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Derivation of effective hydraulic parameters of a karst aquifer from discharge hydrograph analysis

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Abstract. In well-developed karst terrains, three or more distinct portions of the karst continuum can be identified from hydrographs of springs issuing from the karst aquifer. Hydrographs from two karst springs within the same drainage basin at the Crane Naval Surface Warfare Center, Indiana, have been analyzed, and ratios of transmissivity and specific yield (T/S_y) have been established for the conduit and diffuse flow systems. These ratios have been compared with values of T derived from aquifer tests, so that independent values of S_y can be calculated for the diffuse system. Similarly, if the value of S_y is assumed to be 1.0 for a pure conduit, then independent values of T can be calculated for this end-member of the karst continuum. The values of T and S_y derived from this study are similar to values obtained from a dye trace of the conduit-dominated flow system and of values derived from aquifer tests of the diffuse flow system. Values of T for the conduit system of these springs may need to be established at a local scale, while the values for the diffuse flow system may be applicable at a regional scale. A hydrograph separation using isotopic data suggests that the intermediate-flow system represents a mix of water from the conduit and diffuse flow systems. If this portion of the hydrograph is a truly mixing phenomena, ratios of T/S_y cannot be determined from the hydrograph analysis presented herein. However, if instead, the intermediate-flow system represents water released from a third reservoir (such as small fractures), ratios of T/S_y can be established for the intermediate-flow system.

1. Introduction

Groundwater studies in karst terrains are a subject of intense study owing, in part, to the high risk of migration of contaminated groundwater in these area [*Crawford and Ulmer*, 1994; *Assaad and Jordan*, 1994; *Field*, 1992]. Studying these systems is, however, inherently difficult owing to the dichotomy of flow characteristics between the rock matrix and conduit systems [*White*, 1999; *Lakey and Krothe*, 1996; *Dreiss*, 1982]. For example, porosity in the rock matrix of ancient carbonate aquifers is generally considered to be negligible [*White*, 1999]. However, where the aquifer material is fractured or has solutionally enlarged voids, values of secondary porosity can be quite large. As a result, karst aquifers show temporal and spatial variation and abrupt discontinuities between rock matrix and conduit-dominated flow regimes. The variable nature of hydraulic properties in karst aquifers makes it difficult to quantify and predict the movement of groundwater through and/or between different parts of the aquifer.

The characterization of meaningful hydraulic parameters in karst aquifers is further complicated by inadequate techniques of data collection and/or incorrect interpretation of results. Field methods, such as aquifer tests, injection tests, packer tests, and slug tests, which were developed to determine hydraulic properties for diffuse flow systems, may not provide accurate estimates for the conduit system. Even in the rare case where a conduit is either penetrated by or is next to the well being tested, the spatial variation in conduit aperture size and the potential that conduits may not be interconnected limits the applicability of test results to the area immediately around the well. As a result, hydraulic parameters derived from methods relying on well data typically do not provide accurate measurements of conduit properties [*Padilla et al.*, 1994; *Király*, 1975].

In contrast to groundwater moving toward most wells, most karst springs show the response of the entire karst system to areal recharge events [*Lakey and Krothe*, 1996; *Padilla et al.*, 1994; *Teutsch*, 1992; *Sauter*, 1992; *Dreiss*, 1989, 1982; *Király*, 1975]. In well-developed karst terrains, hydrographs from karst springs often show rapid responses to rain events followed by two or more distinct portions of a long recession limb (Figure 1). When quantifying hydraulic properties from hydrographs such as this, the interpretation is that water flowing through portions of the karst aquifer with different conductivities produce the distinctive shape of the hydrograph. The fastest response is thought to be derived from flow through the conduits, and the slowest is thought to be from the diffuse portion of the continuum [*Milanović*, 1976]. This method is based upon a Darcian theory of flow, which may not be valid for higher flow rates through the aquifer. Despite this theoretical limitation this method and other similar hydrograph methods have been successfully applied to several karst systems [*Shevenell*, 1996; *Padilla et al.*, 1994; *Sauter*, 1992; *Milanović*, 1981; *Atkinson*, 1977].

