

The application of quantitative fluorescent dye tracing to evaluate karst hydrogeologic response to varying recharge conditions in an urban area

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Abstract Quantitative dye-tracing methods were utilized in a portion of the greater Springfield, Missouri metropolitan area. These methods were used to evaluate factors influencing groundwater movement through the shallow karst system in the area. Fortuitous timing of these studies with a summer drought allowed for very low-flow conditions to be tested, and the results of these tests suggest that shallow groundwater in the study area occurs in fractures and along bedding planes, with a significant input component from flow along bedding planes or other sub-horizontal features. Based on one unique trace, it appears that recent dye traces may be affected by groundwater elevations, where crossover from one conduit system to another occurs under most water level conditions, but ceases under the lowest flow conditions.

Keywords Dye tracing · Karst · Hydrogeology · Springfield · Missouri

Introduction

The Springfield Plateau in Southwestern Missouri comprises the westernmost portion of the Ozark Plateau physiographic province. In general, the Springfield Plateau is underlain by Mississippian-aged limestone and cherty limestone rocks that have not been extensively dissected, although caves, springs, solution-enlarged joints, and other

karst features are common in the region (Emmett et al. 1978). Soil and regolith in the region are reported to range from a thin veneer to more than 12 m in thickness (Stohr et al. 1981). Geologic factors such as solution-enlarged bedding planes and fractures strongly affect the rate and direction of groundwater flow and have the potential to reroute surface flow from one surface watershed to another through the groundwater system in karst systems (Brahana 1997; White 2002; Gouzie et al. 2010). This study reports results from dye-tracing studies in a rapidly growing urban area on the southern margin of Springfield, MO.

Study area

The study area is located in southwest Missouri in Greene County, in the rapidly developing southern portion of the urban area of Springfield. A map of the project area is shown in Fig. 1.

Climate

Greene County has a humid continental climate with relative humidity ranging from 73 to 77 % and an average annual rainfall of about 1 m. April, May, and June have the most precipitation; the least precipitation occurs in the winter months. Average annual temperature is 15 °C and ranges from −20 °C in the winter to 38 °C in summer (NOAA 2007).

Surface water

Greene County is dissected by streams with a dendritic drainage pattern. Many streams are spring fed. Over 400 mapped springs have been documented in the county

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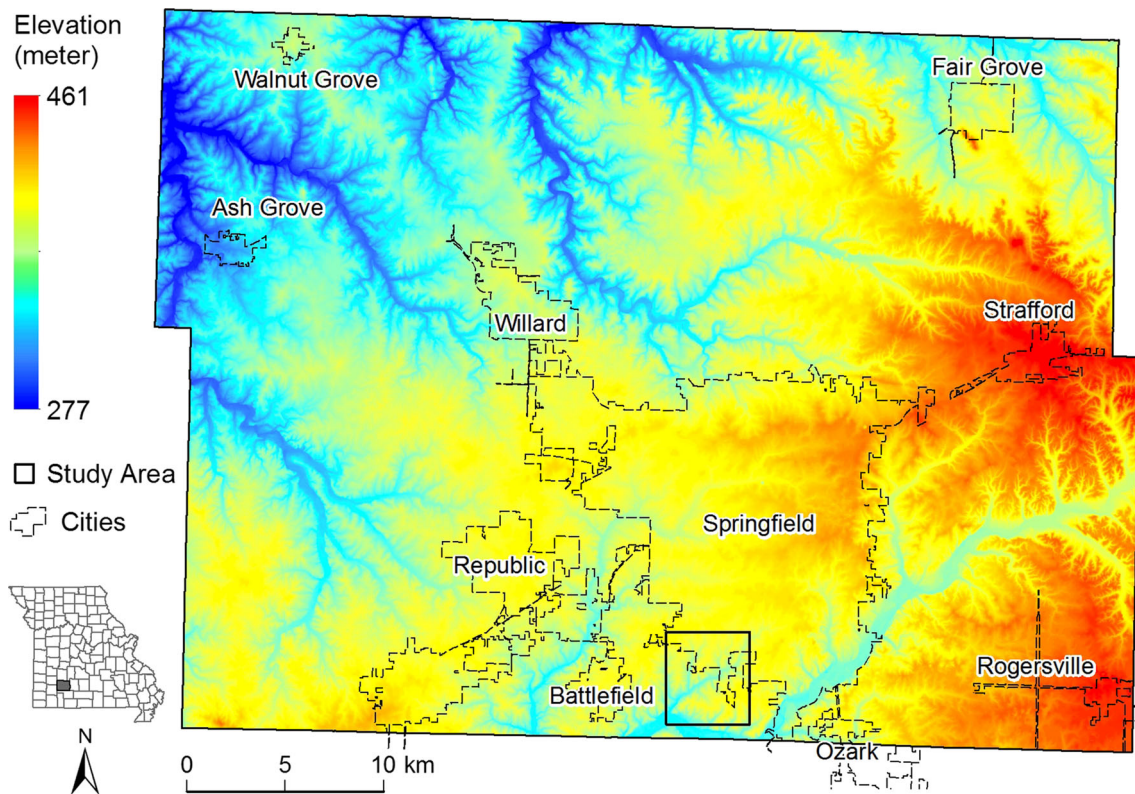


Fig. 1 Greene County, Missouri, with city boundaries and highlighted study area

(Bullard et al. 2001). A number of streams have also been documented to have losing segments (MDNR 2007).

Topography

The study area is situated on the southern edge of metropolitan Springfield (Fig. 1). Elevation in the study area steadily drops from north to south toward the James River valley. The highest elevation is 396 m (1300 feet) at the northern edge of the study area and 341 m (1120 feet) at the James River valley to the south with a total relief of 55 m (180 feet).

Karst hydrology

The study area is located within the Ward Branch watershed, a smaller tributary of the James River basin (Fig. 2). The Ward Branch stream flows to the southwest into the James River, the major drain for the southeastern portion of Springfield. The Ward Branch flows both perennially and intermittently along certain stretches. A small unnamed intermittent stream tributary to Ward Branch is shown on the Springfield USGS 7.5 min topographic map, but is no longer present due to urban roadway construction and modification of the original topography.

Groundwater flow in the study area has been studied through dye traces (MDNR 2007), many of which are shown in Fig. 2. Within the study area, near-surface groundwater generally flows in a southerly direction, with some components of flow to either the southwest or the southeast. The Springfield Aquifer sits atop the Ozark Confining Unit which separates and isolates it from the Ozark Aquifer. Wells completed in the Springfield aquifer usually have low yields of less than 75 L per minute, and the aquifer is therefore only adequate for small-scale domestic water use (Emmett et al. 1978). Due to thin soil cover and extensive sinkholes, fractures, and losing streams, it is highly prone to contamination. Beneath the Springfield Plateau Aquifer is the relatively thin Ozark Confining Unit, Kinderhookian in age and comprising shale, silt, and limestone. Beneath the Ozark Confining Unit is the more productive Ozark Aquifer. The Ozark Aquifer is the region's productive aquifer formation. The measured elevation of the water table in the Ozark Aquifer is around 305 m (1000 feet), which is 42–82 m (140–270 feet) below the surface.

