

# Comparison of Flow Paths to a Well and Spring in a Karst Aquifer

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## **Abstract**

The permeability of some karst aquifers consists of networks of poorly integrated conduits and dissolution-widened fractures. The flow includes conduit flow, especially during storm recharge, but lacks the focused recharge into single master conduits that occurs in more highly developed karst systems. The proportions of conduit and dispersed flow are difficult to quantify in such systems. This paper examines the flow paths in a small karst watershed, based on comparing the physical and chemical response to storm flow at both a spring and a well.

By conducting continuous monitoring at both locations, a better understanding of the flow paths in a poorly integrated network was obtained. A more permeable flow path to the spring leads to faster storm response and lower ion concentrations. The flow path to and from the well is more complicated. The higher ion content and slower storm response suggest slower, more dispersed flow paths. However, the well has greater variation in ion chemistry. Periodic recharge may dilute well concentrations due to faster (conduit or fracture) flow paths. Although karst systems such as this are difficult to characterize, applying a variety of geochemical and physical monitoring techniques at multiple locations illustrates that the flow paths can vary in both space and time.

**KEYWORDS:** karst, recharge/discharge, chemical tracers, time series

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## **Introduction**

Discharge in karstic aquifers reflects both the internal drainage network and how recharge is captured. In some, the internal drainage is through an integrated system of conduits that collects water from all parts of the recharge area and discharges it to surface streams through single large-volume springs. In others, the flow paths are through networks of poorly integrated conduits and solutionally widened fractures and bedding plane partings. These may have the hydraulics of conduit flow, especially during storm recharge, but lack the focus into a single master conduit. In still other carbonate aquifers, the flow system is through relatively unmodified fracture systems so that the hydraulic response is not dramatically different from the flow behavior in fractured granites or other massive rocks.

The difficulty arises where there are multiple flow paths, and it is difficult to characterize the conduit and dispersed flow components. Fully developed conduit systems are amenable to investigation by tracer experiments, by direct exploration of at least parts of the conduit system, and by measurement of spring hydrographs and chemographs (e.g. White 1998, 2002). Aquifers in fractured carbonate rocks with a range of dissolutional modification can be probed by pumping and packer tests on carefully placed wells (Muldoon and Bradbury 2005). Multiple methods are needed to characterize poorly integrated systems.

A number of studies have separated specific components of quick flow and dispersed flow during storms based on hydrographs (Shevenell 1996; Padilla and Pulido-Bosch 1995; Padilla et al. 1994; Felton and Currens 1994) isotopes (Lee and Krothe 2001), CO<sub>2</sub> variation (Vesper and White 2004), and calcite saturation (Desmarais and Rojstaczer 2002). Most such studies have used spring monitoring to elucidate geochemical variation and flow paths. However, Martin and Dean (2001) found dilute stormwater flow from the conduits into the matrix by monitoring a well in a karst aquifer. Seasonal variations in water chemistry of springs have also been used to distinguish conduit versus dispersed recharge (Hess and White 1988; Scanlon and Thrailkill 1987; Wicks 1997; Barnes 1999; Jacobson and Langmuir 1974; Dreiss 1989; Pinault et al. 2001). Variations in conductivity response between springs have been attributed to different degrees of conduit evolution (Grasso and Jeannin 2002). Most of these studies concentrate on the large-volume springs.

The present paper reports an investigation of a carbonate aquifer that represents a poorly integrated karst network. The objective is to gain an understanding of the flow paths based on comparing the physical and chemical responses to storm flow of both a spring and a well. The results presented here point out the need not only for multiple methods, but for looking at multiple locations within the system to characterize both recharge and discharge.

### **Site Description**

The chosen study area is a small catchment that drains through a group of small springs on the banks of Bushkill Creek, just south of the village of Tatamy, Northampton

County, Pennsylvania (Fig. 1). The spring catchment is underlain by the Ordovician Epler Formation, a steeply dipping sequence of interbedded limestones and dolomites. The recharge area includes a small farm and an athletic field that has been plagued with sinkholes. The property is owned by Lafayette College in Easton, PA.

The spring chosen for measurements discharges about 1 L/sec from an enlarged fracture just above water level on the bank of the creek. It is one of a series of small springs in a ground water discharge zone that extends at least 50 m up and down stream. Other discharges in the stream bed are possible. The specific orifice into which measurement probes were inserted is about 5 cm wide.

