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Evaluating Transmissivity Estimates from Well Hydrographs in Karst Aquifers

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Transmissivity Estimates from Well Hydrographs in Karst and Fractured Aquifers

Jefferey G. Powers and Lisa Shevenell

Abstract

Hydrograph recessions from rainfall events have previously been analyzed for discharge at springs and streams; however, relatively little quantitative research has been conducted with regard to hydrograph analysis of recessions from monitoring wells screened in karst aquifers. In previous work, a quantitative hydrograph analysis technique has been proposed from which matrix transmissivity (i.e., transmissivity of intergranual porosity) and specific yields of matrix, fracture, and conduit components of the aquifer may be determined from well hydrographs. The technique has yielded realistic results at three sites tested by the authors thus far (Y-12, Oak Ridge, TN; Crane, IN; and Ft. Campbell, KY). Observed field data, as well as theoretical considerations, show that karst well hydrographs are valid indicators of hydraulic properties of the associated karst aquifers. Results show matrix transmissivity (T) values to be in good agreement with values calculated using more traditional parameter estimation techniques such as aquifer pumping tests and slug tests in matrix dominated wells. While the hydrograph analysis technique shows promise for obtaining reliable estimates of karst aquifer T with a simple, relatively inexpensive and passive method, the utility of the technique is limited in its application depending on site-specific hydrologic conditions, which include shallow, submerged conduit systems located in areas with sufficient rainfall for water levels to respond to precipitation events.

Introduction

Many studies of karst spring discharge and hydrograph analyses have been undertaken (e.g., Milanovic, 1981; Bonacci, 1993; Smart and Hobbs, 1986; Meiman et al., 1988; Recker et al., 1988, and others), whereas relatively little has been done with respect to well hydrographs in which the wells intercept karst or fractured zones within an aquifer. Historically, hydrograph analysis techniques have been developed for stream and spring discharge data (Padilla et al., 1994). Relating ground-water hydrographs in karst to the analysis of karst springs is based primarily on the idea that in a well-developed karst region, karst aquifer water levels directly influence related spring discharges (Bonacci, 1993). Relatively few studies (Rorabaugh, 1960; Atkinson, 1977; Shevenell, 1996) have been conducted that yield quantitative data on aquifer parameters using well hydrographs. Previously, it has been noted that stream flow recession curves can be approximated by three straight line segments on a semilogarithmic plot with each line representing different types of storage: stream channels, surface soil, and groundwater (Barnes, 1940; Linsley et al., 1982). Shevenell (1996) suggests that three segments on recession curves from wells in a karst or fractured aquifer also represent three types of storage upgradient of the monitored point: conduit, fracture and matrix. The data and discussions in Shevenell (1996) indicate the behavior of recessions in wells intercepting karst zones may be a good indicator of the properties of the aquifer in which the wells are screened.

In previous work, Shevenell (1996) presented a method to estimate aquifer parameters at the karst Y-12 site in Oak Ridge, Tennessee (referred to henceforth as "Oak Ridge site") by analyzing the recessions on well hydrographs in an attempt to obtain the same type of hydrologic information on matrix intervals as would be obtained from traditional aquifer testing (pump, slug) methods that are currently in use. Note, the hydrograph analysis method was not employed to obtain travel times in conduits, which can only be obtained in karst aquifers via tracer tests. Transmissivity of a carbonate aquifer is an important parameter to estimate and understand because each portion of a multiporosity aquifer system (conduit, fracture, and matrix) contributes separate components of flow, transport, and storage (Shevenell and Goldstrand, 1997).

One motivation for examining the analysis of hydrographs for estimation of aquifer T and specific yield was that traditional aquifer testing methods often require pumping large quantities of water from the aquifer. This type of test has two major shortcomings: (1) aquifer properties are estimated under stressed, unnatural flow conditions, and (2) production of large quantities of water at contaminated sites results in very costly treatment and disposal of the waste. Hence, the hydrograph analysis technique was investigated because (1) the aquifer parameters could be obtained passively under natural flow conditions in an aquifer that is not stressed, and (2) there is no need to produce water, thus significantly reducing the costs of obtaining aquifer data. Previous preliminary results obtained from the work conducted at the Oak Ridge site showed similar matrix T using limited pumping test analysis results and the hydrograph analysis technique (Shevenell, 1996), and additional pumping test results from specific wells with hydrograph analyses are presented here.

Widespread use of the hydrograph analysis method would not be possible without testing the method at other karst and fractured (or multiporosity) sites. The work described here was conducted to determine if methods largely developed for use in evaluating spring hydrographs could also be applied to well hydrographs. As part of ongoing work, the method has been applied to two additional sites (Main Cantonment Area of Ft. Campbell, KY and Ammunition Burning Ground, Crane Naval Surface Warfare Center, Crane, IN; Figure 1) that are similar (i.e., shallow, submerged conduit systems) to the original aquifer examined at Oak Ridge, and the complete results are presented separately (Powers, 1998). It is hypothesized that the hydrograph analysis technique presented in Shevenell (1996) is a valid procedure for estimating aquifer parameters in multiporosity systems, and field data from three sites are presented here to support this hypothesis.

The goal of this work is to test a technique that shows promise in determining aquifer parameters in shallow, karst, and fractured aquifers. In karst and fractured aquifers, each type of porosity is important in determining the overall flow behavior in the aquifer system. Whereas relatively rapid fluid flows can be expected through fractures and cavities, a much larger percentage of an aquifer is composed of matrix porosity. This porosity can be the site of storage of large volumes of contaminants, which may require much greater periods of time to flush or be removed than from the fractured components of the aquifer (e.g., see Shevenell et al., 1994). It is, thus, beneficial to know matrix T in determining the length of time it would take a contaminant to be completely flushed from a multiporosity system (including transport through pore space). If this hydrograph analysis technique can be demonstrated to be reliable, it may lead to minimization of hazardous waste generation in some geologic settings due to the lack of need for an aquifer pumping test, and hence, ground-water extraction. The use of the technique may also lead to the reduction in the amount of field-intensive man-hours spent at sites, and a lowering of overall cost of field investigation in some circumstances. Data obtained through the use of this methodology may provide an adequate level of certainty to be used in site-specific hydrogeologic models. It should be made clear, however, that matrix T estimation from well hydrographs should not replace traditional methods altogether, but instead be used in concert with other valid parameter estimation methods to better understand the overall behavior of groundwater flow in heterogeneous, multiple porosity systems.