Stratigraphy

The Burlington Limestone is the dominant rock formation outcropping in the study area. This rock unit is a gray to

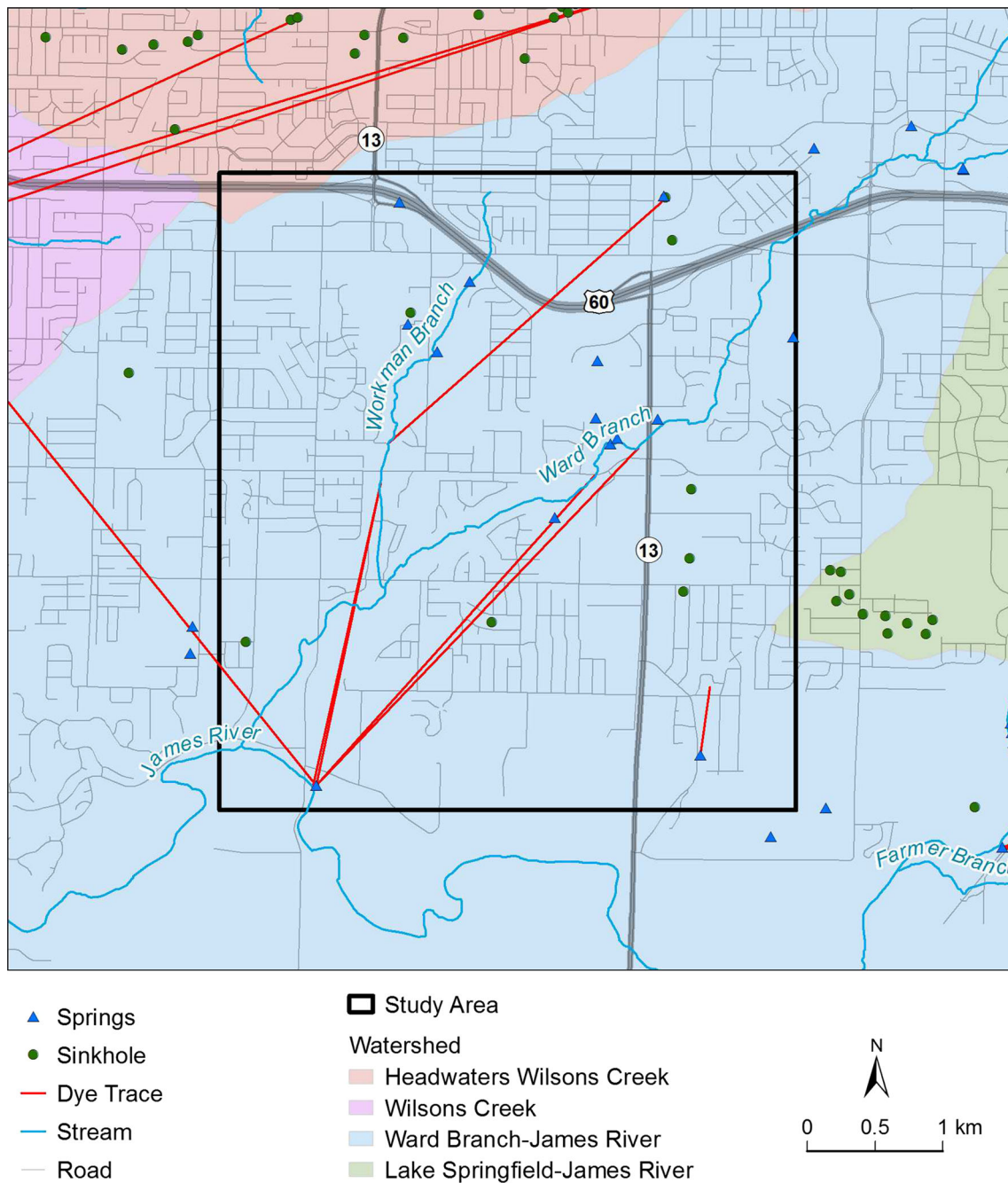


Fig. 2 Study area with relevant hydrological and karst features, including streams, springs, sinkholes, and dye traces

white, reddish-brown to dark gray weathered, coarsely crystalline, crinoidal limestone (Vandike and Shennan 1994). Chert nodules and thin chert horizons can also be found throughout this unit and become more extensive toward the base. This rock unit is near horizontal, with dips less than a few degrees and up to 45 m (150 feet) thick within the study area. The Burlington Limestone is a relatively pure limestone and thus is highly susceptible to dissolution and contains many caves, springs, and sinkholes. The Elsey Formation lies directly beneath the

Burlington Limestone and is distinguishable by its abundance of chert (up to 50 %). Due to the thickness of the Burlington Limestone and low topographic relief of the Springfield Plateau, the Burlington Limestone is the only rock unit to outcrop in the study area.

These local sedimentary rock units are nearly horizontal with a regional west–southwest dip of less than 1°. Structural deformation is limited to west–northwest trending faults and fractures with lesser northeast orthogonal pairs. Faulting is considered to be post-Mississippian and pre- or

syn-Pennsylvanian (Thomson 1986) and may be associated with the Ouachita Orogeny during the Pennsylvanian (Cox 2009).

Chemical weathering along fractures in the Burlington Limestone produces an irregular soil–bedrock boundary. When vertical bedrock fractures widen through dissolution, a series of bedrock high points (pinnacles) are left in between the widened, soil-filled fractures (cutters), resulting in irregular depth to bedrock and soil thicknesses.

Soil

Local soil is thin, and nonindurated material above the epikarst varies from bedrock residuum to stream alluvium deposits. The thickness in the study area varies irregularly from 0 to 14 m (0–45 feet), thickening southward toward the James River. Weathering of the Burlington Limestone produces a dark reddish-brown clay soil. Alluvium in stream valleys consists of rounded to angular chert cobbles and gravel weathered from the limestone along with red clay. Fragments of limestone and dolostone are also found in the alluvium and residuum (Thomson 1986).

Study sites

Within the study area, seven study sites were chosen to characterize the local karst system (Fig. 3). These study sites were chosen based on accessibility, proximity to karst hydrogeologic features, and previous studies.

Site A: Young's Farm cave 1 sinkhole

This site contains a karst window comprising a spring, sinkhole, and cave. A spring flows into the sinkhole from the north, which drains into Young Farm Cave 1 on the southern edge of the sinkhole, at an elevation of approximately 380 m (1248 feet) above mean sea level (MSL). During this study, the cave appeared to be filled with sediment but still drained water from the spring. Dye traces by Tomlin (2010) show that this sinkhole drains southward to the Waffle House Upwell Spring (Site E) and Ward Farm Spring (Site D).