Other researchers have successfully explained the distinctive shapes of storm hydrographs in karst aquifers in terms of water flowing through conduits with constrictions or debris-filled passages [*Halihan et al.*, 1998; *Bonacci and Bojanić*, 1991; *Vine-*

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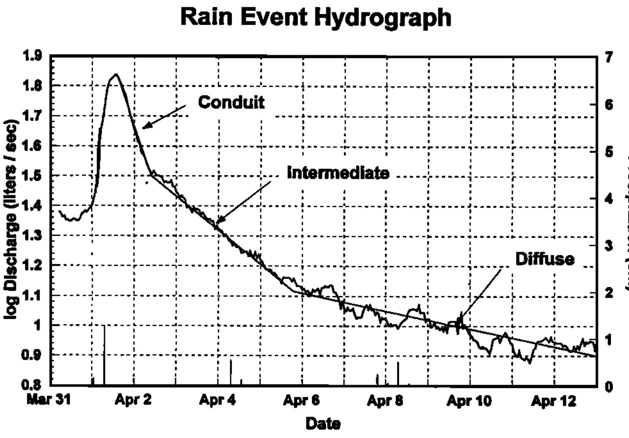

Figure 1. Typical rain event hydrograph from a spring in the study area. Three distinct segments of the hydrograph are labeled: (1) Discharge related the conduit flow system (Conduit), (2) discharge related to a combination of the conduit and diffuse flow system (Mixed), and (3) discharge related the diffuse flow system (Diffuse).

yard, 1958]. Owing to these constrictions or blockages, water is essentially slowed as it travels through the conduits to the spring orifice. The interpretation is that various-sized constrictions delay water flowing through the conduits by different amounts of time. Therefore the distribution of constrictions of various sizes produces a shape that is characteristic to a particular spring hydrograph. To use this method in any quantitative fashion requires that detailed data be gathered to accurately describe the geometry of basin and the conduit system. Unfortunately, such detailed data are often difficult or impossible to obtain for many karst aquifers.

Regardless of the technique used to quantify flow through a karst aquifer, basic assumptions regarding the spatial and temporal distribution of flow characteristics and the conduit/basin geometry relative to aquifer inputs and outputs need to be made. Since data concerning the shape and dimensions of the conduit system are not available for this study, we have chosen to apply the hydrograph analysis technique to attempt to derive meaningful hydraulic parameters of a karst aquifer.

2. Method

The basis for quantifying hydraulic parameters from recession hydrographs comes from the general equation

$$Q_t = Q_0 e^{\alpha(t-t_0)}, \quad (1)$$

which describes concentrated discharge of an aquifer [*Milanović*, 1981]. In (1), α is the recession coefficient and relates to the rate of release of water, Q_t is discharge during the observation period $t - t_0$, and Q_0 is spring discharge at time t_0. Using this technique, the total recession curve can theoretically be represented by the sum of the several best fit exponential functions. In this application the most steeply sloped recession coefficient (α) represents release of water from the conduit end-member of the karst continuum, while the shallowest sloped coefficient corresponds to water released from the diffuse end-member. It is tempting to interpret the intermediate best fit coefficient as representing the release of water from parts of the karst continuum between the conduit and diffuse end-members; however, this may not necessarily be true [*Király and Morel*, 1976]. *Eisenlohr et al.* [1997] used numerical modeling to produce simulated spring hydrographs from a combination of high- and low-permeability elements. The results of this study suggest that it is possible to produce a spring hydrograph with three coefficients even though only two hydraulic conductivities and two storativities may actually be present. In this case the appearance of the intermediate best fit coefficient was [*Eisenlohr et al.*, 1997, p. 313] "... the result of a transient phenomena in the vicinity of the high hydraulic conductivity channel network...."

Using an approach similar to Milanović, *Rorabaugh* [1964] showed that when the recession hydrograph is plotted on a log discharge graph, the slope of the recession curve can be used to calculate properties of the aquifer with the equation

$$T = \alpha 4SL^2/\pi^2, \quad (2)$$

where α is the slope of the discharge hydrograph, T is transmissivity, S is storativity, L is distance from the discharge point to the drainage divide, and t is time of observation. *Atkinson* [1977] rearranged (2) to estimate the hydraulic parameters of an unconfined aquifer from base flow recession curves:

$$\log\left(\frac{Q_1}{Q_2}\right) = \frac{T}{S_y}(t_2 - t_1)\frac{1.071}{L^2}, \quad (3)$$

where S_y = specific yield. In order to establish a value for the variable L in a karst terrain, where the boundaries of the drainage divide can change spatially and temporally under different aquifer conditions, detailed tracing experiments are required. This information typically does not exist for most karst aquifers, so it is common practice to assign each discharge location a value of L that is measured from the discharge point to the topographically defined groundwater drainage divide [*Shevenell*, 1996; *Teutsch*, 1992].

