SEASONALITY OF FLOW PATHS AND STORM RESPONSES IN A FLUVIO-KARST SYSTEM

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Abstract
Understanding water flow through the subsurface is critical to understanding sediment, nutrient, and contaminant flux through karst groundwater systems. To assess variability in flow behavior, we conducted two quantitative dye traces in the Cane Run and Royal Spring basin in the Bluegrass region of Kentucky with dye injections in February and June 2022. Each trace involved injecting dye into the same sinkhole and monitoring dye concentration, water level, temperature, and electrical conductivity in three wells. The June trace also included monitoring of the main spring. The wells provided a unique opportunity to monitor a transect across a phreatic conduit, with one well in the known conduit and two in the fractures and matrix adjacent to the conduit. The winter dye trace showed dominant flow through a main conduit with an initial dye breakthrough curve occurring prior to a storm pulse. A storm event activated the connections between the main conduit and surrounding preferential flow paths, indicated by dye arriving in the adjacent wells. The summer dye trace showed a similar pre-storm event response. During a subsequent storm pulse, a secondary pulse of dye was seen in both the main conduit and spring. However, no dye appeared in the adjacent wells despite similar water level increases during the storm pulse. This difference in trace responses is likely due to lower overall water levels during the summer event, as well water levels were approximately 1.5 m lower than during winter. During higher levels of flow, there are more hydrologic active interconnections between conduits in the subsurface, supporting past interpretations of a braided network of conduits in the area. Complex responses of water level, temperature, and electrical conductivity data to the storm events during the two trace tests provided a foundation for future modeling efforts to characterize preferential flow pathways.

Introduction
Karst groundwater is a globally important resource for human consumption and to support ecosystem function (Bakalowicz 2005, Stevanovic 2019) however karst groundwater systems are also some of the most difficult aquifers to understand in terms of flow pathways and flux through these systems (Hartmann et al. 2014, Bledsoe et al. 2022). Due to the high variability in permeability in karst systems, they are susceptible to both acute and chronic contamination concerns (Kalhor et al. 2019). Rapid infiltration rates provide contamination quick flow paths into the aquifer which can then be transported at surface water rates to springs and wells drawing from the aquifer causing a rapid, acute contamination of the system. Additionally, the interactions between conduits, fractures, and matrix porosity result in the potential for long term storage with slow discharge of contaminants over time, resulting in a chronic, long-term contamination problem.

Researchers have employed a variety of methods to quantify these complex groundwater behaviors in karst systems. Traditional groundwater modeling efforts are often of limited use at the scale valuable for understanding flow paths (Scanlon et al. 2003). Flow and water chemistry monitoring are frequently used to quantify the relationship between fast and slow flow processes (Wilson et al., 2022, Tobin and Schwartz 2012). These provide general insight to flow behavior but only infer behavior upstream. Geophysical techniques have often been used to identify possible conduit locations at a small scale however it is difficult to relate isolated conduit locations to aquifer behavior (Zhu et al. 2011). More complex modeling has been used to quantify sediment and nutrient fluxes (Bettel et al. 2022, Husic et al. 2020) but these models are often limited to site specific development and application. Dye tracing provides the most direct quantification of flow path behavior however it is often limited in its ability to show groundwater behavior outside of the hydrologic conditions during the trace (Goldscheider et al. 2008).

More recently, efforts are being made to combine these approaches to provide greater insight into flow behavior (Zhu et al. 2021). Here we utilize repeated quantitative dye tracing to monitor groundwater response under different hydrologic conditions: winter high flow and summer low flow to assess flow path variability.

Methodology

Study Site Description

The Cane Run – Royal Spring basin is in Fayette and Scott counties in the Bluegrass physiographic region of central Kentucky (Figure 1). Located on Ordovician limestone, Cane Run flows along the surface and eventually sinks completely into the aquifer. This groundwater system flows to Royal Spring which is the water supply for the city of Georgetown, Kentucky.