Methods

In order to determine if the hydrograph analysis method described in Shevenell (1996) (and briefly below) can be expected to provide reasonable estimates of aquifer properties, the method is evaluated here based on (1) basic theoretical considerations, (2) limited field observation of a hydraulically connected spring and well, and (3) results of hydrograph analyses in comparison to results from traditional aquifer testing methods. First, the Bernoulli equation is evaluated in the context of flow through a conduit to a spring, where the conduit upgradient of the spring is intercepted by a nearby well. This equation is used to determine how water levels in a well intercepting a conduit may relate to discharges at the spring, where discharge from the conduit occurs. Second, data from an existing well in a conduit that feeds a local spring are presented to show similar water level responses that are observed in natural conditions when a well intercepts one conduit that feeds the discharge to a spring. The first and second items noted here are evaluated to determine if similar responses can be expected in both well and spring hydrographs for which traditional hydrograph analysis methods were originally developed. Third, 72 wells were monitored at three different sites, of which 49 had recessions that were suitable for use with the hydrograph analysis technique (Powers, 1998). The well hydrograph estimated T are compared here to the T estimated using traditional aquifer testing techniques (pump, slug) to test the applicability of the analysis method described by Shevenell (1996).

Previous Work

Recession limb analysis in karst aquifers often leads to two or more line segments that represent responses in different portions of the ground-water system: (1) a fast response to conduit flow; (2) slower responses owing to flow through fractured and unfractured porous media (White, 1988, p. 186). It has been previously noted that stream flow recession curves can be approximated by three straight line segments on a semilogarithmic plot with the lines representing three different types of storage: stream channels, surface soil, and groundwater (Barnes, 1940; Linsley et al., 1982). It is reasonably assumed that three segments on a recession curve from wells in a multiple porosity karst or fractured aquifer also represent three types of storage (and flow): conduit or larger fractures, fracture, and matrix portions of the aquifer (Shevenell, 1996).

In the well-developed, submerged fracture or conduit systems discussed here where there are multiple porosities from different portions of the aquifer (conduit, variable enlarged fractures, intergranular porosity), two or more straight line segments with different slope values occur in the hydrograph recessions in many of the wells monitored (e.g., see Figure 2). In cases in which there are three slopes on the recession, the first and steepest slope represents the dominant effects of drainage of the larger karst or fractured features, whereas the second, intermediate slope characterizes the emptying of smaller fractures or partially karstified fractures. The third slope represents drainage of the porous, matrix portion (non-fractured, non-conduit; Shevenell, 1996) of the aquifer. The first slope encompasses the effects of all three flow regimes, yet is dominated by the flow through the conduit portion of the aquifer. In some instances, four or more slopes may be observed on a storm recession, indicating additional flow regimes in the multiporosity system.

As an example, a hydrograph from one well at the Oak Ridge site is used to illustrate the hydrograph analysis technique, which is described in detail in Shevenell (1996). The recession portion of this hydrograph from the first storm event shows two inflection points, which are illustrated on a plot of the natural logarithm of the water level versus time (Figure 2). Each of the segments of the hydrograph (Figure 2) has a characteristic slope (λ) for any given storm event, and the slope is defined by the following equation (Moore, 1992):

$$\ln(Y_1/Y_2)/(t_2 - t_1) = \lambda_1 = \ln(Q_1/Q_2)/(t_2 - t_1), \qquad \ln(Y_2/Y_3)/(t_3 - t_2) = \lambda_2 = \ln(Q_2/Q_3)/(t_3 - t_2)$$

$$\ln(Y_3/Y_4)/(t_4 - t_3) = \lambda_3 = \ln(Q_3/Q_4)/(t_4 - t_3) \tag{1}$$

where, Y_1, Y_2, and Y_3 are water levels, and Q_1 and Q_2 are the associated theoretical flows at the well corresponding to the water levels at times t_1 and t_2. Theoretical flow (Q) at a well is somewhat of an abstract concept; however, Q ratios can be obtained by taking successive water level vs. time measurements at a well, and represents the amount of groundwater passing a well during a given period of time as a result of the difference in water levels over that time period. Solving for Q_1/Q_2 in Equation 1, the ratios of the theoretical flows can be calculated, where Q_1 represents conduit dominated flow/drainage, Q_2 represents fracture dominated flow, Q_3 represents diffuse, matrix dominated flow. Units for the Y values are length (L) whereas those for the Q values are L^3/time.

At peak discharge, storage in the aquifer is at a maximum and storage volume decreases at a given rate. The relationship of base flow conditions to changes in ground-water storage volume has been expressed by Moore (1992), after Fetter (1988, p.52), as

$$V_1 = Q_1 (t_2 - t_1) / \ln(Q_1/Q_2). \tag{2}$$

Combining with Equation 1 yields

$$V_t = Q_t / \lambda , \tag{3}$$

where V_t is the volume of water in dynamic storage at any time t, and Q_t is the flow rate produced by the stored water at time t. It is assumed that the flow rate Q_t from storage is reflected in the well hydrograph by the hydraulic head Y_t, and the two are related by Equation 1. Using the discharge (Q) ratios above, the volumes (V_t) can be cast in terms of one Q (e.g., Q_1). The volume of storage related to each segment on a well hydrograph can be expressed as a function of each of the individual Q values. The change in storage volume can be expressed as (Moore, 1992)

$$(V_1 - V_2) = (Q_1 - Q_2) / \lambda , \tag{4}$$

or equivalently as

$$(V_1 - V_2) = A\, S_y\, (Y_1 - Y_2). \tag{5}$$

Using Equation 4 to obtain $(V_1 - V_2)$ as a function of the Q associated with the segment of the hydrograph being considered, and substituting this value as a function of Q into Equation 5 allows determination of a value for the ratio ASy_t/Q_t for each segment of the hydrograph, where A is the basin drainage area and S_y the specific yield. Using the ratios of Q_1/Q_2, etc., the S_y for each portion of the hydrograph (conduit, fracture, matrix regions) can be expressed as a function of one of the Q values (Shevenell, 1996):