Equation (3) can be rearranged so that the ratio of transmissivity to specific yield (T/S_y) for each segment of the recession curve can be calculated once a value of L has been established and the slope of each segment of the recession curve is known,

$$\frac{T}{S_y} = \frac{\log\left(\frac{Q_1}{Q_2}\right)}{(t_2 - t_1)}\frac{L^2}{1.071}. \quad (4)$$

Equation (4) has been used to determine hydraulic parameters for the conduit, diffuse, and mixed flow systems of a karstic aquifer in south central Indiana. Where possible, hydraulic parameters derived from this method are complimented with and compared to results obtained from well tests of the diffuse flow system and dye traces of the conduit system.

3. Hydrogeology of the Study Area

The Ammunition Burning Ground (ABG) at the Naval Surface Warfare Center (NSWC), Crane, Indiana, is located in south central Indiana and is drained by Little Sulphur Creek (Figure 2). The geology of the NSWC consists of the Pennsylvanian age Mansfield Formation and the Mississippian age Golconda/Haney Limestone, Indian Springs Shale, Big Clifty Formation, Beech Creek Limestone, and the Elwren Formation (Figure 3). Together the Big Clifty Formation and the Beech Creek Limestone comprise the Big Clifty-Beech Creek (BC-BC) aquifer. The Beech Creek is typically a dense, karstified limestone ~6.1 m thick. Locally, drillers have encounter voids and solution cavities in the unit [*Hunt*, 1988; *Murphy and*

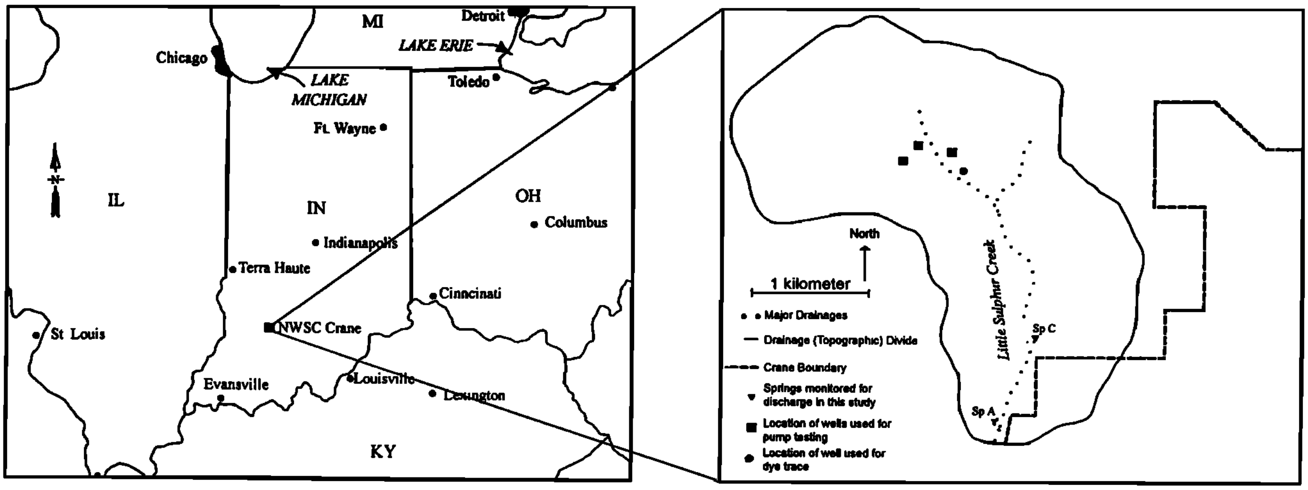

Figure 2. Location of study area and spring A (Sp A) and spring C (Sp C) within the Little Sulphur Creek drainage basin at the Naval Surface Warfare Center, Crane Division, Indiana.

Ciocco, 1990], confirming the karstic nature of this unit. It is desirable that predictive models of the fate and transport of groundwater contaminants at the ABG account for the acknowledged differences in hydraulic parameters of the diffuse flow and conduit systems.

The hydrology of the study area is controlled to a large degree by the karstic nature of the BC-BC aquifer. Rain and surface water percolate into the Big Clifty Formation, which is predominately sandstone, and moves vertically and laterally by diffuse flow. As a result of local jointing, groundwater in this unit also flows vertically by fracture flow, which recharges the underlying Beech Creek Limestone. The Elwren Formation is a shale at the base of the Beech Creek Limestone that restricts further vertical movement of groundwater through the Beech Creek; however, lateral movement continues via diffuse and conduit flow [*Hunt*, 1988; *Murphy and Ciocco*, 1990].