A well was drilled specifically for monitoring the same catchment (i.e., same recharge area) and to intersect a void that was anticipated based on data from resistivity surveys. The surveys showed an anomaly between two lines perpendicular to each other, which is typical for karst features (Maule et al. 2000). Also the well was sited along strike from the spring and from several sinkholes detected in a field uphill from the site. The well is located about 350 m from the creek at an elevation of about 110 m compared with 91 m at the creek. Depth to water averages 16 m, placing the water surface only a few meters above the creek level. The well was drilled to a depth of 20 m and screened across a void detected between 16.5 and 17.5 m. The horizontal extent of the void is unknown. The void is water filled, except for a few months in the summer when the water level drops below the top of the void but still partially fills the opening. To the extent that it can be deduced from a single observation well, the gradient is 0.007 or about 2.5 meters of head difference between standing water levels in the well and base

flow of the creek. The head difference is within the flood range of Bushkill Creek so that back-flooding into the zone of high permeability is expected during flood flow.

The degree of karstification in the Epler carbonate aquifer is difficult to assess. It seems clear that the ground water basin of interest does not contain a fully integrated conduit system. The discharge is through a sequence of small springs and seeps rather than from a single master spring. There are a few caves known in the Epler Formation in Northampton County (Snyder 1989) but none is very large and none is known in the immediate vicinity of the study site. Many sinkholes are known throughout the area (Kochanov 1986); however, tributary sinking streams are not observed here or in nearby catchments. A few kilometers upstream from the study site between Tatamy and Stockertown, Bushkill Creek and its tributary Little Bushkill Creek lose water due to sinkhole development within the creek beds but this may be the influence of a large quarry adjacent to the stream. The degree of conduit connectivity is not clear from surface expression of the ground water basin.

## **Field, Experimental, and Computational Methods**

### *Sampling*

Samples were collected monthly to bimonthly for 18 months from March 2003 to August 2004. Samples for analysis of ions and suspended sediment were collected at the spring mouth by reaching back into the spring opening to avoid collecting creek water. Samples were collected from the well using a bailer. *In situ* pH, conductivity, and temperature were recorded at the time of sample collection. Water levels of the well and spring were also recorded in the field.

In the laboratory, major ions were measured using Dionex ion chromatography, except for alkalinity. Alkalinity was measured using standard titration. The data were checked for ion balances and entered into the US Geological Survey geochemical modeling program PHREEQC (Parkhurst and Appelo 1999) to calculate the partial pressure of CO<sub>2</sub> (P<sub>CO2</sub>) and saturation index (SI) with respect to calcite.

#### *Data loggers*

Data loggers were installed in the well and the spring mouth to record temperature, water level, and conductivity at 20-minute intervals. A Global Water logger was placed in the spring, and a Solinst logger was placed in the well because the casing diameter (3 cm) required a small logger. The conductivity sensor in the well behaved erratically so the record is discontinuous; after sampling of the well by bailer the meter would not equilibrate back to well water for several days. Another Global Water logger was placed in the creek to monitor conductivity and temperature so that excursions of creek water into the spring mouth during storms could be detected. The geochemical data reported here are from samples collected at baseflow, when the spring water was clearly distinct from the creek. During three or four large storms, the water level in the spring was influenced by the creek water level.

#### *Tracer test*

A qualitative dye trace from the well to the spring was initiated in April 2004. About 160 g of sodium fluorescein was dissolved in 4 L of deionized water. The dye solution was injected into the well using a garden hose to direct the tracer to the depth of the void opening.

Charcoal packets were used as dye receptors. The charcoal packets were placed in the spring monitored with data loggers and also at an additional nine springs along a 50 m length on the bank of the Bushkill Creek. Charcoal packets were placed in the springs before the tracer test to provide a background check for interferences with the dye detection. Two spiked packets were also placed in the field to make sure that dye would be retained on the charcoal under field conditions. In addition, an ISCO sampler was placed in the monitored spring for several storm events to see if storm pulses released dye.

The packets were replaced at weekly intervals for two weeks, then at longer intervals after storm events during the dry season (June and early July). The dye was elutriated from the charcoal with a solution of 5% potassium hydroxide and 70% isopropyl alcohol. The dye concentration in solution was measured with a Jasco spectrophotometer.