$$ASy_1 / Q_1 = X_1,\ ASy_2 / Q_1 = X_2,\ ASy_3 / Q_1 = X_3 \qquad (6)$$

where X_n are numerical values. If it is assumed that the drainage area (A) corresponding to volume changes represented by the three line segments are the same, then the $ASy_t / Q_1 = X_t$ expressions can be solved for Q_1 and equated. The resulting expressions yield numerical values for the ratios of S_y values associated with each segment of the hydrograph. In current and previous work, the S_y of the matrix has been obtained from either laboratory measured S_y values from samples of matrix rocks, or by averaging the S_y from multiple pumping tests at the investigated site. Note, the assumption of a constant A is invalid in cases of direct pipe flow to conduits via a sinkhole, for example. Such a case was not encountered in the work presented here.

In estimating the average non-conduit T of an unconfined aquifer from a base flow recession curve from a spring, Atkinson (1977) presented the following expression (after Rorabaugh, 1960; 1964):

$$\log (Q_3 / Q_4) = (T / S) \bullet (t_4 - t_3) \bullet (1.071 / L^2) \qquad (7)$$

where L is the distance from discharge to ground-water divide, and S is the storage coefficient, which is equal to the S_y for unconfined aquifers. By inserting the Q ratios obtained previously, and an estimated distance from recharge area, estimates for the ratios of T/S can be obtained from Equation 7. The value for S, or S_y, obtained from pumping tests in matrix intervals, site knowledge, or laboratory testing, is then inserted into Equation 7 to obtain matrix values of T in the karst aquifer. The previous derivation results in T estimates in base flow conditions, which are more representative of the slower diffuse flow in matrix intervals than the more rapid conduit flow. Equation 7 was developed for use with spring hydrograph data, and the following sections indicate that the expression is also valid for use with well hydrograph recession data due to similar types of responses being observed in wells intercepting conduits and/or fractures as are observed in springs.

Results

Fluid Dynamics Theory

A definable potentiometric surface in karst terrain is not straightforward. Although pores are saturated below the water table in an unconfined, well-developed karst aquifer, rapid flow occurs in the enlarged channels, or conduits, and behaves hydraulically as pipe flow (Fetter, 1988) with fracture and matrix intervals draining to the conduits. Velocities may be great enough that turbulent flow conditions exist, particularly in incompletely submerged conduits. However, all conduit systems discussed here and tested thus far are completely submerged.

The concept of comparing hydrograph recession responses for wells screened in conduit zones to similar responses in spring hydrograph recessions is founded in fluid dynamics theory (e.g., Streeter and Wylie, 1985). During a recharge event, a spring's discharge will increase, crest, then decrease in response to a pressure pulse and subsequent storm water pulse moving through the system. Similarly, the water level in a nearby well, and hence, the hydrostatic pressure in the pipe intercepted by the well, or conduit feeding the spring, will rise, crest, then fall as the water drains from the pipe. Similar responses are, therefore, expected to be observed in wells and springs indicating it is reasonable to extend spring hydrograph analysis methods to water level variations in wells.

For simplification, we evaluate the most basic case where a single, straight, completely submerged, cylindrical and smooth conduit feeds a single spring. In comparing well and spring hydrographs, we must first assume that a simplified, submerged conduit in karst is equivalent to a closed pipe with no water free-surface (pipe full condition). This is a reasonable assumption because all three sites to which the method has been applied thus far are submerged conduit systems. It is recognized that such ideal conditions do not wholly exist in nature; however, the Bernoulli equation is used for qualitative purposes to determine how the rise or fall of water in a piezometer is related to spring discharge. Assuming the simplest conduit geometry (Figure 3), and that frictional losses are not appreciable, Bernoulli's equation (energy equation) for streamlines is applied (Streeter and Wylie, 1985):

$$v_1^2/2g + p_1/\gamma + z_1 = v_2^2/2g + p_2/\gamma + z_2 \qquad (8)$$

where v_1 = velocity of water in conduit (L/T), v_2= velocity of water at spring (L/T), p_1 = conduit fluid pressure (Force/L^2), p_2= pressure of water at spring (F/L^2), z_1 = elevation of conduit (L), z_2 = elevation of water at spring (L), g = gravitational acceleration (L/T^2), γ = specific weight of water (F/L^3). The assumption of steady, frictionless, incompressible flow along a streamline must hold in order for Equation 8 to be valid. Even for unsteady flow with gradually changing conditions (e.g., the emptying of stored aquifer water in a submerged, karst conduit type system), Bernoulli's equation can be applied without appreciable error (Streeter and Wylie, 1985).

Figure 3 shows where parameters of Equation 8 would be measured, and we consider a simplified case and assume that a single conduit feeds a nearby spring where fracture and matrix flow into the conduit between the closely spaced well and spring is assumed neglegible. Given the large difference in magnitude of flow in conduits during a storm pulse versus that in matrix intervals entering the conduit, the assumption of no flow into the conduit aong the short distance betweent the hypothetical spring and well is reasonable. Point 1 of Figure 3 corresponds to the conduit within the screened interval of the monitoring well, and Point 2 corresponds to the conduit discharge point, or spring. By defining the elevation reference datum of zero at the elevation of the spring, the z_2 term becomes zero, and z_1 is the elevation of the conduit at Point 1 above the spring. The p_2 term is zero because the pressure on a free-liquid surface exposed to atmospheric pressure is zero by definition (Streeter and Wylie, 1985). The water pressure in the conduit at Point 1 (p_1) is equal to the specific weight of water multiplied by the distance between the height of the water and the conduit. From Equation 8, it is apparent that p_1 and z_1 are directly proportional to the square of the velocity at the spring. Since the velocity is equal to discharge (Q) divided by cross-sectional area (A), p_1 and z_1 are also directly proportional to the square of spring discharge, and:

$$v_2 = Q_2 / A_2 . \qquad (9)$$

Substituting Equation 9 into 8, and multiplying all terms by 2g, we obtain:

$$v_1^2 + 2g\,p_1/\gamma + 2g\,z_1 = Q_2^2/A_2^2 , \qquad (10)$$

where Q_2 = discharge at spring (L^3/T), A_2 = cross-sectional area at the spring (L^2)

From Equation 10 and Figure 3, water level in a monitoring well that is screened within a conduit is directly proportional to the corresponding discharge at a nearby spring in the same conduit. Since the head at point 1 is proportional to the square of the velocity in Equation 10, water level changes in a well due to a storm event are expected to be amplified relative to spring discharge changes.