The results of three aquifer tests performed on wells screened in the BC-BC aquifer suggest that transmissivities T of the unit range from 3.2×10^{-6} to 6.7×10^{-5} m^2 s^{-1} and that specific yields S_y range from 5.4×10^{-5} to 3.6×10^{-4} (W. L. Murphy, written communication, 1995). On the basis of observations that the water table was depressed very little during the aquifer test and that only very low pumping rates were capable of being sustained during the test (0.006 to 0.03 L s^{-1}) and core data from wells adjacent to the pumping wells, it is believed that the wells used for these tests were screened in the unfractured, diffuse portion of the aquifer. Additionally, given that the average thickness of the BC-BC aquifer is 6.1 m, an approximate hydraulic conductivity k of this unit can be calculated to be 5.2×10^{-7} to 1.1×10^{-5} m s^{-1}. These values are near the upper bound of the typical range of K for unfractured limestones ($\sim 10^{-6}$ to $\sim 10^{-9}$ m s^{-1}) as reported by *Freeze and Cherry* [1979]. These data further support the belief that the wells represent the unfractured, diffuse portion of the aquifer.

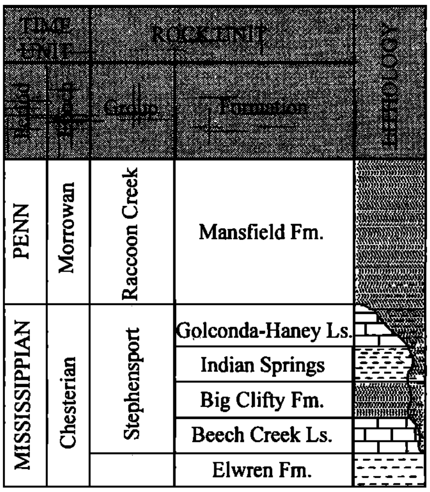

Figure 3. Stratigraphic column of rock units within the Naval Surface Warfare Center, Crane Division, Indiana.

Two dye traces in the BC-BC aquifer suggest that several springs, designated Sp A and Sp C (Figure 2), are the primary outlets for karstic groundwater in the study area [*Murphy and Ciocco*, 1990; *Baedke*, 1998; *Baedke and Krothe*, 2000]. Groundwater velocities determined from these studies are 0.04–0.08 m s^{-1}. Using these values, approximate hydraulic conductivities for the spring A conduit flow system can be calculated with the equation

$$v = (-K/n)(\partial h/\partial l), \tag{5}$$

where v is the groundwater velocity, n is the porosity of the conduit, K is the conductivity of the conduit, and dh/dl is the hydraulic gradient between the tracer injection point and the spring orifice.

The porosity of the conduit will be influenced by such things as sediments in the conduit and variations in the size and shape of the conduit. However, since these details are not known for the study area and since dye was injected directly into the open portion of the conduit, a maximum value of 1.0 for porosity is assumed. During the dye trace conducted by *Baedke and Krothe* [2000] the hydraulic gradient dh/dl was 0.006. No measurement of hydraulic gradient was made for the other dye trace, and since the gradient is dependent upon rainfall amounts and the resulting water level changes, it will not be identical to the that observed by Baedke and Krothe. Therefore no calculation can be made of the hydraulic conductivity for the other dye trace.

Using the previously mentioned values, an approximate hydraulic conductivity for the conduit is calculated to be ~ 13 m s^{-1}.

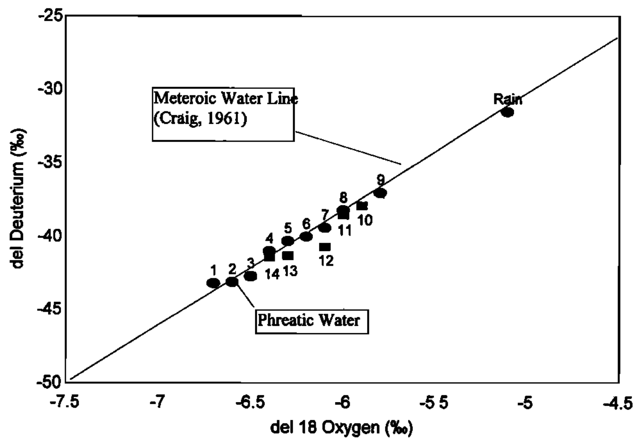

Figure 4. Mixing trend of rainwater and groundwater as seen in a comparison of deuterium and oxygen isotopes from spring A following a rain event (data are from *Noriega* [1997]). Numbers next to the symbols indicate the sequential order that samples were collected. Ovals show the progression of isotopic composition of spring water from a phreatic signature shortly before the rain event toward the composition of rainwater. Boxes indicate the return of the isotopic composition of spring water toward a phreatic signature.

