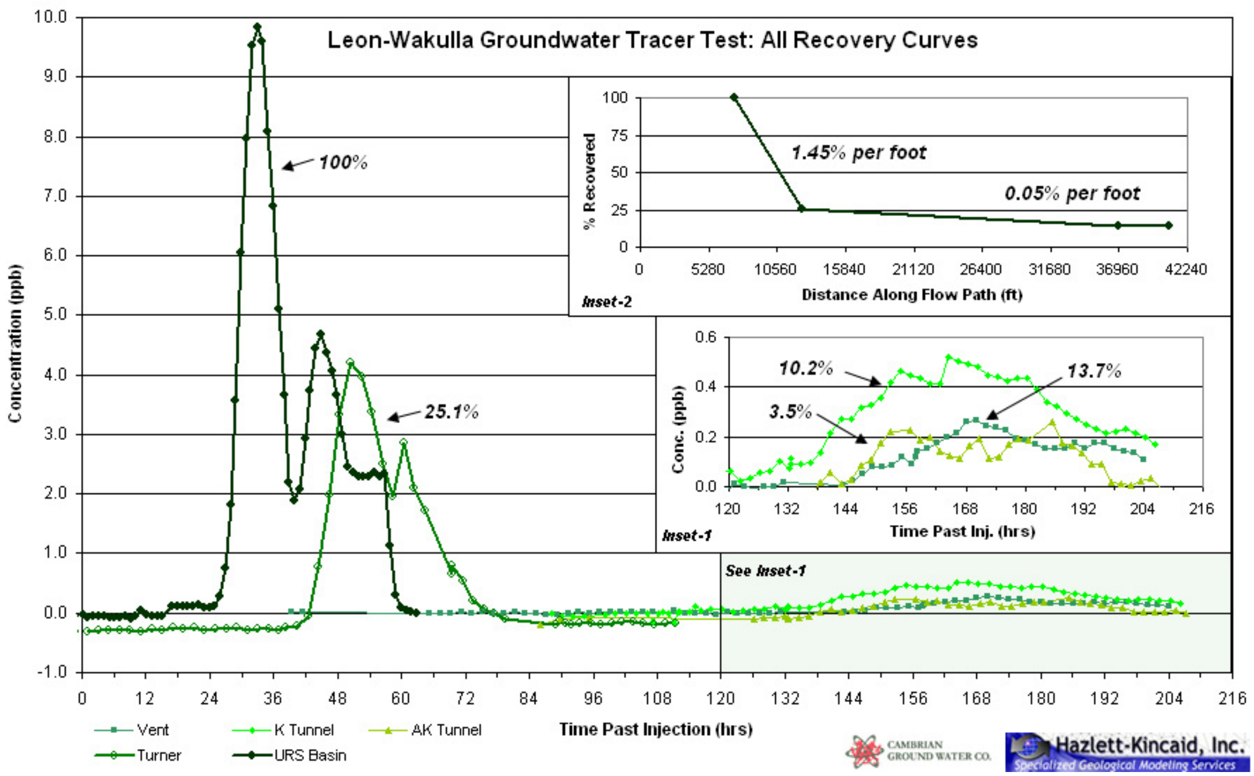


Figure 4-25. Uranine concentration recovery curves measured during the 2004 Leon Sinks – Wakulla tracer test, Woodville Karst Plain Florida showing the calculated mass recoveries and a plot of reduction in mass recovery vs. distance along the conduit flow path. Mass recoveries at Upper River Sink, Turner Sink, and Wakulla K-Tunnel and AK-Tunnel are based on an assumption of 100% recovery at Upper River Sink an assumption of constant flow between Upper River Sink and Wakulla K-Tunnel. The mass recovery calculated for the Wakulla Spring Vent is based on the average flow measured at that location during the testing period by the Falmouth hydraulic meter.

There are three important things to note in Figure 25.

1. There is an apparent loss of nearly 75% of the tracer between Upper River and Turner Sinks, which are separated by only approximately 7000 feet along the main Leon Sinks conduit.
2. There is a significantly lower apparent loss of tracer between Turner Sink and Wakulla K-Tunnel and AK-Tunnel, which are separated by nearly 35,000 feet along the traced pathway. Note that if the flow was higher than the assumed value at K-Tunnel and AK-Tunnel the apparent loss would be further reduced.
3. There is no apparent loss between the K-Tunnel / AK-Tunnel junction in Wakulla Cave and the Wakulla Spring Vent, which are separated by nearly 4000 feet along the main Wakulla conduit.

In the context of the above observations, there are two important things to note in Figure 4-33.

1. There is less than a 2% loss in the recovered uranine between the Indian Cave and Wakulla Spring Vent sampling stations.
2. There is an apparent 92% loss in the phloxine-B between the same sampling stations.

In both plots the largest apparent loss in recovered tracer occurs nearest to the injection points where the tracer concentration is highest. This observation indicates that adsorption and/or absorption are likely mechanisms for the apparent decline in mass recoveries because either process will be most effective when the tracer concentrations are highest in the conduit water.

Fluorescent dyes are known to be highly adsorptive on organic molecules such as charcoal, which provides the means by which charcoal traps have been shown to be effective dye collectors in qualitative tracer tests (Smart and Laidlaw, 1977; Alexander and Quinlan, 1992). The waters in the Ames Sink flow path and particularly within the Leon Sinks Cave System contain significant quantities of aqueous organic material derived from rapid infiltration from swallets and the conduit walls contain significant mineralization such as goethite. Both provide opportunities for significant adsorption and/or absorption.

Though it is certainly possible that some portion of the water from Ames Sink was diverted to down-gradient springs such as Spring Creek and thus not detected, the possibility that adsorption/absorption contributed significantly to the low apparent mass recoveries is strong. Further investigations need to be carried out to evaluate both of these possibilities such that the prominence of the respective flow paths can be effectively evaluated.

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7 APPENDICES

7.1 Appendix I: Stage Data for Ames Sink and Flow Data for Ames, Ames2, and Kelly Sinks (Attached CDROM).

7.2 Appendix II: Tracer Recovery Data from the 2005 Ames Sink Tracer Test

7.3 APPENDIX III: FLUORESCENCE DATA MEASURED BY THE INDIAN CAVE IFF DURING THE 2005 AMES SINK TRACER TEST (ATTACHED CDROM).