Site B: Interchange detention basin and sinkhole

This site is a surface water detention basin on the southwest side of the James River freeway/South Campbell Interchange. Within the basin is a newly forming sinkhole, visible as a north–south elongated surface depression and soil scarp, 26 by 13 m wide and 1 m deep at the center. Extensional cracks in the soil are visible around the perimeter of the sinkhole. No previous dye traces have been performed here.

Site C: Ward Branch Stream sink

This site contains a stream sink in the Ward Branch stream located within the Twin Oaks Golf Course. The Ward Branch stream flows from the north and goes into the sink at an approximate elevation of 366 m (1202 feet) MSL, beneath a cart bridge. During low-flow conditions the sink pirates most of the stream flow, resulting in the Ward Branch becoming dry downstream to the Waffle House Upwell Spring. Previous dye traces by Tomlin (2010) show this stream sink drains all flow in Ward Branch for most flow conditions and resurfaces at the Waffle House Upwell Spring (Site E).

Site D: Ward Farm Spring

Two springs on a southward facing hillside flow into the Ward Branch at this site. One of the springs is perennial and is marked by an old brick spring house and issues forth at an elevation of approximately 355 m (1165 feet) MSL. The second spring, a few meters to the east, flows intermittently as an overflow of the main spring. Combined discharge of these springs during base flow conditions is typically 28–85 L/s (1–3 cubic feet per second). Previous dye tracing by Tomlin (2010) shows that sinkholes to the north (including Young's Farm Cave 1) drain to this spring.

Site E: Waffle House Upwell Spring

This site contains a perennial upwelling spring and cave spring which flow into Ward Branch stream. The perennial rise pool is at an elevation of approximately 357 m (1170 feet) MSL and is the source of flow for Ward Branch downstream from this reach. Upstream Ward Branch is typically dry, flowing only during intense storms.

Discharge of the spring during baseflow conditions is typically 85–140 L/s (3–5 cubic feet per second). A cave in the hillside also provides a source of flow during high-flow conditions and storm events. Dye tracing by Tomlin (2010) indicates that this upwell spring is mostly recharged from the Ward Branch stream sink.

Site F: Ward Branch stream/James River confluence

This site is along the Ward Branch stream just upstream of its confluence with the James River. Surface water flows from the north into the James River, which then flows west. Discharge at this location is typically 56–113 L/s (2–4 cubic feet per second) during base flow conditions. Between this location and Ward Farm Spring, the Ward Branch stream is dry for about half of the total 2.5 km distance.



Fig. 3 Aerial photograph of study area showing the location of dye injection and resurgence sites. **a** Young’s Farm cave 1, **b** Interchange detention basin, **c** Ward Branch Stream sink, **d** Ward Farm Spring,

e Waffle House Upwell Spring, **f** Ward Branch at James River confluence, and **g** Patterson Spring

Site G: Patterson spring

This site contains a spring which flows out of a bedding plane along the northern bank of the James River. Patterson Spring is found about 30 m (100 feet) east of the first bridge crossing the James River just south of Riverbluff Cave on County

Road 141. Occasional high flow of the James River scours sediment and exposes the fractured bedrock layer. Water has been seen flowing through the fractures during these times of exposure, issuing from the bedding plane for about 30 m (100 feet) along the river bank. Discharge of the spring during base flow is visually estimated at 850–1400 L/s

(30–50 cubic feet per second). Previous dye traces by the Missouri Geologic Survey (MDNR 2007) show that this spring is recharged from the north.

Methods

Flow paths in karst aquifers are seldom apparent from the surface. Because of this, dye tracing was developed for use in karst aquifer systems. Dyes can be injected into sinkholes or caves and dye observation at downgradient detection points gives insight into the local conduit network based on dye breakthrough times, discharge, and multiple concentration peaks due to dye bifurcation, or splitting and rejoining conduit paths (Smart and Karunaratne 1988).

Dye injection

Using constant-rate dye injection along with automatic water samplers allows for a unique way to conceptualize karst conduit geometry. By using the quantitative constraints placed on the dye trace, concentration of injected dye, rate of dye injected, spring discharges, and concentration of dye in spring water, a model of the karst conduit system can be conceptualized. This also allows for dye recovery to be calculated as a ratio between dye discharge into losing streams and dye discharge out of springs, as opposed to the traditional method of the ratio between total mass of dye recovered to total mass of dye injected (Thraillkill and Gouzie 1984). Treating these dye traces as mass balance calculations gives insight into the conduit system by showing which flow paths act as open or closed systems indicated by variations in dye concentration and spring discharge.

For this part of the study, a 12-V, low-volume, steady-rate dye pump system injected Rhodamine WT liquid dye into the Ward Branch stream sink. While the dye pump system was operating, single injections of Lissamine Flavine FF and Pylaklor Orange dyes were input as 4–8 L slugs of dye and then flushed with additional water (municipal supply) into the interchange detention basin sinkhole (Site B) on two separate occasions.

Dye monitoring

Passive-dye receptors (carbon packets) were prepared with 3.0 g of activated carbon secured in a screen mesh and secured to wire and concrete anchors. Hach Sigma 900 24-bottle portable autosamplers were used for collecting 500 mL water samples on an hourly schedule. Autosampler bottles were replaced every 24 h until the end of each 72-h dye trace and the water from each bottle was analyzed for the presence of the specific dyes within a day of collection. Carbon packets were typically replaced every 2–3 days.

Carbon packets were rinsed to remove dirt and debris, dried 24–48 h in a dark cabinet, then emptied into an eluent of 19 mL 95 % ethanol and 1 mL ammonia hydroxide (Tomlin 2010), agitated for 10 s, and left for 1 h to elute the dye from the charcoal. The resulting eluent was analyzed for the presence of dye. Autosampler bottles required no processing before dye concentration could be measured.

Fluorometric analysis

Dye concentrations in spring water and eluent were measured using a Hitachi F-2500 Fluorescence Spectrophotometer. Spectral working curves were produced using prepared solutions with known concentrations of each dye. The photometer was programmed to excite a sample with a specified wavelength and scan for fluorescence emission in a different specified wavelength. Rhodamine WT maximum excitation wavelength was 530 nm and maximum emission fluorescence was at 555 nm. Lissamine Flavine FF excitation wavelength was 422 nm and maximum emission was at 512 nm, and Pylaklor Orange excitation was at 515 nm and emission was at 540 nm.

Results

Dye tracing

For this study, two dye traces were performed for two hydrologic conditions: a medium-flow trace and a low-flow trace. The medium-flow trace was performed during early July, with a total of 33.5 mm of rainfall during the 10 days preceding the trace and the low-flow trace was performed during late August when there had been no precipitation (0 mm) during the 10 days preceding the trace. For both traces, diluted Rhodamine WT liquid dye was injected into the Ward Branch Stream sink (Site C) using the constant-rate pump system. Lissamine Flavine FF was flushed into the Site B sinkhole during the medium-flow trace, while Pylaklor Orange dye was flushed into the Site B sinkhole during the low-flow trace. Automatic water samplers were installed at the Ward Farm Spring (Site D) and Waffle House Upwell Spring (Site E). Carbon packets were also placed at these sites for redundancy and additional packets were placed at Ward Branch near its confluence with the James River (Site F). A carbon packet was placed at Patterson Spring (Site G) during the low-flow trace.