This order of magnitude estimate will be used as a check on the hydrologic parameters derived from the hydrograph technique.

Springs A and C are perennial and show large increases in discharges with rapid recessions after rainfall. These springs are in hydrologic connection with both the conduit and diffuse flow systems. Following the technique of *Fritz et al.* [1976], *Krothe et al.* [1996] used isotopes of deuterium and oxygen to show that discharge at spring A, following a rain event, can be explained in terms of a two-component (binary) mixing model. One end-member of the model is rainwater delivered to the spring via karst conduits, while the other end-member is water released from the rock matrix and discharged from the springs. All points between the two end-members, representing the mixed flow portion of the hydrograph, can be explained by mixing of the two end-members (Figure 4). Examination of Figure 4 shows the progression of isotopic composition of spring water from a phreatic signature, representative of the diffuse flow system, shortly before the rain event toward the composition of rainwater (oval numbers 1–9, corresponding to the order in which samples were taken). The numbered boxes indicate the sequential return of the isotopic composition of spring water back toward a phreatic signature (box numbers 10–14, corresponding to the order in which the samples were taken).

The results of this isotopic study suggest that discharge at spring A can be broken into three components derived from two isotopically different reservoirs: (1) discharge from predominantly rainwater flowing through the conduits (conduit flow system), (2) discharge originating from the rock matrix (diffuse flow system), and (3) discharge resulting from a mixture of the conduit and diffuse flow systems (mixed flow system). The study by *Krothe et al.* [1996] does not suggest the presence of an intermediate, isotopically different reservoir in the BC-BC aquifer supplying water to spring A.

4. Hydrograph Analysis Determination of Hydraulic Parameters

Discharge from springs C and A were continuously monitored for a 2 month period with weirs that were calibrated for a range of flow conditions with a rating curve. Hourly discharge measurements were calculated and recorded for each spring with pressure transducers and programmable data recorders. Precipitation data were also continuously recorded for the 2 month period with a tipping bucket style rain gauge and a data recorder that was programmed to provide hourly totals of rainfall. These data are presented in Figure 5.

During this period, nine rain events caused noticeable discharge response in both springs. Enough time elapsed between six of the rain events for at least one segment of the hydrograph recession curve to be clearly identified for the purposes of recession analysis. Individual segments of the recession curve were initially identified by visually picking breaks in slope on the recession hydrograph. The duration of each segment was then refined by maximizing the R^2 value resulting from a least squares regression used to calculate a best fit line through the data. The best fit lines are superimposed on the hydrograph data of Figure 5.

In all calculations we have assumed an "average" value of L, the distance to the topographically defined drainage boundary. Spring C (Sp C in Figure 2) is centrally located along a west-east line in the basin, and the value of L is 840 m. Spring A (Sp A in Figure 2) is ~220 m away from the western divide and 520 m away from the eastern divide. Although groundwater flowing from the western divide is likely to dominate the response of the hydrograph, we present a range of results using 220 and 520 m as the values for L.

The resulting slopes of the best fit line and the length term L were then used to calculate ratios of T/S_y for each segment. These values along with arrows pointing to their respective segments are also presented on Figure 5. Averages and ranges of averages of the values of T/S_y for each segment are tabulated in Table 1 for both springs.

4.1. Results

Three components of flow are identifiable for each spring, inasmuch as each component has a distinctly different slope on the discharge hydrographs (Figure 5). Both spring hydrographs show nearly identical timing of responses and duration of time that each segment tends to dominate the hydrograph. However, the magnitude of response to recharge (precipitation) is different between springs A and C, with spring C having greater discharge after each rain event.

The steeply sloped segment of the recession hydrograph immediately following peak discharge represents flow that is predominately through conduits. The water in the conduits is quickly discharged at the spring and dominance of the hydrograph by the conduit system ceases. This portion of the hydrograph is followed by an intermediate, less steeply inclined segment, which could potentially represent either (1) a mixing of water moving through the conduits and the arrival of a pulse of rain-derived groundwater moving through the rock matrix or (2) a source of water coming from an third reservoir, such as smaller-scale fractures. Regardless of the interpretation of the intermediate segment, this portion of the hydrograph gradually dissipates, and spring discharge becomes dominated by groundwater released from the pores of the rock matrix. This last component of flow is seen on the recession hydrograph as the line segment with the lowest slope. A summary of the data presented in the following discussion is tabulated in Table 1.

