Y-12

Y/TS-1263

OAK RIDGE Y-12 PLANT

MARTIN MARIETTA

ANALYSIS OF WELL HYDROGRAPHS IN A KARST AQUIFER: ESTIMATES OF SPECIFIC YIELDS AND CONTINUUM TRANSMISSIVITIES

L. A. Shevenell
Nevada Bureau of Mines and Geology

November 1994

Submitted to:
Journal of Hydrology

Prepared for the
Environmental Management Department
Health, Safety, Environment, and Accountability
Organization
Oak Ridge Y-12 Plant
Oak Ridge, Tennessee 38731

managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract
DE-AC05-84OR21400

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

RECEIVED

MAR 31 1995

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

OS 11

DT

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

COPYRIGHT NOTICE

The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-84OR21400. Accordingly, the U.S. Government retains a paid-up, nonexclusive, irrevocable, worldwide license to publish or reproduce the published form of this contribution, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, or allow others to do so, for U.S. Government purposes.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

November 1994

Y/TS-1263

**ANALYSIS OF WELL HYDROGRAPHS IN A KARST AQUIFER:
ESTIMATES OF SPECIFIC YIELDS AND CONTINUUM TRANSMISSIVITIES**

Prepared by:

L. A. Shevenell
Nevada Bureau of Mines and Geology
University of Nevada, Reno

Submitted to:
Journal of Hydrology

Prepared for the
Environmental Management Department
Health, Safety, Environment, and Accountability Organization
Oak Ridge Y-12 Plant
Oak Ridge, Tennessee 37831

MASTER

managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

Analysis of Well Hydrographs in a Karst Aquifer: Estimates of Specific Yields and Continuum Transmissivities

Lisa Shevenell

Abstract

Hydrograph analysis techniques have been well developed for hydrographs obtained from streams and springs, where data are cast in terms of total discharge. The data obtained from well hydrographs provide water level versus time; hence, a method of hydrograph analysis is required for situations in which only water level data are available. It is hypothesized here that three segments on a recession curve from wells in a karst aquifer represent drainage from three types of storage: conduit (C), fracture (F), and matrix (M).

Hydrographs from several wells in a karst aquifer at the U.S. Department of Energy Oak Ridge Y-12 Plant* are used to estimate the specific yields (S_y) associated with each portion of the aquifer (C, F, M), as well as continuum transmissivities (T). Data from three short injection tests at one well indicate continuum T at this well bore is $\sim 5 \text{ m}^2/\text{d}$, and tests at numerous other wells in the aquifer yield results between 1 and 7 m^2/d . The T estimated with well hydrographs from two storm events indicates a T of 9.8 m^2/d . Well developed conduit systems in which water levels in wells show a flashy response typically show S_y values of 1×10^{-4} , 1×10^{-3} , and 3×10^{-3} , for C, F, and M. Less well developed conduit areas show more nearly equal S_y values (8.6×10^{-4} , 1.3×10^{-3} , 3×10^{-3}). Areas with no evidence for the presence of conduits have only one, or in some cases two, slopes on the recession curve. In these cases, water level responses are slow. Recession curves with a single slope represent drainage from only the lower T matrix. Those with two slopes have an additional, more rapid response, segment on the recession curve, which represents drainage from the higher T, lower S_y , fractures in the system.

Introduction

Several waste disposal sites are located adjacent to a karst aquifer composed of the Cambrian Maynardville Limestone (Cmn) and Copper Ridge Dolomite (Ccr) at the U.S. Department of Energy Oak Ridge Y-12 Plant in Oak Ridge, TN (Fig. 1). The Maynardville Limestone is recognized throughout eastern Tennessee and is the youngest formation of the Conasauga Group (Miller and Fuller, 1954). The Maynardville Limestone underlies the southern portion of Bear Creek Valley and is considered to be the primary pathway for ground-water leaving the Y-12 Plant boundaries. As part of a larger program to characterize this aquifer, one of the methods selected for evaluation of the karst features was continuous monitoring of specific conductance (SC), temperature (Temp), and water levels from which hydrographs are constructed.