The groundwater basin has been the focus of numerous studies since the 1980s and has a well delineated basin from extensive dye trace efforts (Thrailkill and Gouzie 1984, Currens and Ray 1996, Currens et al. 2002). Work in the basin also included assessment of contaminant transport (Bandy et al. 2020, Husic et al. 2020), sediment flux (Bettel et al. 2022), temporal patterns in groundwater processes (Husic et al. 2021), and the development of numerical flow models (Al Aamery et al. 2021),

Previous efforts suggest a complex set of flow paths including sinking streams, traditional dolines, fracture network flow, conduit networks, and a primary cave system draining the aquifer to Royal Spring (Thrailkill and Gouzie 1984, Al Aamery et al. 2021). These complexities are used to explain the spatial and temporal patterns seen in contaminant, nutrient, and sediment fluxes through the system (e.g. Husic et al. 2020).

As part of these previous efforts, a well network was installed and successfully intersected a major conduit in the system. Completion of these wells and confirmation of a well intersecting the main conduit are described in Zhu et al. (2011). These studies have provided a clear insight into the complexity of the groundwater system; however, efforts have exclusively focused on utilizing the well that intersects the conduit and the spring but have not actively monitored the adjacent wells during tracer studies: a component that was included in this study. The combination of existing understanding of the system and the well network provides an ideal location for repeated quantitative dye traces to understand the heterogeneity of groundwater flow paths.

Field Methods

Dye injections were conducted in February and June 2022 (Figure 2). During each injection, the sinkhole was first primed with water, then 250 mg of rhodamine

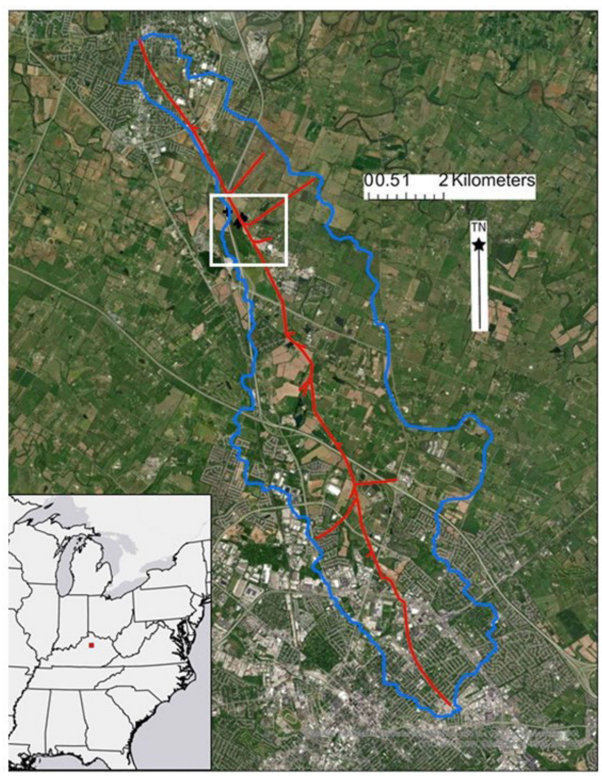

Figure 1. *Cane Run- Royal Spring drainage basin showing dye traced flow paths. The spring is in the city of Georgetown, KY at the north end of the map (blue circle) and the headwaters are in the city of Lexington, KY. Figure 2 location is highlighted in white. The Royal Spring groundwater basin is outlined in blue with the assumed conduit location in red.*

WT, mixed with tap water, was injected into the same sinkhole, which was then flushed with water. In total, 900 l of water was used for each injection. The February dye injection was aided by flow from a small stream that drains into the sinkhole. This stream was dry during the June injection.

For both dye injections, three wells (1, 18, and 20) were instrumented with an In-Situ Aqua Troll 600 that included a Rhodamine WT probe, with a detection limit of 0.5 mg/l, and recorded temperature, water level, and specific conductance at a 15-minute interval. These wells are approximately 700 m northwest of the injection location. Well 20 intersects a main conduit 18 m below the surface. Well 1 is located 24 m northeast of well 20 and well 18 is 9 m southwest of well 20 (Figure 2). The three wells are part of a line of wells forming a southwest-to-northeast transect perpendicular to the regional groundwater flow direction. For the June dye injection, an additional Aqua Troll 600 with same sensors as those deployed in the three wells was placed at Royal Spring, the downstream outlet of the system. The instruments were installed 24 hours prior to injection and left in situ