*Time series analysis and data distributions*

The water level responses in the well and the spring were compared using autocorrelation and cross correlation. Autocorrelation defines the dependence of a data point on prior points, as follows:

$$r_k = \frac{\sum_{i=1}^{n-k} (x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=1}^{n-k} (x_{i+k} - \bar{x})^2}$$

The sum across the series of the mean-differenced data value  $(x - \bar{x})$  at point  $i$  multiplied by the mean-difference at a series of following points is divided by the sum of

the mean-difference squared at following points. The resulting autocorrelation coefficient ( $r_k$ ) provides a quantitative measure of how dependent following points are on the point  $i$ . When the autocorrelation function ( $r$  from 1 to  $k$  data points) falls off to 0.2, the autocorrelation ( $r_k$ ) loses significance (data become noisy) based on previous studies (Mangin 1984). The time it takes to reach  $r_k = 0.2$  is sometimes called the memory of the system or the response time (Massei et al. 2006). It indicates the time at which a hydrograph returns to “normal”. A quadratic trend was subtracted to eliminate seasonal variations in water level before the autocorrelation coefficient was calculated.

Cross correlation similarly compares data points, but from two different data sets rather than within a single data set. For two series  $x(i)$  and  $y(i)$  at points  $i = 0,1,2\dots n-1$ , with means  $\bar{x}$  and  $\bar{y}$ , and standard deviations  $\sigma_x$  and  $\sigma_y$ , the cross correlation  $r_d$  at every lag  $d$  is

$$r_d = \frac{\frac{1}{n} \sum_{i=1}^{n-d} [(x(i) - \bar{x}) * (y(i + d) - \bar{y})]}{\sigma_x \sigma_y}$$

The lag  $d$  is the time between measurements. The cross correlation function  $r_d$  gives the lag time between response for the two series, and the shape of the response provides clues about the system function (Padilla and Pulido-Bosch 1995).

## Results

### *Tracer test*

The tracer test showed a connection between the well and the nine springs along the shore of Bushkill Creek, but with a delay of at least two weeks and possibly three months. The injection and sampling history is related to storm events as seen on a water level plot during this time period (Fig 2). The tracer was injected in mid April the day

after a large storm event that raised the water level in the well about 40 cm. The charcoal packets and samples were collected a day later, a week later, and an ISCO sampler was used to obtain storm samples two weeks later. These samples were all below the detection limit for the dye. The water level in the well showed a seasonal decline during these two weeks. Furthermore, dye was visible in water bailed from the well. The charcoal packets were then left in place until the occurrence of a storm event large enough to raise the water level significantly. Such an event occurred on July 12, raising the water level about 25 cm. Charcoal packets collected after this storm event showed detectable tracer. Tracer was detected in all nine springs sampled along the 50 m stretch of stream bank, although higher levels were observed within 6 m of the monitored spring and at one spring 40 m upstream. The appearance of dye in all of the monitored springs indicates that these springs represent a ground water discharge zone for the aquifer and not springs with individual small catchments. Within two weeks after the tracer was detected at the springs, the well no longer had visible dye.

#### *System response to storm events*

Continuous data logs of water levels showed the timing of response to storms in the well and spring. The time series analysis evaluated how quickly the water level rose after storms. Cross correlation between water level in the well and the spring was used to compare the response times. The well tended to respond 7 hours later than the spring, as shown by the peak in the cross correlation (Fig. 3). The broadness of the peak, however, indicates that there was variability in the travel times rather than a unique lag between peaks.

The well took longer to recover from storm events than the spring. The memory of the well was 73 hours and the spring 43 hours (Fig 4). The well had a more gradual slope to the response curve than that of the spring, showing greater influence of dispersed flow paths (Massei et al. 2006). The secondary peak in the spring autocorrelation at 200 days is due to the coincidence of two large storms approximately 200 days apart; hydrologic events are not truly correlated at that time interval. In a comparison of wells in non-karst aquifers in Pennsylvania, Herman et al (submitted) found porous media memories between 11 and 46 days. In this study, the well drilled into a karst void responded in about three days. The Bushkill spring response was also faster than the other karst springs analyzed by Herman et al., which had memories from 5 to 22 days, but the springs in that study had an order of magnitude or larger discharge.

The slopes of the recovery hydrographs vary from storm to storm at both the well and the spring (Fig 5). Some storms have two components in the recovery hydrograph, some storms have three different slopes, and the response is not always the same at the well and the spring. This difference in recovery hydrographs suggests that the storm pulse travels through the various conduits and fractures along different pathways depending on ground water levels and storm intensities (Shevenell 1996). The dispersed component has a shallow slope, which is not always observed. Large storms showed more components in the hydrograph (Fig 5a) and small storms in series showed fewer components (Fig 5b). When water levels are high and pores spaces are saturated, the influence of conduit flow may be enhanced over dispersed flow paths.