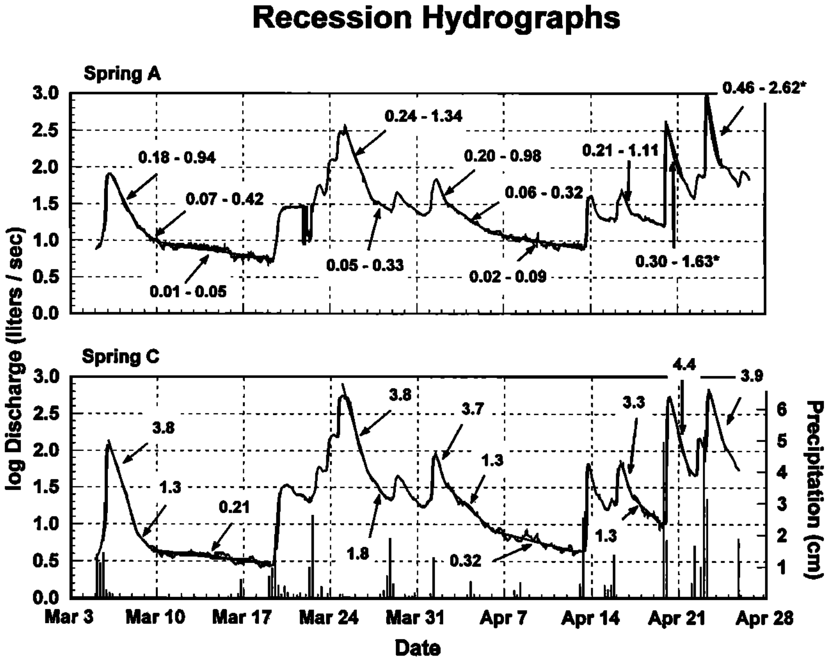

Figure 5. The 56 day discharge hydrographs for springs A and C. Superimposed on the hydrographs are the best fit lines representing the conduit, mixed, and diffuse flow systems. Numbers correspond to the ratio of T/S_y ($m^2\ s^{-1}$) calculated from the corresponding segment of the hydrograph. An asterisk next to a value of T/S_y indicates that discharge exceeded the calibrated range of the weir for the rain event, and this value was not used in the discussions of results. Precipitation (in cm on the right-hand Y axis) is shown on the diagram as vertical spikes.

4.2. Hydraulic Parameters of the Conduit Flow System

Using (4) and the range of L values discussed previously, T/S_y ratios of this portion of the hydrograph for spring A range from 0.18–0.94 to 0.24–1.34 $m^2\ s^{-1}$, with an average range of 0.21-1.1 $m^2\ s^{-1}$ (R^2 average of best fit lines is 0.985; R^2 range of best fit lines is 0.978–0.995). Note that the last two rain events caused discharges at spring A to exceed the calibrated range of the weir and are therefore not included in the calculations. Analysis of the spring C hydrograph results in T/S_y ratios of 3.3–4.4 $m^2\ s^{-1}$, with an average of 3.8 $m^2\ s^{-1}$ (R^2 average of best fit lines is 0.979; R^2 range of best fit lines is 0.960–0.995).

By definition, S_y is the ratio of the volume of water drained from storage per unit surface area of an aquifer per unit decline in the water table [*Freeze and Cherry*, 1979]. In a pure conduit the volume of water released from the conduit is equal to the surface area of the open conduit multiplied by the decline of head in the conduit. It is commonly assumed that the maximum value of S_y for the conduit is equal to 1.0 [*Shevenell*, 1996; *Sauter*, 1992]. This assumption is made since conceptually this portion of the hydrograph represents discharge from only the water directly entering and exiting the pure conduit and not from the matrix of the aquifer. Therefore it is assumed

Table 1. Summary of Values for Hydraulic Parameters Calculated From the Hydrograph Method Presented in This Study and From Other Methods