The shape of the rising limb of a hydrograph is largely dictated by the characteristics of a storm event, whereas, the shape of the recession limb is largely independent of the character of the storm (Linsley et al., 1982). In large basins in which runoff may occur over different parts of the basins during different storm events, the recession curve may vary. Recession limb analysis often leads

* Managed by Martin Marietta Energy Systems, Inc. for the U.S. Department of Energy under contract DE-AC05-84OR21400.

to two or more line segments which represent responses in the different portions of the ground-water system: (1) a fast response to conduit flow; (2) slower responses due to flow through fractured and unfractured porous media (White, 1988).

The most useful hydrographs are those obtained during abrupt, intense storm events in which a sharp pulse is transmitted to the karst system. Rapid water level responses are expected in conduits, in contrast to slower responses in the more diffuse portions of the aquifer. Because conduit systems have little hydraulic resistance in comparison to porous media, recharged water is expected to drain quickly. The porous media portion of the system has much lower hydraulic conductivity and responds more slowly to transient events. Hence, it does not remain in phase with the conduit system (White, 1988). In an ideal system, the recession limb of a hydrograph decreases exponentially until the water level reaches the pre-storm water level, assuming no other precipitation events interfere with the water level decline. A system with a well-developed conduit system will respond rapidly to precipitation events (flashy), whereas responses in aquifers with poorly developed, or non-existent, conduits will be more subdued (White, 1988).

Typically, hydrograph analysis techniques are developed for hydrographs obtained from discharge rates at spring and stream locations (e.g., Padilla et al., 1994). Relatively few studies (Atkinson, 1977; Rorabaugh, 1960) have been conducted which yield quantitative data on aquifer parameters using well hydrographs. It has been previously noted that streamflow recession curves can be approximated by three straight lines on a semilogarithmic plot with the lines representing three different types of storage: stream channels, surface soil, and ground water (Barnes, 1940; Linsley et al., 1982). It is hypothesized here that three segments on a recession curve from wells in a karst aquifer also represent three types of storage: conduit, fracture, and matrix portions of the aquifer. The data presented in this report do not include fluid discharge rates; hence, a method of hydrograph analysis is developed for situations in which only water level data are available.

The purpose of this paper is to develop a scheme to quantitatively analyze well hydrographs in karst terranes when corresponding stream or spring discharge rates are not available. Estimates of T and S_y in different portions of the flow regime are obtained with the use of water level hydrographs.

Methods

Data Collection

All wells were monitored between the months of November and March when rainfall is high and water demand from vegetation is lowest. Pressure transducers were installed in up to 10 monitor wells in a particular Picket area (see Fig. 1 for Picket locations), and Hydrolab probes were also installed, measuring Temp and SC, in up to five monitor wells. All data loggers (Omnidata) were set to the same time, or as close as practicable, so that responses from different wells could be directly compared. In general,

pressure transducers (Druck) were placed ≈ 0.9 to 1.5 m below the static water level. Hydrolab probes were placed at the depth of the completion intervals in each of the wells for which Temp and SC measurements were desired. When the probes were installed in or removed from a well, they were checked for proper operation and calibration, and recalibrated if necessary. Periodically during the monitoring (e.g., every other week), the batteries were checked, and the water levels were field checked with an electronic water level indicator.

Generally, the readings on pressure transducers were scanned every 2 minutes and recorded every 30 minutes during the monitoring period. The pressure measurements were automatically converted into water level above mean sea level and recorded in the data logger file. The data loggers in the monitored wells were operational during a minimum of two precipitation events, with up to six storms being monitored in some wells.

The weather station from which precipitation data were obtained for all the storm events is located in the town of Oak Ridge. The approximate distance between the weather station and the individual picket locations follows: Picket W = 7.7 km, Picket A = 6.4 km, Picket B = 5.3 km, Picket C = 4.4 km, and Picket J = 1.6 km.