### *Geochemical results*

Temporal variation in geochemical parameters revealed contrasts between the spring and the well (Fig. 6). While the calcium and bicarbonate concentrations of each varied synchronously, as expected from a limestone source rock, the bicarbonate concentration varied from 70 to 240 mg/L in the spring and from 260 to 560 mg/L in the well. Similarly, the calcium concentration was higher in the well and varied over a wider range.

The spring tended to have a lower saturation index with respect to calcite than the well (Fig. 7). Many measurements on both well and spring were essentially at equilibrium within the expected error of measurement. However, the spring waters often spiked down to strong undersaturation whereas the well waters, although sometimes undersaturated, sometimes spiked upward to supersaturation. The well also had a higher partial pressure of CO<sub>2</sub> and lower pH than the spring (Fig. 7), which is expected if the well is sampling ground water fed mainly by dispersed infiltration through the soil. The CO<sub>2</sub> partial pressures of both spring and well waters were highly variable. The spring water has CO<sub>2</sub> pressures similar to that found for other carbonate springs. The well waters were often in the range of 3 – 10 volume percent CO<sub>2</sub>, values that imply a direct connection with an organic-rich soil.

Concentrations of nitrate were also quite variable in the well and the spring. The range in concentration was from about 1 mg/L as N to 10 mg/L as N for both sites. However, the pattern was not the same. In April through August of 2003, the nitrate concentrations were low in both well and spring, only 1-3 mg/L. There was apparently little nitrate in the soil zone, and uptake by plants in the growing season kept concentrations low. During September of 2003 the nitrate concentrations in both well

and spring increased, reaching 5 to 8 mg/L after the growing season ended and plant uptake was reduced (Fig 8). However, in February of 2004 the nitrate concentration decreased in the well but not as much reduction was observed in the spring. The following period showed variable nitrate concentration in the spring. There may have been more nitrate stored along the flow path to the spring, so that any infiltration mobilized nitrate stored in the soil zone. However, the shallow flow path to the well may have been blocked by snow, then flushed and diluted by a large snowmelt in early February. A 4 m rise in water level was observed in the well at this time, which could have diluted the soil zone around the well. Similar seasonal changes in nitrate concentrations were observed in Nolte spring in central Pennsylvania (Toran and White, 2005).

The mean concentration of chloride is higher in the spring than in the well (15 mg/l in the spring; 5 mg/L in the well). Mean nitrate is also slightly higher in the spring (5 mg/L) than in the well (3 mg/L). Thus, ions from anthropogenic sources such as agricultural activity are lower in the well. In contrast, the concentration of calcium and other ions dissolved along the flow path are higher in the well (200 mg/L mean calcium in the well, 110 mg/L in the spring). The geochemical data show a contrast in flow paths at the two locations, with longer flow paths but more dilution at the well.

### **Discussion: The Nature of the Flow Path**

The advantage of investigating small watersheds is that physical and chemical details of individual storm events are not averaged out before the water reaches the spring. The disadvantage of investigating small watersheds is that the wealth of detail

may be difficult to interpret. The data presented above offer some evidence of the permeability distribution in this small watershed, mixed limestone/dolomite aquifer. The watershed displayed a distribution of fast and slow flow paths that can vary in both space and time. The data characterize both the recharge area and the discharge area because of contrasts observed in the well and spring data.

#### *Evidence for quickflow pathways*

The most obvious evidence for conduit flow is visible conduits. The discharge is from a sequence of small springs of which the monitored spring is only a 5-cm wide enlarged fracture. The well intersected a 1m high void, but the horizontal extent of the void cannot be determined from the well log alone. Both void and spring openings are larger than the 1-cm threshold for non-linear flow hydraulics.

Neither the well nor the spring conduits appeared to be isolated based on the data collected. The spring responded rapidly to storm events, and water levels recovered in about 43 hours based on the autocorrelation statistics. These response times suggest fast flow paths. For some storms the well responded rapidly, but the recovery time was longer than the recovery time of the spring. The swiftness of the response in both the spring and well indicates that conduit flow paths are likely available to both.

The tracer test established a connection between the well and the spring. However, the long time that visible dye remained in the well and the appearance of dye in the charcoal packs only after a large storm shows that the well and the springs are connected by pathways that are activated only during storm flow.