Aquifer Portion (Technique Used to Define)	T/S_y, $m^2\ s^{-1}$	T, $m^2\ s^{-1}$	S_y
Conduit			
Hydrograph analysis spring A[a]	0.21–1.1	0.21–1.1	1.0[b]
Hydrograph analysis spring C[c]	3.8	3.8	1.0[b]
Dye trace[d]	NA	79	NA
Diffuse			
Hydrograph analysis spring A[a]	1.5×10^{-2} to 7.0×10^{-2}	2.8×10^{-5}[e]	1.9×10^{-3} to 3.6×10^{-4}
Hydrograph analysis spring C[c]	0.26	2.8×10^{-5}[e]	1.1×10^{-4}
Aquifer tests	5.9×10^{-2} to 0.19	3.2×10^{-6} to 6.7×10^{-5}	5.4×10^{-5} to 3.6×10^{-4}
Intermediate[f]			
Hydrograph analysis spring A[a]	0.06–0.36	NA	NA
Hydrograph analysis spring C[c]	1.4	NA	NA

[a]Range of L values is 220–520 m.
[b]Value is derived from the definition of y_S for a conduit as discussed in the text.
[c]Value of L is 840 m.
[d]*Baedke and Krothe* [2000].
[e]Value is the mean of data obtained from aquifer tests of the diffuse system (W. Murphy, written communication, 1995).
[f]Intermediate is assuming that the intermediate segment represents the release of water from a third reservoir (i.e., small fractures) and not mixing of water from the conduit and diffuse portions of the aquifer.

that the value of S_y for the conduit has reached the maximum value that it can and should be equal 1.0. Similarly, as the aquifer begins to make a proportionally larger contribution to the discharge hydrograph (as evidenced by the other recession coefficients), the value of S_y will diminish until all discharge at the spring is attributed to water released from the diffuse flow system.

For the conduit system we have assumed that a value of S_y equal to 1.0 is applicable. This results in the transmissivity of the conduit system feeding each spring being equal to the respective T/S_y ratios (Table 1). Knowing that the BC-BC aquifer averages 6.1 m in thickness, the effective hydraulic conductivity K calculated from the previously discussed dye trace can be used to provide an estimate of the T for the conduit system at each spring as 79 $m^2 s^{-1}$. This procedure overestimates the T of the conduit systems since the entire 6.1 m thickness of the BC-BC aquifer is not likely to be karstic throughout the aquifer and the porosity of the conduit is probably not equal to 1.0 as was previously assumed. Given these limitations, the dye trace derived T appears to provide an order-of-magnitude estimate that is in the range of T derived from the hydrograph analysis method.

As evidenced by the magnitudes of response to recharge and the differences in the values of T for the conduit systems of springs A and C, the hydraulic parameters for the conduit system are only locally accurate around each spring studied. Therefore the hydraulic parameters of the conduit system are only accurate at a relatively local scale.

4.3. Hydraulic Parameters of the Intermediate Flow System

Interpretation of the intermediate portion of the recession curve is more difficult than either the conduit or diffuse flow systems. The previously mentioned isotopic study suggests that there may only be two reservoirs of water discharged by the springs. Furthermore, the modeling work of *Eisenlohr et al.* [1997] suggests that it is possible to observe three distinct segments on a recession hydrograph with only two distinct reservoirs (conduit and diffuse) of flow. With this interpretation of the data the method of hydrograph analysis produces meaningless results for the intermediate flow system. This is because the method only produces meaningful estimates of T/S_y when applied to a physical reservoir of water. In this interpretation of the data a physical reservoir does not exist for the intermediate segment of the hydrograph.

An alternate interpretation of the data could be made if the intermediate segment truly represents flow from a separate reservoir of water, such as flow from small fractures. Following the same approach described above, the T/S_y ratios calculated for the intermediate-flow system gives a range of values for spring A from 0.05–0.33 to 0.07–0.42 $m^2 s^{-1}$ with an average range of 0.06–0.36 $m^2 s^{-1}$ (R^2 average is 0.955; R^2 range is 0.915–0.986). For spring C the T/S_y values are 1.3–1.8 $m^2 s^{-1}$ with an average of 1.4 $m^2 s^{-1}$ (R^2 average is 0.974; R^2 range is 0.969–0.980). Since no data exist that assess either T or S_y of this hypothetical reservoir, only ratios of T/S_y can be established under these conditions.

4.4. Hydraulic Parameters of the Diffuse System (Rock Matrix)

During the time of this study the diffuse flow component of the system dominated the hydrographs during only two periods. Hydrograph analysis for spring A suggests that the ranges of T/S_y for these two periods are 0.01–0.05 and 0.09–0.08 $m^2 s^{-1}$ (R^2 average of best fit lines is 0.751; R^2 values of best fit lines are 0.666 and 0.836). For spring C the values are 0.21 and 0.32 $m^2 s^{-1}$ (R^2 average of best fit lines is 0.812; R^2 values of best fit lines are 0.793 and 0.830). The R^2 values calculated for the best fit lines are noticeably lower than for the either the conduit or mixed flow segments. This is likely due to the brief periods of rain that cause only slight variations in discharge over the extended periods of time that these segments dominate the hydrograph.