Medium-flow trace

This trace was performed after a single rainfall event following a week of previous rainfall events which totaled 33.5 mm. Beginning approximately 7 h before the

Lissamine dye injection, Rhodamine WT dye was pumped into the Ward Branch Stream sink (Site C), and the Rhodamine pumping continued for approximately 60 h. The Rhodamine dye was detected at both the Ward Farm Spring (Site D) and Waffle House Upwell Spring (Site E), with dye concentrations at the Waffle House Upwell Spring (Site E) significantly greater than at the Ward Farm Spring (Site D) (Fig. 4). The Lissamine dye was detected in carbon packets at the Waffle House Upwell Spring (Site E), Ward Farm Spring (Site D), and Ward Branch near the confluence with the James River (Site F). A map of the detected dye paths is shown in Fig. 5.

Instantaneous dye recovery (C %) is calculated for each spring by assuming a steady-state condition and comparing the rate of Rhodamine WT dye being injected into Ward Branch Stream sink (Site C) with the rate of dye recovered at the Waffle House Upwell Spring (Site E) and Ward Farm Spring (Site D). This was done following a method established by Thrailkill and Gouzie (1984).

The resulting values show distinct and consistent differences in relative amounts of dye reaching both the Waffle House Upwell Spring (~90 %) and Ward Farm Spring (~10 %). A slug trace by Tomlin (2010) to these same two springs from a different sinkhole northeast of the study area shows a similar split flow between the springs, with 94 % of recoverable dye detected at the Ward Branch Upwell and 6 % detected at Ward Farm Spring. Dye recovery by Tomlin (2010) was calculated by plotting dye concentration with time and measuring area under the curve (resulting in mass of dye recovered) and comparing to the known mass of dye injected.

For this test, both the (1) instantaneous discharge method used here and (2) area under the concentration

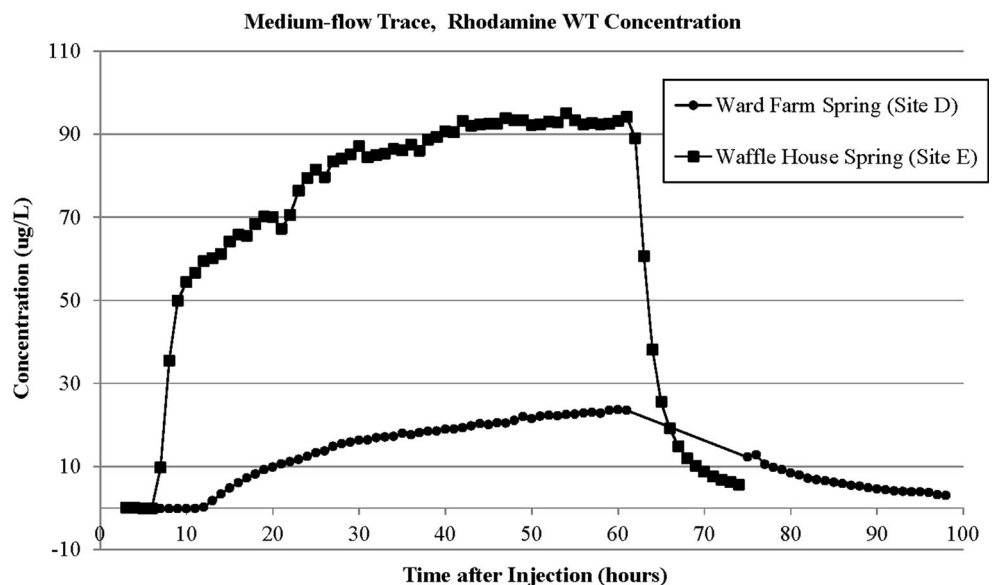
curve method by Tomlin (2010) show a similar and reproducible behavior of flow concentrations to both the Ward Farm Spring (Site D) and Waffle House Upwell Spring (Site E).

Low-flow trace

This trace was performed during lower flow conditions and was not immediately preceded by a rainfall event (zero precipitation in the 10 day interval before the trace). Flow was still present at the Ward Branch Stream sink and at all springs. As with the medium-flow trace, Rhodamine WT dye was pumped into the Ward Branch Stream sink beginning 6 h before any other dye injections. However, equipment difficulties left the injection system running for only approximately 30 h after the initial Rhodamine injection. The Rhodamine WT dye was detected at the Waffle House Upwell Spring (Site E) (Fig. 6), but was not detected at Ward Farm Spring (Site D) by either the automatic water samples or carbon packets. Rhodamine WT dye was detected at Patterson Spring (Site G), but not detected at Ward Branch at the confluence with the James River (Site F). Pylaklor Orange injected into the detention basin sinkhole (Site B) was not detected at any springs by any of the detection methods. A map of the detection locations for both dyes (Rhodamine WT and Pylaklor Orange) is provided in Fig. 7. Instantaneous dye recovery of Rhodamine WT was also calculated for this test and a high recovery rate (~85 %) was observed at the Waffle House Upwell Spring.

For the lower flow conditions of the second trace, the concentration of Rhodamine WT in the injection system tank was reduced, which allowed for other comparisons. At

Fig. 4 Rhodamine WT dye concentration (µg/L) in spring water versus time at both the Waffle House Upwell Spring (squares) and the Ward Farm Spring (circles) from hourly water samples