The variability in concentrations of calcium and bicarbonate is also typical of conduit flow. The calcium and bicarbonate ions are particularly sensitive to flow paths

because approach to equilibrium with respect to the rock depends primarily on the travel time and thus on variation in pathways. The calculations showing highly undersaturated water at the spring are direct evidence for quickflow paths feeding the springs.

If the well and the spring were along a direct flow path, the storm pulse would arrive first at the well, then at the spring. The lack of a direct open pathway between the well and the spring is also indicated by the differing chemical responses of these two sampling points. Note that the discovery of a void by resistivity measurements and by test drilling does not prove that the void is part of an integrated conduit system. Thus, the conduit system near Bushkill Creek appears to be a type that is poorly integrated, and includes a significant component of dispersed flow.

#### *Evidence for dispersed flow*

The higher concentration of calcium and bicarbonate in the well than the spring indicates a longer travel time through dispersed flow paths, which allows more dissolution of carbonate rocks. The well had a higher SI with respect to calcite than the spring and higher  $P_{CO_2}$  (Fig. 7), suggesting greater contact with the rock and soil. However, both locations showed evidence for dispersed flow in calcite SI near saturation and  $P_{CO_2}$  above atmospheric values. The stable concentrations of non-carbonate species also suggests that dispersed flow, particularly in the recharge area, is important, as observed in a previous study (Toran and White 2005).

Additional evidence for dispersed flow comes from hydrograph separation. Both the well and the spring showed three components in some storms, particularly large storms. The third portion of the hydrograph, with a shallow slope, is attributed to a dispersed flow component, which is likely micro-fractures or possibly pores.

Finally, the long response time of the well after storm events suggests that dispersed flow is important. The autocorrelation coefficient takes 73 hours (3 days) to dissipate, suggesting slow drainage rather than fast drainage from conduits. The well flow path appears to be longer, based also on the delayed water level response to storm events (cross correlation showing 7 hours slower than the spring response).

## **Conclusions**

Based on the evidence provided by storm hydrographs, chemographs, and the tracer test results, it is possible to construct a conceptual model of a small karst watershed with poorly integrated conduits. Although the portions of conduit and dispersed flow are difficult to quantify in this or any system, comparison of data from both a well and a spring provided insights into the relative portions. The spring is fed by a larger component of the quickflow path than the well, based on the faster response and lower ion concentrations. In contrast, the well showed higher ion content and slower storm response suggesting slower, more dispersed flow paths. A useful lesson is that finding a well intersecting the solution cavity does not necessarily mean that one has drilled into the conduit system. Nonetheless, the well provided insight into the phreatic storage in this karst system. In particular, longer flow paths do not explain the variability in well response, but rather periodic recharge may dilute well concentrations due to faster (conduit or fracture) flow paths.

Thus, the pathways are not necessarily the same at different locations and different times. Trying to map a “direct connection”, such as tracing between a well and a spring, may not always be a useful context for understanding behavior in these poorly integrated systems since the pathways and contributions change. This study shows that

contrasts in geochemical data and water level response from two locations in a karst watershed provides a better understanding of the variety of flow paths in both space and time.

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Fig 1: Location and sketch map of study area, showing land use, well and reach of springs monitored along Bushkill Creek.

Fig 2: History of tracer test injection and sample collection overlain on well and spring hydrographs. The well elevation (right hand scale) is plotted relative to the spring elevation.

Fig 3: Cross correlation between the water level of the spring and water level of the well showing 7 hour lag between peaks in storm hydrographs between February 2004 and August 2004.

Fig 4: Autocorrelation of water levels for the spring and the well between February 2004 and August 2004, showing the longer memory in the system for the well than the spring. The second peak in the spring is an artifact of two large storms at the beginning and end of the sample period.

Fig 5: Examples of storm hydrograph components in the well and the spring The well elevation (right hand scale) is plotted relative to the spring elevation.

a) Storm with three components, b) storm with one component in the well and two components in the spring. 1=quickflow from conduits, 2=intermediate slope from fracture flow, 3=shallow slope from dispersed flow.

Fig 6: Variation in Ca and HCO<sub>3</sub> concentrations in the well and the spring baseflow samples through time.

Fig. 7 Time series data for saturation index, SI<sub>C</sub>, and calculated carbon dioxide partial pressure for well and spring.

Fig 8 Variation in nitrate concentration in the spring and the well. Both show an increase in nitrate after the growing season ends. The well shows less nitrate after the winter snowfall where the spring is more variable.