Hydraulically Connected Spring and Well (Example)

The generalized situation described by Figure 3 above has been observed in a natural karst system at the Oak Ridge site. At this site, well GW-684 and spring SS-5, one of the largest carbonate springs discharging from the Maynardville Limestone, are located ≈27 m apart. The well and spring are known to be hydrologically connected via a conduit or fracture because the spring discharge became more turbid (muddy) during the drilling of the well (Shevenell et al., 1992). In addition, during injection tests into the GW-684 well, increased and turbid flow to the spring was observed. Water level changes in the spring and well were measured with pressure transducers placed below the water level in each to monitor changes in head over a period of ≈42 days. Figure 4 (after Desmarais, 1995) illustrates the ambient water level changes that were observed between the spring and the monitoring well. From Figure 4, it is evident a strong correlation exists between storm-induced water level fluctuations of spring SS-5 (as measured by water level rise/fall in a pool fed by the spring) and monitoring well GW-684. The hydrograph trends are nearly identical, with simply a shift in water level elevation and a slight dampening of water level fluctuation of the spring compared to well GW-684. The observed behavior between spring and well hydrographs in this case suggests that techniques originally developed for spring hydrograph analysis can be extrapolated to analyze well hydrograph recessions.

Hydrograph Analyses

Hydrographs were obtained from numerous wells at three field sites (Figure 1) in which the well completion intervals contained cavities, fractures, and/or strictly matrix intervals. Although detailed statistical analyses of the types of water zones present in completion intervals within the monitored wells has not been conducted at all three sites, data from the Oak Ridge site have been compiled and evaluated (Shevenell and Beauchamp, 1994). Of the 800 water bearing intervals encountered during drilling, 36% were identified as cavities, 32% were identified as fractures, and 32% as slow flow (matrix) water producing intervals (C, F, M in Table 1). Cavities were noted when an obvious drop in the drill string occurs during drilling; fractures were noted when cuttings or core had oxidized or altered surfaces, or if significant drilling rig chatter occurred in an interval. Water zones are defined when none of the above characteristics were observed, yet small increases in water production were observed during drilling. Unfortunately, in many cases, drilling/lithologic logs from all three sites note nothing in the completion interval, and it is difficult to assign a water zone type (C, F, M) with any degree of certainty. Of the wells from the Oak Ridge site, 66% of the wells that have been drilled in carbonate units have encountered at least one cavity during drilling, although not necessarily within the completion interval. This large percentage of cavities encountered during drilling activities at the Oak Ridge site indicates that cavities are pervasive throughout the site (Shevenell and Beauchamp, 1994). It is unknown what percentage of wells encounter cavities at the other two sites investigated here, but it is expected that the percentage may be somewhat lower than at the Y-12 Plant. The data pool for the three sites at present is insufficient to adequately address influence of well design (screen with filter pack vs. open-rock well) on the data set as a whole. In the future, a subset of the wells with sufficient data will be selected from which to evaluate possible effects of well design. However, where well design is known, similar responses are observed among wells regardless of design.

In the following sections, the results of the hydrograph analyses at the three sites are presented and compared to T values obtained using traditional aquifer testing techniques. Table 1 summarizes the results of the data collection at the three sites. Hydrographs were obtained from a total of 72 wells over multiple storm events, of which 49 wells exhibited the hydrograph responses required for use with the hydrograph analysis method.

Crane Site, Indiana

Hydrographs were obtained from eight wells, of which five exhibited hydrograph responses useful for the analysis method discussed here. Slug tests were conducted on six wells suspected to be completed in cavities, and an additional two wells suspected to be completed in water or fracture zones. Three of the wells for which hydrograph estimated T were computed were also tested using slug tests, and these results appear in Table 2. All three wells for which both types of tests are available are suspected to be completed in cavities, and the slug test T values are one to three orders of magnitude larger than those computed with the hydrograph method. This is due to the fact that slug tests monitor a much smaller portion of the aquifer dominated by conduit flow near the well bore whereas the hydrograph T is more representative of the matrix values of T in the aquifer. This feature is also demonstrated by comparing the hydrograph T with that obtained from pumping tests in four nearby wells completed in matrix intervals (Murphy, 1995). The hydrograph T values are similar to the values obtained from the slug tests in matrix intervals, and to those obtained from the pumping tests.

Fort Campbell Site, Kentucky

Hydrographs were obtained from 22 wells, of which 13 exhibited responses useful for the hydrograph analysis method for estimating T. The vast majority of the reported new hydrograph data were collected by A.D. Little, Inc. (ADL, 1997a, 1997b, 1997c) and supplied digitally to us for use in this work. Slug tests were conducted on eight wells known to be completed in cavities, and an additional five wells known to be completed in water or fracture zones. Five of the wells for which hydrograph estimated T were computed were also tested using slug tests (Table 2). Three of the five wells for which both types of tests are available are completed in cavities, and the slug test T values are two or more orders of magnitude larger than those computed with the hydrograph method. Similar to the Crane wells, the higher slug test T is due to the fact that slug tests monitor a much smaller portion of the aquifer dominated by conduit flow near the well bore, whereas the hydrograph T is more representative of the matrix values of T in the aquifer. In contrast, wells completed in a fracture (Table 2) show lower slug test estimated T values that are much closer to those measured using the hydrograph method (approximately a one order of magnitude difference). One well (2m5d) had estimated T from all three different methods (hydrograph, slug test, and pumping tests), and all three indicate nearly identical values of T for this well of ≈ 0.1 m^2/d. This well is not completed in a cavity, but in a fractured interval, and the response shows that the method provides realistic T estimates in non-karst, but multiple porosity aquifer systems.