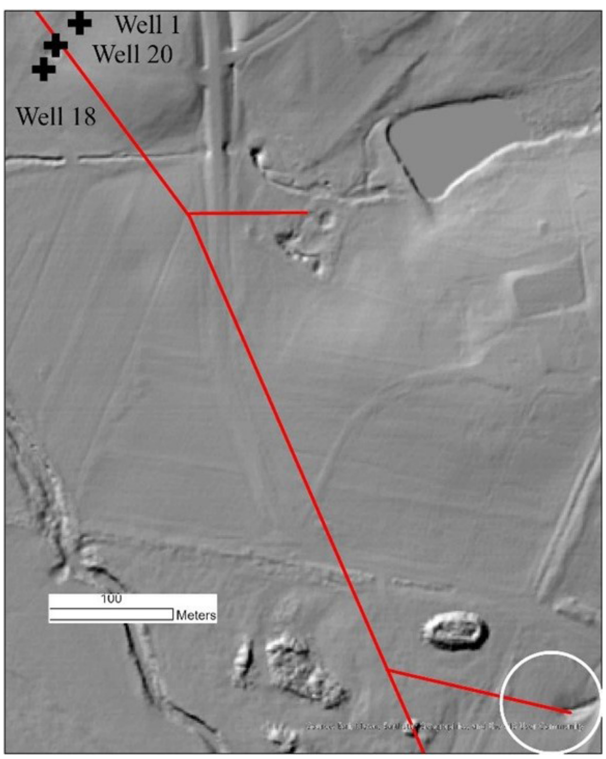

Figure 2. Relative locations of well network (black crosses, assumed conduit locations (red) and injection sinkhole (white) in the Kentucky Horse Park.

for two weeks after the injection. Continuous monitoring of dye concentration in conjunction with additional water quality parameters provides a high-resolution data set that allows for direct comparison of the monitored variables.

Analyses

To compare the response between wells during the dye trace events and the subsequent storm response, a series of cross-correlation analyses were conducted. With the assumption that changes in temperature, specific conductance, and water level were associated with storm water moving into the system, we determine the relationship in response timing between these variables and dye (Tobin et al. 2021). Additionally, the response behavior of the dye between each well was also assessed using the same process. For this analysis, the combination of water level, specific conductance, and temperature were assumed to be proxies for storm pulses moving through the system.

Results

Winter Dye Trace

Dye injection occurred on February 16, 2022 at 11:00am, with a storm event of 70.8 mm occurring on February 17, 2022. Dye was observed at well 20, in the main conduit, within 2 hours of injection. Dye was not seen in the adjacent wells until after a storm event pulse was seen in the main conduit.

The arrival of the dye in the main conduit (Figure 3) was not associated with changes in water level, temperature, or specific conductance. This suggests that the dye was transported into the conduit during baseflow and moved through the conduit prior to the storm pulse. The dye at well 20 did have a small, secondary peak that occurred during the storm pulse (Figure 4). All three sites showed similar storm responses with an increase in water level occurring simultaneously (Figure 5).

Dye arrival in well 1 was strongly correlated with an increase in water level, an increase in specific conductance, and a decrease in temperature (Table 1). The cross-correlation analysis showed that the dye concentration peaked quickly after the increased water level and decreased temperature and occurred at the same time as increased conductivity. This suggests that a storm pulse brought the dye into well 1.

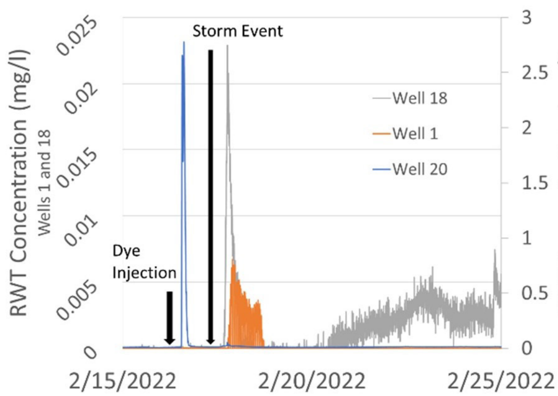

Figure 3. *Dye recovery at three wells in the Kentucky Horse Park. Well 20 intersects the conduit, well 18 is 9 m southwest, and well 1 is 24 m northeast of the known conduit. Well 20 shows a response within 2 hours of dye injection while wells 18 and 1 only show dye moving through following a small storm event on February 17.*