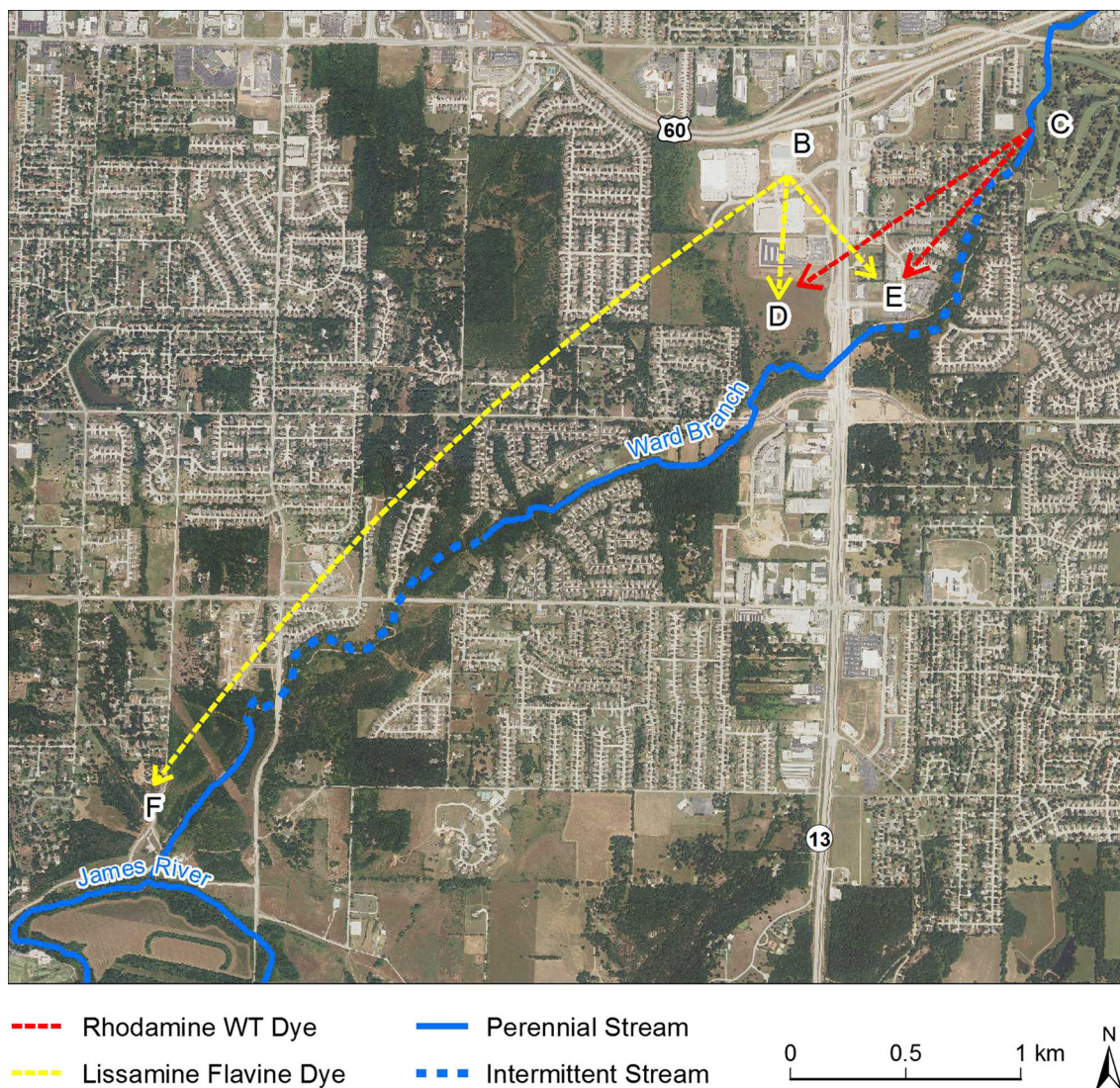


Fig. 5 Map of point-to-point dye flow paths for the medium-flow trace. Rhodamine WT dye (red arrows) injected at the Ward Branch Stream sink (c) was detected at highest concentration at the Waffle House Upwell Spring (e) and at lesser concentrations at the Ward Farm Spring (d). Lissamine Flavine dye (yellow arrows) flushed into

the interchange detention basin sinkhole (b) was detected at the Waffle House Upwell Spring (e), Ward Branch Spring (d), and Ward Branch/James River confluence (F). Solid blue lines in Ward Branch represent perennial flow, whereas dashed lines represent intermittent flow

the Waffle House Upwell Spring (Site E), this change in tank concentration of Rhodamine WT dye from the medium-flow trace (118,000,000 $\mu\text{g/L}$) to the low-flow trace (16,100,000 $\mu\text{g/L}$), or 87 % reduction, produced a similar change in maximum detected Rhodamine WT concentration from the medium-flow trace (94 $\mu\text{g/L}$) to the low-flow trace (14 $\mu\text{g/L}$), or 85 % reduction.

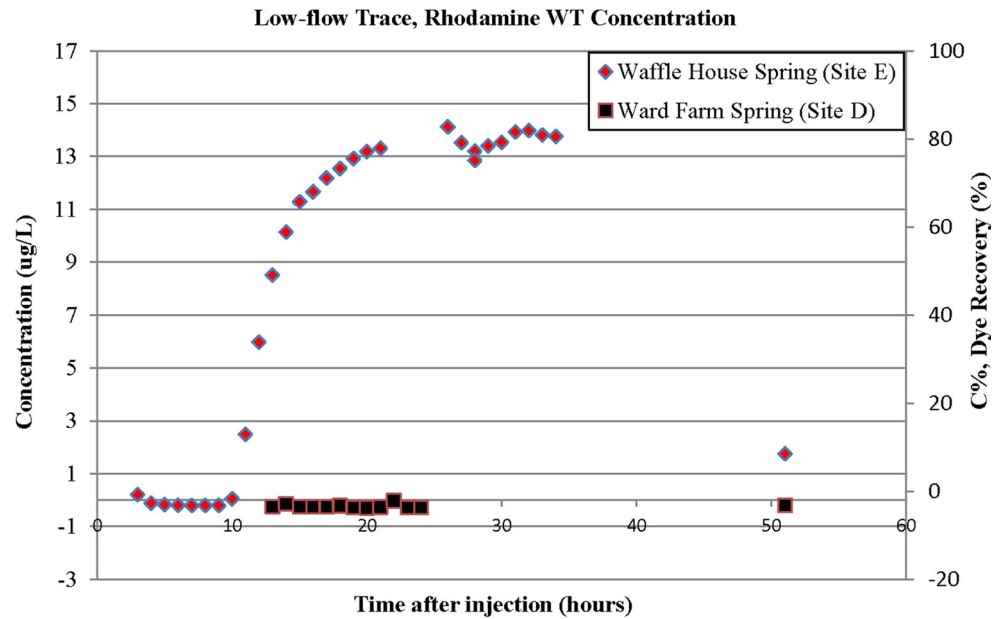
A similar change in concentration of Rhodamine WT from the medium-flow to low-flow trace should be anticipated at the Ward Farm Spring (Site D). In the medium-flow trace, maximum detected Rhodamine WT at the Ward Farm Spring was 22 $\mu\text{g/L}$. During the low-flow trace, then, Rhodamine WT should have been reduced by 85 % to a

maximum concentration of 3 $\mu\text{g/L}$. Although low, this is within the range of detectable fluorescence. The lack of fluorescence during the low-flow trace is therefore likely the result Rhodamine WT dye failing to reach the Ward Farm Spring (Site D).

Groundwater velocity

Velocity of groundwater was determined from timing of the dye plume breakthrough from time–concentration data. The greatest velocity (0.056 m/s) was observed between the Ward Branch Stream sink (Site C) and the Waffle House Upwell Spring (Site E) during the medium-flow dye

Fig. 6 Rhodamine WT dye concentrations with time at the Waffle House Upwell Spring (*diamonds*) and Ward Farm Spring (*squares*) during the low-flow dye trace. Instantaneous dye recovery is plotted on the *secondary axis*



trace (Table 1). During the low-flow trace, groundwater velocity between the Ward Branch Stream sink and Waffle House Upwell Spring decreased from 0.056 to 0.032 m/s. These calculated velocities range from 0.027 to 0.056 m/s, which is within the most common range of karst ground water velocities reported by Worthington (2007).