Oak Ridge Site, Tennessee

Hydrographs were obtained from 42 wells, of which 31 exhibited a hydrograph response useful for the analysis method discussed here. Slug tests were conducted on two wells known to be completed in cavities, and three wells known to be completed in matrix intervals in nearby wells. Nine of the wells for which hydrograph estimated T were computed were also tested using aquifer pumping tests, and these results appear in Table 2. Four of the wells for which both types of tests are available are suspected to be completed in cavities, and slug tests were conducted on two of these wells. As at the other two sites, these slug tests show higher T than the hydrograph (or pumping test) results, whereas the pumping test and hydrograph T values are more nearly equal. For those wells completed in fractures or matrix intervals, hydrograph and pumping test T compare well in all five cases (GW-056, GW-057, GW-603, GW-685, GW-714). For wells in which the well screen intercepts a cavity (GW-715, GW-734, GW-735), pumping test and hydrograph T values differ by one to two orders of magnitude.

Discussion and Conclusions

Results based on field observations and theoretical considerations show water level variations in wells in response to storm events are similar to those monitored in springs discharging in karst aquifers. Methods have long been used to analyze spring hydrograph recession curves, and the work presented here suggests these methods can be extended to analyze the similar well hydrograph recessions. In this work, hydrograph analysis results, which provide an estimation of T in matrix intervals, were compared to results obtained from traditional aquifer testing methods.

Hydrograph analysis results are compared to results obtained from traditional aquifer testing methods rather than to tracer test results. In the case of the Oak Ridge site, few reliable tracer tests have been conducted from which any meaningful comparisons could have been made. Furthermore, tracer results are specifically used to evaluate quick flow portions of the aquifer where velocities are rapid, whereas the hydrograph analysis method provides information on T in the matrix intervals. In these multiple porosity systems, it may be more appropriate to compare tracer test results to the slug test results that were obtained from wells completed in conduits, and that are more representative of the quick flow component of the aquifer through cavities.

The hydrograph analysis method could only be tested against a relatively small number of results obtained from pumping tests. During this study, no wells could be pumped at the Crane site, only one could be pumped at the Ft. Campbell site, yet several wells at the Y-12 site could be pumped. However, at all three sites numerous wells were tested with the use of hydrographs, which do not require withdrawal of groundwater, and this is precisely one of the main reasons to investigate the non-invasive hydrograph method.

Table 3 summarizes results of the estimation of aquifer T at all three sites. Arithmetic means were computed at individual wells in cases where there were multiple T estimates for the well. Geometric mean values were computed when averaging T from multiple well locations because this parameter is usually considered to be spatially log-normally distributed. At all three sites, results of the hydrograph analysis technique closely match (within an order of magnitude) those of traditional, invasive aquifer parameter estimation techniques (aquifer pumping tests and slug tests conducted in matrix intervals). Slug tests conducted in wells completed in cavities show much higher estimated T values as a result of the larger component of quick flow through conduits relative to matrix intervals (Tables 2 and 3). The fact that differences in T values occur between techniques may be explained by the difference in scale-of-measurement between techniques. For example, slug testing is usually considered a valid indicator test for T within close radial proximity to the tested well, whereas pumping tests provide a T estimate for a larger portion of the aquifer measured radially outward from a well. Hydrograph analysis may provide aquifer T estimates for a larger area than that of pumping or slug tests, not radially from a well, but upgradient and dependent on the aquifer drainage geometry.

The results reported in the previous sections support the hypothesis that well hydrographs may be used to quantitatively assess the hydraulic properties of a well-developed, submerged, fractured or karst aquifer. Results from particular wells (e.g., 2m5d) indicate that the method may be useful in areas that do not contain cavities, but that do have multiple porosities that are drained (e.g., matrix plus varying fracture sizes/porosities). Wells in larger cavities appear to influence the hydrograph T to a higher degree than purely matrix values and this aspect will be evaluated as part of future work.

There are limitations to this methodology. Sharp storm pulses and, hence, well-defined hydrograph recessions with multiple limb slopes are required to make useful quantifications. Complete recessions must occur before the hydrograph is influenced by the next storm. It was assumed that the karst drainage area does not change with time, since the L parameter in Atkinson's equation (equation 7) must be a constant for each theoretical flow ratio equation. Simplifications in conduit geometry were assumed so that general relationships between aquifer properties could be obtained, although these simplifying assumptions were not incorporated into the quantitative analysis. Instead, quantitative analysis focuses on the concept of karst aquifer storage depletion as a whole based on the work of Rorabaugh (1964), and conduit drainage (independent of specific conduit shape) as recorded by the well hydrograph during periods of storm recession.

The aquifer parameter estimation technique to obtain matrix T presented here is an alternative to the commonly used pumping and slug testing methodologies. This method provides realistic estimates of aquifer parameters without the need of stressing the aquifer, and hence provides information during times of natural flow conditions. The conduit, fracture and matrix portions of the aquifer upgradient of the monitoring point are represented in this technique providing a better understanding of aquifer behavior than would be obtained using point measurement techniques alone. A similar argument can be made for the case of discharge from a prominent spring. Such hydrographs provide for an understanding of the upgradient aquifer a spring drains by separately accounting for primary and secondary water storage rather than grouping all permeabilities together. The work presented here suggests that the well hydrograph analysis technique could prove useful in multiporosity areas where pumping test data are lacking or where groundwaters are contaminated and pumping is either too costly or simply not permitted.