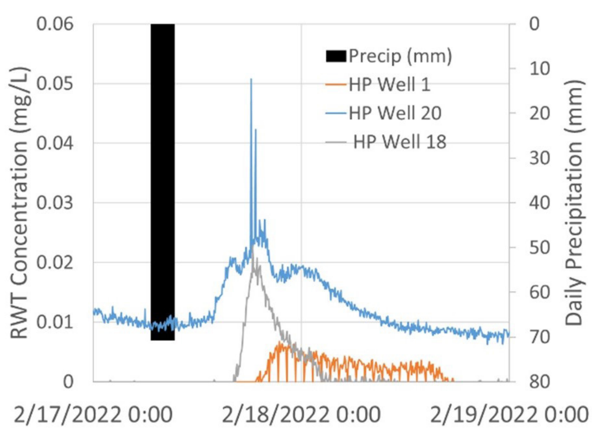

Figure 4. *Dye recovery at three wells in the Kentucky Horse Park focused on the post-storm response.*

Dye arrival in well 18 was also correlated with an increase in water level, an increase in specific conductance, and a decrease in temperature. These correlations were weaker and more delayed. This suggests that the storm pulse may have mobilized dye into this pathway. However, the dye lagged the storm response (depth and specific conductance) by greater than 0.5 days. The lower correlation between dye concentration and specific conductance and temperature suggest the dye may have been mobilized into well 18 via piston flow.

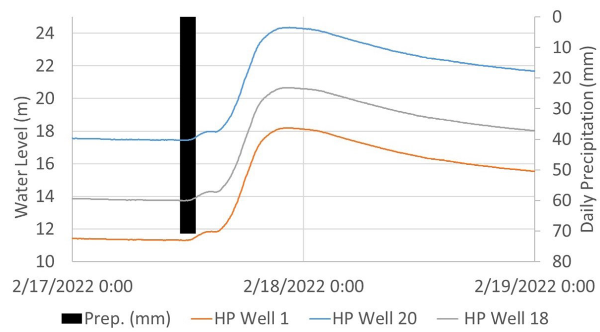

Figure 5. *Water level response at each well relative to the February 17 storm event. To show relative behavior, Water level is shown as water depth above transducer.*

Summer Dye Trace

Dye injection occurred on June 30, 2022 at 10:00am with a storm event of 11.9 mm occurring on July 2, 2022. A slower timing of dye response was seen in the main conduit during the summer, with a primary peak mobilized prior to a storm event. However, the first arrival at well 20 was 14 hours after injection. In the storm event response, instead of dye being mobilized into adjacent wells, a secondary pulse was seen in the main conduit well associated with the storm response 70 hours after the dye injection. The response at Royal Spring (6,250 m downstream from the injection location) shows a similar dual peak response, with the first peak arriving 82 hours after the injection and a second pulse 137 hours after the injection (Figure 6).

Table 1. *Cross-correlation results between dye recovery curves at each well as well as between dye recovery curves and temperature (temp), specific conductance (SpC), and water level at the same well. Lag time is the time (in minutes) that variable 2 lagged variable 1.*

Variable 1	Variable 2	Lag Time	Correlation
Well 1 RWT	Well 1 Temp	-225	-0.84
Well 1 RWT	Well 1 SpC	0	0.756
Well 1 RWT	Well 1 depth	-75	0.537
Well 18 RWT	Well 18 Temp	-45	-0.513
Well 18 RWT	Well 18 SpC	1065	0.421
Well 18 RWT	Well 18 depth	720	-0.459
Well 20 RWT	Well 20 Temp	15	-0.156
Well 20 RWT	Well 20 SpC	45	0.135
Well 20 RWT	Well 20 depth	3000	-0.147
Well 20 RWT	Well 1 RWT	3000	-0.03
Well 20 RWT	Well 18 RWT	-3000	-0.06
Well 1 RWT	Well 18 RWT	-555	0.543

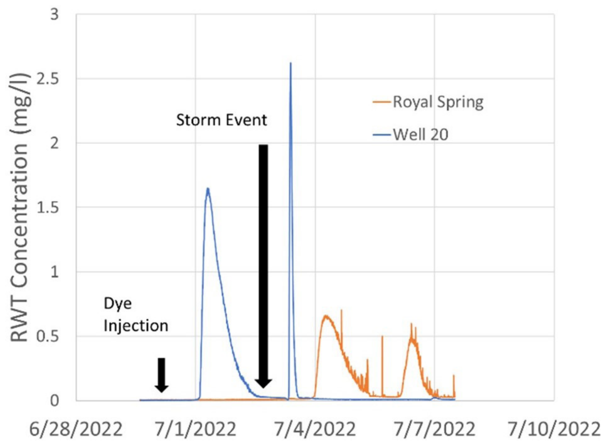

Figure 6. *Dye recovery at the main conduit well at the Kentucky Horse Park and Royal Spring. Both sites show an initial dye peak prior to arrival of storm water and a second peak associated with storm event water.*

All three well sites showed similar storm responses with an increase in water level occurring simultaneously (Figure 7).