Calculated spring discharge

The quantitative nature of the Rhodamine WT traces allow for the calculation of spring discharge (Q_c in L/s) at each spring:

$$Q_c = \frac{C_t Q_t}{C_s \times 60,000} \text{ (L/s)}, \tag{1}$$

where (C_t) is the concentration of Rhodamine WT dye in the pump tank in $\mu\text{g/L}$, measured from a tank sample before dye injection; (Q_t) is the tank pump rate in mL/min, measured on-site once injection begins; (C_s) is the concentration of dye in $\mu\text{g/L}$ at the spring, measured from collected automatic water samples; and 60,000 is a conversion factor to convert mL/min values into liters per second (L/s).

Because the calculated discharge equation assumes a closed system connection between a single surface water input (losing stream) and output (spring), applying it uncorrected to the first dye trace results in higher than observed discharges at the Waffle House Upwell Spring and Ward Branch Spring. This is due to the calculations assuming 100 % of the injected dye being recovered at each spring, which is not possible. Based on dye concentration and observed discharge values, it was determined that

about 90 % of the injected dye reaches the Waffle House Upwell Spring, while the remaining 10 % is diverted beforehand and emerges at Ward Farm Spring. A correction factor representing estimate proportion of dye recovered ($C_{r, 0-1}$) for each site ($C_r = 0.9$ for Waffle House Upwell Spring and $C_r = 0.1$ for Ward Farm Spring) is then included in the calculated discharge equation to account for the unequal distribution of dye traveling to each spring:

$$Q_c = \frac{C_r C_t Q_t}{C_s \times 60,000} \text{ (L/s)}. \tag{2}$$

Equation (2) results in spring discharge values at the Waffle House Upwell Spring which are very similar to the visually estimated field discharge values. The medium-flow dye trace has the highest calculated spring discharge, leveling off at 76 L/s (2.7 cfs), and the low-flow dye trace has the lowest calculated spring discharge, leveling off at 62 L/s (2.2 cfs). These are comparable to observed spring discharge values during each dye trace, indicating that, along with the high rate of dye recovery, the groundwater flowpath between the Ward Branch Stream sink and the Waffle House Upwell Spring behaves like a closed system, with only minor dye loss and change in net discharge.

However, applying Eq. (2) to the dye concentrations at Ward Farm Spring results in a calculated discharge of about 1700 L/s (60 cfs), 30 times higher than the field-observed discharge of 56 L/s (2 cfs). In other words, to account for the remaining 10 % of dye in a closed system with the low concentrations measured at Ward Farm Spring, a discharge of around 1700 L/s (60 cfs) would be required.

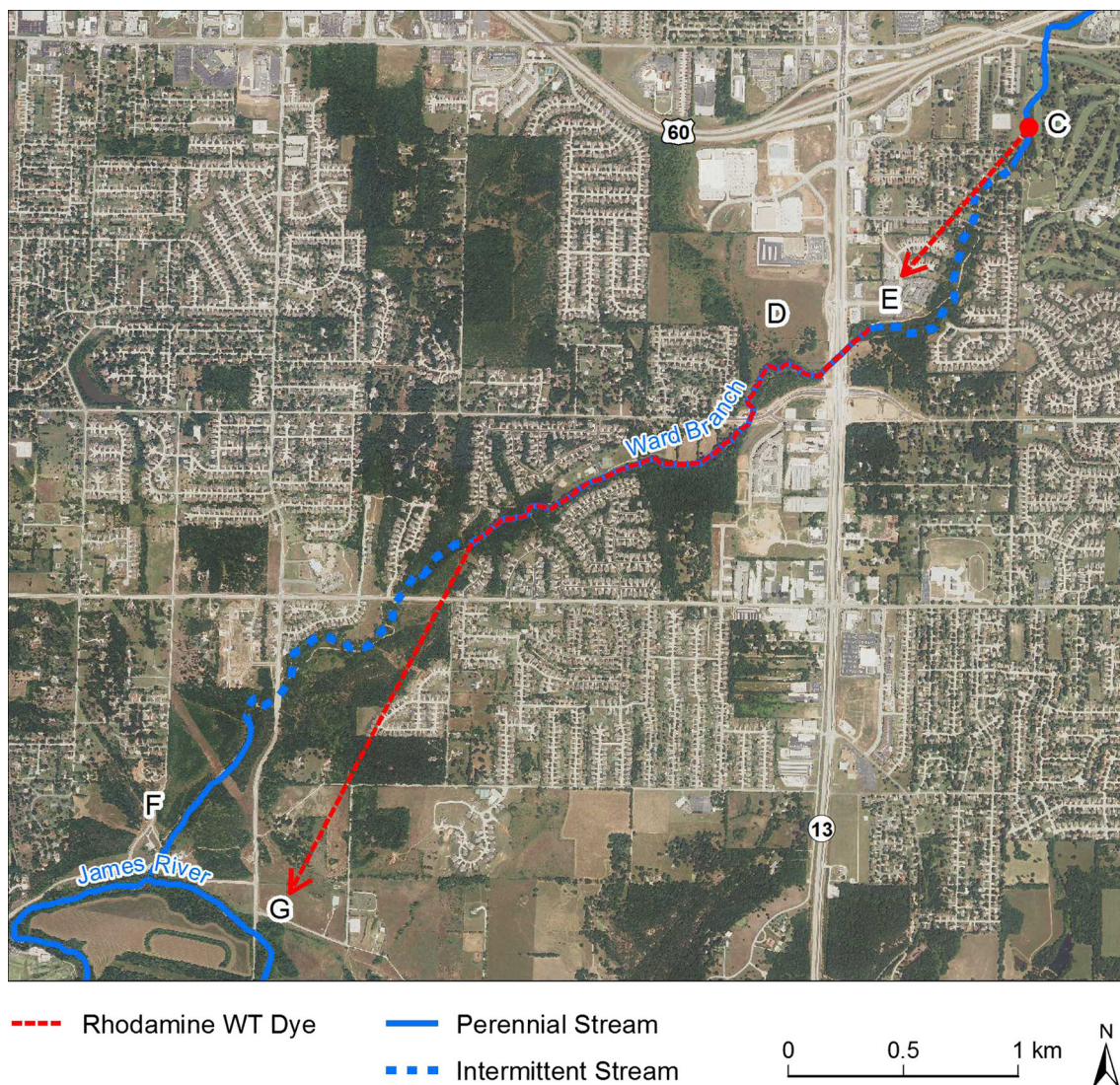


Fig. 7 Map of dye flow paths for the low-flow dye trace. Rhodamine WT dye injected at the Ward Branch Stream sink (c) was detected in water collected with Hach autosamplers at the Waffle House Upwell Spring (e), but not at the Ward Farm Spring (d) as in the medium-flow

trace. Rhodamine WT dye was also detected with carbon packets at the Waffle House Upwell Spring (e) and Patterson Spring (g), but not at the Ward Farm Spring (d) or Ward Branch (f)