In using this well hydrograph analysis method, commonly collected hydrograph data are used to go beyond conventional, qualitative methods, and begin to quantify some aspects of the karst aquifer. What transmissivities (T) mean in any highly heterogeneous aquifer is a contentious issue, subject to considerable debate. The results presented here from 49 wells at three different karst sites were compared with those of more traditional aquifer testing methods (pumping, slug). At all three sites, the hydrograph T (which estimate matrix T) agree quite well with data obtained from pumping tests from the same wells, or from slug tests in nearby matrix dominated wells. What the T from hydrograph, pump or slug test results represent in the context of a karst aquifer is debatable, yet the latter two methods are frequently used now, and the hydrograph data provide the same level of information as other, more traditional methods that stress the aquifer. Use of the well hydrograph technique in determining matrix T, in combination with (1) traditional tracer test results to obtain flow velocities in quick flow portions of the aquifer, (2) slug tests in quick flow dominated portions of the aquifer to estimate T of the conduit/fracture zones, and (3) estimates of the percentage of the aquifer to which to apply the differing S_y values will allow improved characterization of hydrologic parameters in heterogeneous, multiple porosity systems.

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Figure 3. Conceptualization of simple pipe flow to a spring.

Figure 4. Comparison of hydraulically connected well and spring hydrographs.

Table 1. Summary of transmissivity values (m²/d) computed with the hydrograph analysis method, slug tests, and pumping tests.

Well Number	Total Depth (m)	Screen Depth (m)	Lithology/ Formation	Log Avail?	Zone Type Screen Int?	Useful Hyd Response?	# Storms for T estimates	Min T Value (m²/d)	Max T Value (m²/d)	Ave. T (m²/d)	Standard Dev. T (m²/d)	Slug Test T (m²/d)	Pumping Test T (m²/d)
Crane site													
03-06	0.0	11.4-14.2	BC LS	N	?	NA	0	--	--	--	--	7.3	--
03-24	0.0	12.8-15.7	BC LS	N	C	Y	10	0.4	3.1	1.1	0.8	a	--
03-31	0.0	na	BC SS	N	C?	N	7	--	--	--	--	57.4	--
03-32	0.0	na	BC SS	N	C?	Y	1	0.1	--	0.1	--	102.4	--
03-33	0.0	na	BC SS	N	C	N	7	--	--	--	--	134.8	--
03-34	0.0	na	BC SS	N	C?	Y	5	0.5	4.6	1.5	1.7	151	--
03-C11	0.0	14.5-17.5	BC LS	Y	M	NA	0	--	--	--	--	9.7	--
03-C5	0.0	9.8-12.8	BC LS	Y	C	NA	0	--	--	--	--	0.7	--
03C02	0.0	36.4-39.5	BB LS	Y	C	N	8	--	--	--	--	--	--
03C02P2	0.0	11.6-14.6	BC LS	N	C	Y	5	6.5	22.8	14.3	6.8	--	--
03C24	0.0	6.7-8.2	BC LS	Y	C	Y	2	1.0	1.4	1.2	0.3	11.6	--
Average of 4 nearby matrix wells (Murphy, 1995):													0.80
Fort Campbell site													
141mw1	0.0	18.3-21.3	clay/gravel	N	M	Y	2	0.62	0.67	0.65	0.036	--	--
141mw2	0.0	25.9-29.0	SL LS	N	F	Y	1	0.62	--	0.62	--	--	--
146mw1	0.0	37.8-40.9	SL LS	Y	M	Y	2	0.51	0.81	0.66	0.21	--	--
149mw1	0.0	10.7-13.7	silty clay	Y	M	Y	2	5.2	5.8	5.5	0.45	--	--
15m7e	0.0	25.2-28.3	SL LS	Y	C	NA	0	--	--	--	--	17.2	--
15mw3	0.0	13.1-16.2	silty clay	Y	C	Y	6	4.8	20.9	11.3	6.6	--	--
15mw5	0.0	26.8-29.9	SL LS	Y	C	Y	3	21.1	24.5	23.2	1.7	454.9	--
28mw11s	0.0	10.6-13.7	clayey gravel	Y	M	Y	3	8.6	55	26.9	24.8		--
2m5d	0.0	25.5-28.4	SL LS	Y	F/C	Y	4	0.074	0.13	0.092	0.023	0.1	0.09
2m8e	0.0	19.3-22.0	SL LS	Y	M	NA	0	--	--	--	--	0.2	--
2mw4	0.0	26.8-29.9	SL LS	Y	F	Y	2	0.077	0.09	0.084	0.0092	0.3	--
33m2e	0.0	10.5-13.6	SL LS	Y	C	NA	0	--	--	--	--	113.4	--
33m3e	0.0	9.6-12.6	SL LS	Y	C	NA	0	--	--	--	--	45.9	--
47mw2	0.0	4.6-7.6	SL LS	Y	C	N	5	--	--	--	--	27.2	--
47mw3	0.0	2.4-5.5	SL LS	Y	C	Y	1	0.008	--	0.008	--	580.6	--
5mw3	0.0	21.3-24.4	SL LS	Y	C	Y	4	0.39	0.51	0.47	0.051	30.9	--
5mw6	0.0	18.9-22.0	SL LS	Y	M	NA	0	--	--	--	--	19.4	--
6mw3	0.0	21.3-24.4	SL LS	Y	C	NA	0	--	--	--	--	2.4	--
7m3e	0.0	24.8-27.9	SL LS	Y	M	NA	0	--	--	--	--	0.01	--
9mw2	0.0	7.0-10.1	clay, LS	Y	C	Y	9	0.067	0.84	0.4	0.25	--	--
9mw4	0.0	11.6-14.6	SL LS	Y	F?	Y	4	0.088	0.47	0.22	0.17	--	--