Cross correlation analysis showed a poor relationship between storm event parameters (temperature, specific conductance, and water level) and dye at well 20 but did show some relationship between the parameters and dye recovery at Royal Spring (Table 2). This suggests that the dye flow behavior was influenced by the storm event as it moved between the well and Royal Spring.

Discussion

Our dye traces show that the flow rate in the main conduit is faster in winter than in summer, with initial

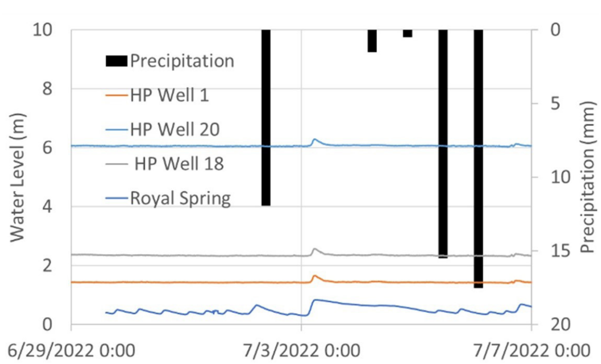

Figure 7. *Water level response to storm events (daily total precipitation) at each well and Royal Spring during the July 2 storm event. To show relative behavior, Water level is shown as water depth above transducer.*

dye being observed in well 20 2 hours in winter and 14 hours in summer after the dye injection. This observation is consistent with the overall higher flow conditions in the winter relative to the summer. Additionally, both seasons showed that some dye was held up in storage and remobilized during subsequent storm events. Alternately, the lower dye concentrations in wells 1 and 18 may suggest a slower flow pathway between the main conduit and these wells. This could be a sign of connections between matrix, fracture, and conduit flow paths. This is also supported for well 18 by the likelihood of a piston flow driven response to the winter storm event.

Beyond this difference in timing, the most notable storm event response was the activation of adjacent conduits through the winter event. This is likely a result of generally higher water levels in the system during the winter coupled with a larger storm event. During this time, less of a change in water depth was needed to activate the upper conduits in the system.

The dual peaks of the dye trace in both summer and winter suggest that there is rapid storage that is easily mobilized along the traced flow path. This may be associated with the soil and adjacent fractures present within the injection sinkhole. While the storage location is likely similar across seasons, during winter months these intermittent storage locations are more directly connected to an overflow network of braided conduits while during

Variable 1	Variable 2	Lag Time	Correlation
RS RWT	RS Temp	3315	0.524
RS RWT	RS SpC	-5130	0.493
RS RWT	RS depth	3705	0.613
Well 20 RWT	RS RWT	3315	-0.208
Well 20 RWT	Well 20 Temp	-585	-0.283
Well 20 RWT	Well 20 SpC	225	0.214
Well 20 RWT	Well 20 depth	660	0.339

Table 2. *Cross-correlation results between dye recovery curves at the main conduit well and Royal Spring as well as between dye recovery curves and temperature (temp), specific conductance (SpC), and depth at the same sites. Lag time is the time (in minutes) that variable 2 lagged variable 1. The relatively low correlation values indicate that there is little relationship between storm response parameters and dye recovery.*

lower flow conditions in summer, this storage is more directly tied to the main conduit.

Conclusion

Our results show seasonal variability in flow path activation as well as variability in remobilization pathways of dye during storm events. This seasonal difference indicates that sediment and contaminant flux behaviors have the potential to differ drastically dependent on antecedent hydrologic conditions. Storm response flow paths may vary drastically between high flow and low flow conditions.

The seasonality of connectivity in this braided conduit network highlights the complexity of karst groundwater systems and the difficulty of conceptualizing these behaviors. These results provide initial insight into these behaviors and can potentially be incorporated into future modeling efforts to better quantify the heterogeneity of karst aquifer behavior.

Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant No. EAR-1933779.

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