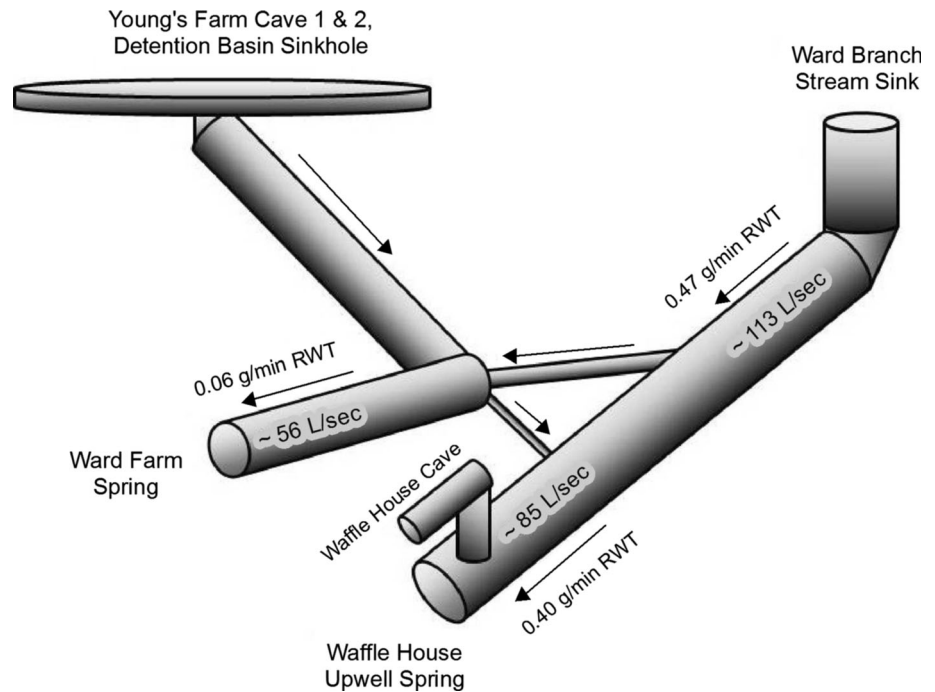
Table 1 Groundwater velocities determined from time of dye arrival and a straight line map distance

	Distance (m)	Main plume arrival (h)	Velocity (m/sec)
Medium-flow trace			
Ward Branch Stream sink to Waffle House Upwell Spring	1610	8	0.056
Ward Branch Stream sink to Ward Farm Spring	2010	13	0.043
Waffle House Upwell Spring to Ward Farm Spring	480	5	0.027
Low-flow trace			
Ward Branch Stream sink to Waffle House Upwell Spring	1610	11	0.041

In this case, the calculated discharge (Eq. 2) overestimates the discharge because the masses of dye and spring water fail to properly balance. This is most simply explained as the flow between the Ward Branch Stream sink

and the Ward Farm Spring is not a closed system. If it is assumed that discharge at Ward Farm Spring is a diversion from Ward Branch Stream sink, then a diversion of 10 % of the dye toward Ward Farm Spring should mean that its

Fig. 8 Conceptual model of karst conduit system between Young’s Farm Cave (Site A), interchange detention basin (Site B), Ward Branch Stream sink (Site C), Ward Farm Spring (Site D), and the Waffle House Upwell Spring (Site E), based on quantitative dye traces



spring discharge should be 10 % of “total system” water if it were a closed system.

Water discharge into the Ward Branch Stream sink is observed to be about 113 L/s (4 cfs). If this were a closed system, then the Waffle House Upwell Spring would receive 90 % of the flow (based on 90 % of recovered dye), or about 85 L/s (3 cfs), which is similar to both the observed and calculated. The Ward Farm Spring, then, should receive 10 % of the flow (based on the 10 % of recovered dye), or about 9 L/s (0.3 cfs). Actual observed flow is significantly larger than this, around 56 L/s (2 cfs). This discrepancy shows that the majority of flow out of the Ward Farm Spring is due to another flow source which is not observed between the Ward Branch Stream sink to the Waffle House Upwell Spring.

Using the visually estimated discharge, previous dye traces, and quantitative dye data, a conceptual model of the conduit system can be visualized (Fig. 8). Qualitatively, discharge at both Ward Farm Spring (~56 L/s) and the Waffle House Upwell Spring (~85 L/s) may be explained as a nearly equal split of flow from the Ward Branch Stream sink (~113 L/s). But quantitatively, comparing Rhodamine WT dye recovery rates at both springs compared to dye injection rates shows that dye does not follow an equal split, and that most of the dye is recovered at Waffle House Upwell Spring, whereas a smaller fraction is diverted toward Ward Farm Spring. Discharge at Ward Farm Spring cannot be accounted for solely as a result of the similar proportion of dye diversion and so must be explained by additional recharge from an area not receiving

dye. Dye traces from the north at Young’s Farm Caves 1 and 2 along with the interchange detention basin sinkhole appear to be likely candidates for this enhanced recharge area. The connection between the Ward Farm Spring and Waffle House Upwell Spring allows for some multidirectional flow, similar to an estevelle, but becomes disconnected during low-flow conditions. Because Tomlin (2010) reported approximately a 1.5 m (5 foot) elevation difference between Waffle House Upwell Spring and Ward Farm Spring, it is plausible that water rising through bedrock at the Waffle House Upwell Spring could find an “overflow” outlet at a higher elevation than the Waffle House Upwell rise pool and the overflow could pass water and dye along to the flowpath toward Ward Farm Spring.

Results from both dye traces indicate the three perennial stretches of Ward Branch are recharged by two source areas (Fig. 9). The upstream stretch is recharged from the northeast, the middle stretch is recharged from the northeast with some input from the north, and the downstream stretch receives flow from the north. Flow between the Ward Branch Stream sink (Site C) and the Waffle House Upwell Spring (Site E) shows very little flow loss or gain while also having the highest velocity. Based on field observations of the rise pool (where multiple boils form along a trend roughly oriented toward the known sinks feeding this spring from the northeast), this is interpreted as most likely flowing along a fracture. Flow from due north is widespread with lower velocities and results in dye discharge discrepancies, more characteristic of bedding plane flow. Capture of flow from the middle stretch emerges at a