Well Number	Total Depth (ft)		Lithology/ Formation	Log Avail?	Zone Type Screen Int?	Useful Hyd Response?	# Storms for T estimates	Min T Value	Max T Value	Ave. T	Standard Dev. T	Slug Test T	Pumping Test T
Oak Ridge site													
GW-052	0.0	4.1-5.6	Cmn	N	?	Y	5	11.5	40.4	25	12	--	--
GW-054	0.0	10.7-11.3	Cmn	core	?	Y	4*	6.1	47.4	18.5	19.6	--	--
GW-056	0.0	16.2-16.8	Cmn	core	?	Y	4*	1	5	3.6	1.8	--	2.1
GW-057	0.0	6.3-7.0	Cmn	core	?	Y	4*	0.8	6.3	4.5	2.6	--	1.3
GW-058	0.0	12.9-13.5	Cmn	core	?	Y	2	4	4.7	4.3	0.5	--	--
GW-059	0.0	7.0-7.6	Cmn	core	?	Y	7	5	1.6	3.4	6.4	--	--
GW-061	0.0	6.0-7.5	Cmn	core	?	Y	7	8.3	63	19	19.7	--	--
GW-167	0.0	7.9-9.2	Cmn	N	?	Y	1	25.9	--	25.9	--	--	--
GW-220	0.0	10.6-13.6	Cmn	N	?	Y	5	3.3	21	8.1	7.1	--	--
GW-225	0.0	45.7-61.0 (O)	Cmn	N	?	Y	2	7.8	9.6	4.1	1.2	--	--
GW-226	0.0	13.7-16.8 (O)	Cmn	N	M	Y	2	4.4	8.6	6.5	2.9	--	--
GW-603	0.0	19.8-22.9	Cmn	N	M	Y	2	10.1	10.1	10.1	0.01	--	7.6
GW-604	0.0	31.3-34.3	Cmn	N	M	Y	2	10.3	10.3	10.3	0.05	--	--
GW-621	0.0	7.6-12.3	Cmn	N	C	Y	7	0.9	7	3	2.1	--	--
GW-683	0.0	44.5-60.0	Ccr	Y	C	Y	2*	0.31	0.64	0.48	0.23	--	--
GW-684	0.0	34.7-39.1	Ccr/Cmn	Y	C	Y	2*	0.19	0.8	0.49	0.43	97.7	--
GW-685	0.0	27.0-42.2 (O)	Cmn	Y	F/C	Y	4*	0.91	5.9	3.2	2.1	--	4
GW-694	0.0	47.0-62.3 (O)	Cmn	Y	M	Y	2	1.6	3.3	2.4	1.2	--	--
GW-695	0.0	16.0-19.0	Ccr	Y	M	Y	3	3.2	4.2	3.7	0.5	--	--
GW-704	0.0	75.0-78.0 (O)	Cmn	Y	F	Y	3	2.1	2.9	2.6	0.4	--	--
GW-706	0.0	47.9-55.6 (O)	Cmn	Y	F	Y	1	2.8	--	2.8	--	--	--
GW-714	0.0	35.1-44.2 (O)	Cmn	Y	M	Y	1	8.7	--	8.7	--	--	6.9
GW-715	0.0	10.1-13.1	Cmn	Y	C	Y	7*	5.1	33.3	21.5	14.6	--	0.4
GW-728	0.0	90.2-93.1 (O)	Cmn	Y	C	Y	3*	2.8	7.9	5.7	2.6	--	--
GW-734	0.0	18.1-31.4 (O)	Cmn	Y	C	Y	4*	9.4	37.4	22.3	14.6	50.8	--
GW-735	0.0	20.7-23.8	Cmn	Y	C	Y	2*	26.8	40.1	33	9	--	0.3
GW-736	0.0	28.2-31.3	Cmn	Y	F	Y	1	2.8	--	2.8	--	--	--
GW-737	0.0	24.2-27.3	Cmn	Y	F/C	Y	2	4.8	7.5	6.2	2	--	--
GW-738	0.0	20.5-26.7	Cmn	Y	F/C	Y	3	0.41	2.4	1.4	1	--	--
GW-748	0.0	5.2-8.2	Cmr	Y	M	Y	2	8.1	10	9	1.3	--	--
GW-750	0.0	19.0-22.1	Cmn	Y	M	N	4	--	--	--	--	--	6.8
Average of 5 nearby matrix wells:												0.8	

The number of storms listed (# Storms) for wells with useful hydrographs is only the number with hydrographs that were analyzed. In most cases, other storms could not be analyzed (i.e., incomplete recessions, etc.). For those without useful hydrographs, this number is the total number of storms that occurred during the monitoring period.

Lithology/Formation: BC LS - Beech Creek Limestone; BC SS - Big Clifty Sandstone; BB LS - Beaver Bend Limestone; SL LS - St. Louis Limestone; Ccr - Copper Ridge Dolomite; Cmn - Maynardville Limestone; Cmr - Maryville Limestone.
Zone Type: M - matrix, F - fracture, C - cavity.
a this well recovered very rapidly (1 to 2 seconds) and the data could not be analyzed.

Powers and Shevenell

* The hydrograph T analyses omitted hydrographs with double peaks (i.e., those with partial recessions before an additional water level rise due to a subsequent storm.

Table 2. Comparison of transmissivities estimated by different methods for individual wells at the three sites.

Well	Total Depth (m)	Zone Type	Average Hydrograph T (m²/d)	Pumping T (m²/d)	Average Slug T (m²/d)
Crane site					
03-32	13.7	C?	0.1		102
03-34	15.2	C?	1.5		151
03c24	8.6	C	1.2		11.6
Average of 4 nearby matrix wells (Murphy, 1995):				0.8	
Fort Campbell site					
2m5d	28.6	F	0.09	0.09	0.1
2mw4	29.9	F/C	0.08		0.3
5mw3	24.4	C	0.47		31
15mw5	30.3	C	23		455
47mw3	6.1	C	0.008		581
Oak Ridge site					
GW-056	16.8	?	3.6	2.1	
GW-057	7.6	?	4.5	1.3	
GW-603	22.9	M	10.1	7.6	
GW-684	39.5	C	0.5	0.6	97.7
GW-685	42.2	F/C	3.2	4.0	
GW-714	44.2	M	8.7	6.9	
GW-715	13.6	C	21.5	0.4	
GW-734	31.4	C	22.4	5.4	50.8
GW-735	25.3	C	33.0	0.3	
Average of 5 nearby matrix wells:					0.8

Zone Type: M - matrix, F - fracture, C - cavity.

Table 3. Summary of computed transmissivities estimated by different methods at the three sites.