The previously discussed aquifer tests suggest that an average transmissivity of the diffuse system is $\sim 2.8 \times 10^{-5}$ $m^2 s^{-1}$. Assuming this average T, values of S_y can be calculated from the ratios of T/S_y derived from the hydrograph analysis for the diffuse system. Performing these calculations leads to an average range of S_y for spring A to be 1.9×10^{-3} to 3.6×10^{-4} and a S_y of 1.1×10^{-4} for spring C. It is also possible to substitute the values of S_y from the aquifer tests and calculate the result T value. Regardless of which value is calculated, the process of complimenting the hydrograph derived ratios of T/S_y with aquifer test data for the diffuse flow system provides a means of comparison for the results of the two methods.

The values of S_y derived from the hydrograph analysis are similar in magnitude and range to the values of S_y determined by aquifer tests (3.6×10^{-4} to 5.4×10^{-5}), suggesting that the hydrograph analysis may be an effective tool for determining hydraulic properties of the diffuse flow system in this karst system. As is commonly done with aquifer test data, it may be possible to apply the values of hydraulic parameters derived from the hydrograph analysis to regional or subregional portions of the diffuse system in karst aquifers.

5. Summary and Conclusions

Two karst springs, springs A and C, at the Crane Naval Surface Warfare Center, Indiana, have been continuously monitored for discharge. Rain event recession hydrographs show distinct segments that represent flow derived from (1) conduits, (2) rock matrix, and (3) a mixture of water from the conduits and rock matrix or, alternatively, water from small fractures. When plotted on a log discharge versus time graph, the slope of each segment of the recession curve and the distance of the spring from the drainage divide can be used to calculate ratios of T/S_y for the three portions of the karst continuum identified in this study.

Assuming a maximum value of S_y as 1.0 for the conduit system allows us to calculate a T of the conduit system. Owing to the location of spring A a range of distances representing the shortest distance and longest distance from the spring to the drainage divide were used to make the calculations of the T/S_y ratios. Incorporation of the S_y value for the conduit results in an average range of T values of 0.21–1.1 $m^2 s^{-1}$ for spring A. This value is smaller than but comparable to T values obtained by dye trace of the spring A conduit network (79 $m^2 s^{-1}$). Since spring C was centrally located in the basin, a single distance value was used to calculate the average value of T as 3.8 $m^2 s^{-1}$. Since conduit systems typically display considerable spatial variability, T values for this part of the continuum need to be established at a local scale.

Although an intermediate flow segment is clearly identifiable on the hydrographs, the necessity that this segment represents reservoir of water is questionable. The modeling results of *Eisenlohr et al.* [1997] suggest that a well-defined intermediate segment could be produced by a mixing of water derived from the conduit and diffuse flow reservoirs. Additionally, an

isotopic analysis of water discharged at the spring suggests that the water budget of the hydrograph may be explained in terms of a two-component (conduit and diffuse reservoir) mixing model. If the intermediate segment truly results from a mixing of the two other reservoirs of water and not a separate reservoir the calculated ratios of T/S_y for this portion of the hydrograph are meaningless. However, for karst systems with a significant contribution from a third reservoir of water, such as small fractures, then meaningful ratios of T/S_y can be calculated for this portion of the karst continuum. Such an analysis of our data would result in an average range T/S_y values for spring A of 0.06–0.36 $m^2 s^{-1}$. For spring C the average T/S_y is 1.4 $m^2 s^{-1}$.

Aquifer tests from the unfractured part of the aquifer show values of T for the rock matrix of 3.1×10^{-6} to 6.7×10^{-5} $m^2 s^{-1}$ and S_y of 3.6×10^{-4} to 5.4×10^{-5}. Assuming an average value of 2.8×10^{-5} $m^2 s^{-1}$ for T, S_y values from analysis of the hydrographs can be calculated. The results show that the S_y for the two springs are in general agreement with the values calculated from the pumping tests. For spring A the range of values are 1.9×10^{-3} to 3.6×10^{-4}. For spring C the resulting S_y is 1.1×10^{-4}. It is likely that the values of hydraulic parameters derived from the hydrograph analysis are representative of regional or subregional portions of the diffuse system in the study area.

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