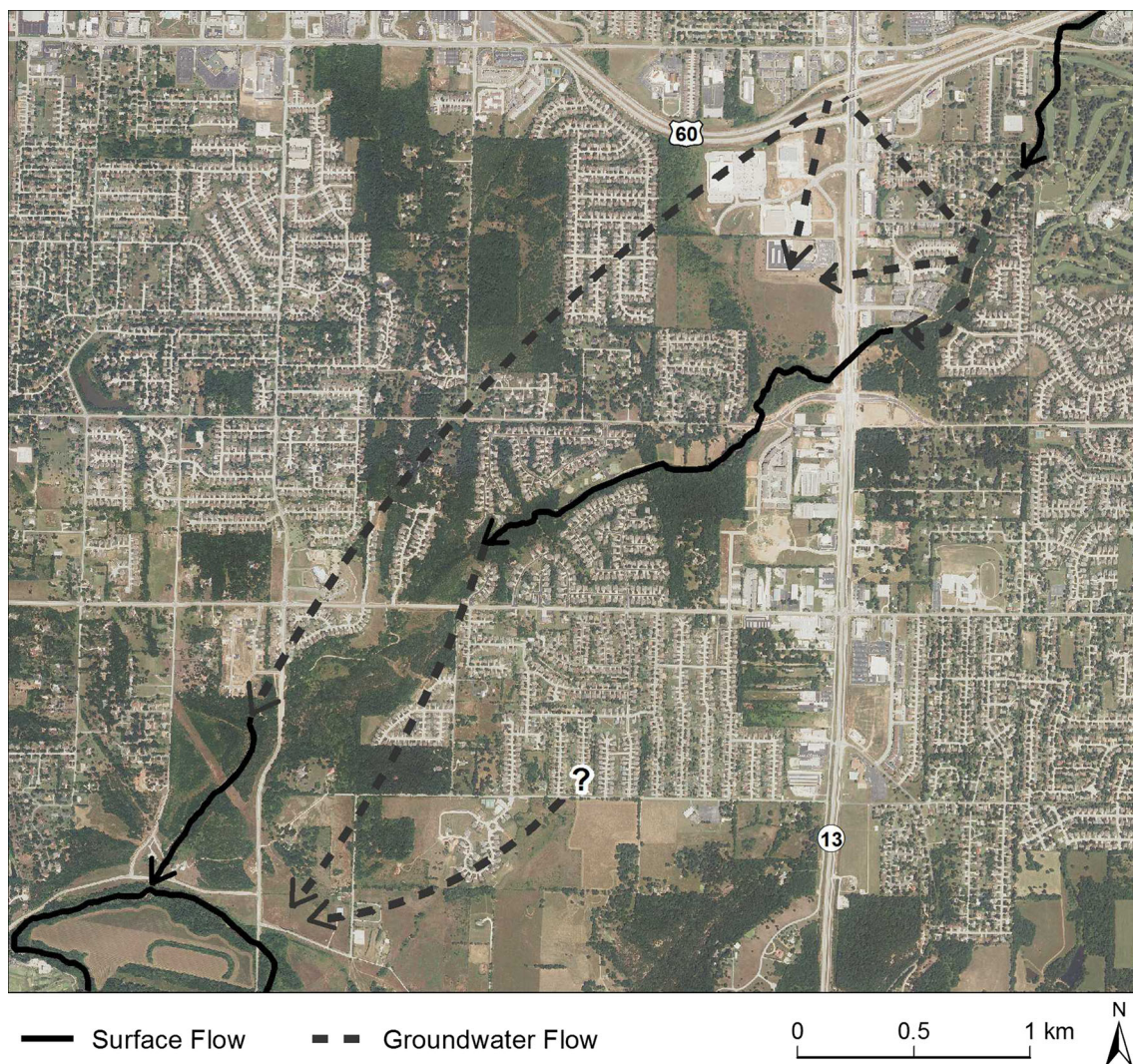


Fig. 9 Surface flow (*solid arrows*) and groundwater flow (*dashed arrows*) map within the study area based on medium- and low-flow dye traces

widened bedding plane at Patterson Spring (Site G), greater than the discharge of Ward Branch consistent with the idea that it is fed by more than the disappearing Ward Branch.

Reviewing the elevation data for the area, the Ward Branch stream sinks has an elevation of about 366 m (1202 feet) MSL and the Ward Branch Upwell Spring has a water surface elevation of about 356 m (1170 feet) MSL. Any “overflow” outlet which would divert flow from the Ward Branch Upwell Spring toward the Ward Farm Spring would need to occur above an elevation of 356 m (1170 feet) and below an elevation of 366 m (if the diversion occurred at an elevation above 366 m, the constant-rate injection dye would not have flowed downward into the Ward Stream sinkhole). Using a 1:24,000 scale USGS topographic map of the study area, this range of elevations occurs in the dry surface channel on the eastern side of highway 13, the main north–south roadway in the study area. Because the main roadway dissected portions of the

dry stream valley, it is reasonable to believe that subsurface conduits or bedding planes which capture most surface runoff still may be connected beneath the roadway. Anecdotal reports of flooding during rainstorms in low-lying elevations of the dry channel on the east side of the highway 13 are consistent with the concept that water flowing through an eastern conduit feeding the Waffle House Upwell Spring may “back up” into surface pools and a subsurface diversion pathway during periods of higher flow.

Fracture flow versus bedding plane flow

Geophysical surveys (e.g., electrical resistivity, electromagnetics) and dye traces can provide evidence of whether groundwater is flowing through fractures or along bedding planes (Berglund et al. 2014). Within the study area, both types of flow can be inferred between different sites,

although bedding plane flow appears to be the most dominant.

Fracture flow best explains the flow between the Ward Branch Stream sink (Site C) and Waffle House Upwell Spring (Site E). Flow between these two sites shows a very high dye recovery rate ($\sim 90\%$) and the greatest groundwater velocity. A northeast–southwest trending photolineament extends from the Ward Branch Stream sink southwest to the region around the Ward Farm Spring and Waffle House Upwell Spring, and would be consistent with the presence of a fracture.

The change in hydraulic connectivity between Waffle House Upwell Spring (Site E) and Ward Branch Spring (Site D) from medium to low-flow conditions seems to suggest that this connection exists along a near-horizontal bedding plane which was abandoned due to a drop in water levels, rather than a vertical fracture which could be expected to maintain connectivity when groundwater levels drop. This hypothesis is supported by the small vertical elevation differences (less than 7 m) in the vicinity between Site B (detention basin sink) and Site E (Waffle House Upwell Spring), and also by field observation of flow along bedding planes at both Ward Farm Spring and Patterson Spring. At Ward Farm Spring, electrical resistivity profiles show that flow appears to be along a horizontal layer instead of a discrete conduit. At Patterson Spring, visual observation shows that flow occurs along an extensive bedding plane.

Conclusions

The use of a steady-state dye injection system allows greater insight into the subsurface conduit system than traditional dye-tracing methods. Simple mass balance methodologies allow for the determination of inflows or diversions of dye moving through a system and therefore allow reasonable quantitative estimates of groundwater fluxes. Combining these dye injection results with topographic and geophysical data yields an enhanced understanding of subsurface flow systems not available from traditional methods or studies using only one methodology.

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