	Average Matrix T (m²/d)			Average
	Slug Test	Pumping Test	Hydrograph Analysis	Slug Test T (m²/d) in Cavities
Crane site	8.4	0.8[1]	1.2	32 ± 63
Number of wells tested	2	4	5	6
Total number of tests	16	4	45	54
Ft. Campbell site	0.3	0.1	0.8	51 ± 226
Number of wells tested	4	1	13	9
Total number of tests	24	1	48	50
Oak Ridge site	1.1[2]	2.2	5.6	70 ± 33
Number of wells tested	5	8	31	2
Total number of tests	30	8	64	5

Averages are geometric mean T values computed for all wells in the particular category (slug, pumping, hydrograph). The total number of wells tested for each type of test (e.g., slug) is listed on the first line following the geometric mean T value. The total number of the particular test (e.g., slug) conducted at all wells tested is listed on the second line following the T value.

[1] Summarized from Murphy, 1995.

[2] Summarized from Jones, 1997, unpublished data, and Shevenell (unpublished data).

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Figure 1, Powers

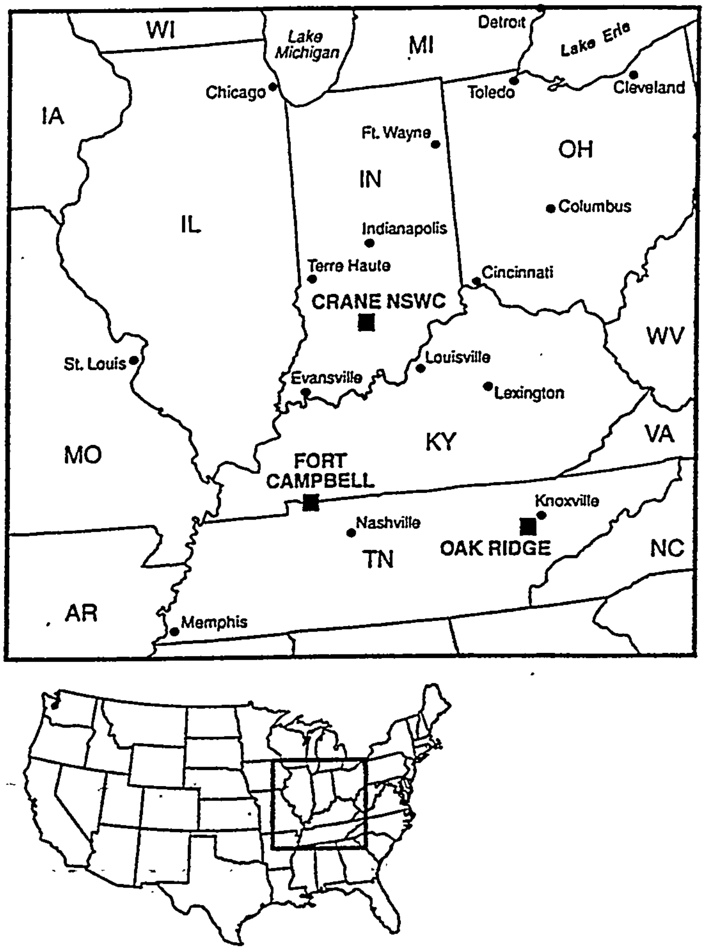

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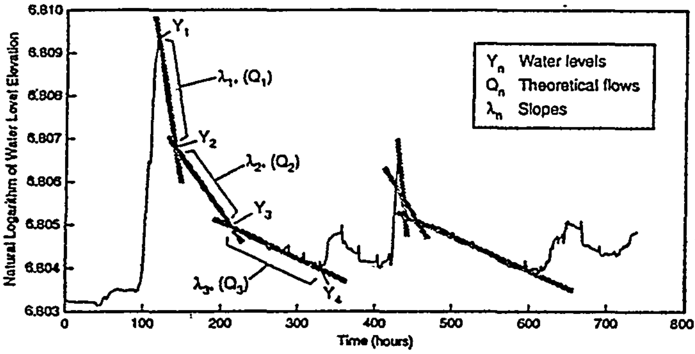
Figure 2, Powers



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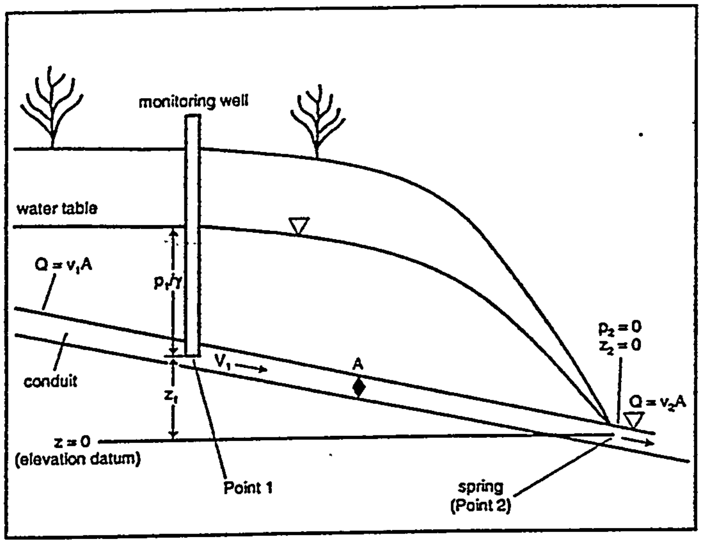

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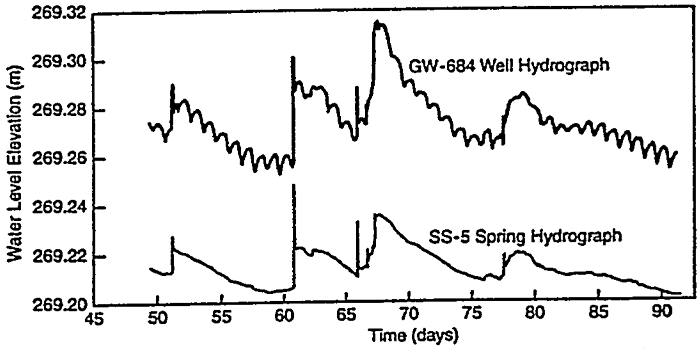
Figure 4, Powers



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