Hydrograph Analysis Technique

Short lag times between initiation of precipitation and water level rise in monitored areas may be suggestive of quickflow, if other aspects of the hydrographs support the conclusion. However, the lag time between storm impulse and water level rise is not the time for water to flow to the monitoring point, but the time required to transmit an impulse (i.e., a pressure pulse) in the aquifer. The response time t_R is determined by fitting the recession limb of the hydrograph to an exponential function:

$$Q = Q_0 e^{-\epsilon t}$$

where, ϵ is the exhaustion coefficient and the slope of the recession curve of $\ln(Q)$ vs time, and $t_R = 1 / \epsilon$ (Burdon and Papakis, 1963). The coefficient ϵ represents the capability of the aquifer to release water. This value decreases as the underground retardation increases. When ϵ is large, the underground has poor retardation capability (Milanovic, 1981).

In well-developed karst systems, three straight line segments with different values of ϵ occur in the recession. Greater or less than three slopes may be observed depending on the complexity of the system (Milanovic, 1981). The first and steepest slope represents the dominant effects of drainage of the larger karst features, whereas the second, intermediate slope characterizes the emptying of well-connected and partially karstified fractures. The third slope represents drainage of the porous portion 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.

As an example, a hydrograph from the GW-734 well (Picket J area, Fig. 1) is used to illustrate the hydrograph analysis technique. The recession portion of the hydrograph from the first storm event shows two inflection points, and this is more clearly illustrated on a plot of the natural logarithm of the water level versus time (Fig. 2). The first segment is interpreted to represent rapid drainage of the main conduits intersected by this well. Water levels decrease more slowly after about 30 hours. This second segment suggests drainage is dominated by the intermediate permeability features (fractures), whereas the third segment illustrates the slower hydrologic response as the matrix intervals are drained and water levels return to baseflow conditions throughout the continuum.

Each of the three segments of the hydrograph (Fig. 2) has a characteristic slope (λ) for any given storm event, and the slope is defined by the following equation (Moore, 1992):

$$\frac{\ln(Y_1 / Y_2)}{(t_2 - t_1)} = \lambda = \frac{\ln(Q_1 / Q_2)}{(t_2 - t_1)}, \quad (1)$$

where, Y_1 and Y_2 are water levels, and Q_1 and Q_2 are the associated flows (discharges) corresponding to the water levels at times t_1 and t_2 . 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.

Hydrograph data give information on the changes in ground-water storage. At peak discharge, storage in the aquifer is at a maximum and this storage volume decreases at a given rate. The changes in subsurface storage associated with conduit flow will be more rapid than those associated with drainage from matrix or fractured zones. The relationship of baseflow conditions to changes in ground-water storage volume has been expressed by Moore (1992), after Fetter (1988, p.52), as

$$V_1 = Q_1 (t_2 - t_1) / \ln(Q_1 / Q_2). \quad (2)$$

Combining with equation 1 yields

$$V_t = Q_t / \lambda \quad (3)$$

where V_t is the volume of water in storage at any time t , and Q_t is the flow rate produced by the stored water. 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)

$$(V_1 - V_2) = (Q_1 - Q_2) / \lambda \quad (4)$$

or equivalently as

$$(V_1 - V_2) = A S_y (Y_1 - Y_2). \quad (5)$$

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 (ie. $(Q_1 - Q_2)/\lambda = AS_y (Y_1 - Y_2)$) allows determination of a value for the ratio AS_y/Q_1 for each segment of the hydrograph. Using the ratios of Q_1/Q_2 , etc. obtained previously, 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. For instance, expressions of the following form will be obtained:

$$\frac{AS_{y_1}}{Q_1} = X_1, \frac{AS_{y_2}}{Q_1} = X_2, \frac{AS_{y_3}}{Q_1} = X_3 \quad (6)$$

where $X_1 \neq X_2 \neq X_3$ are numerical values. If it is assumed that the drainage area corresponding to volume changes represented by the three line segments are the same, then the $AS_{y_i}/Q_1 = X_i$ 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 order to conduct a meaningful, quantitative hydrologic analysis, estimates for the values of T and storativity (storage coefficient) must be obtained. In estimating the average non-conduit T of an unconfined aquifer from a baseflow recession curve, Atkinson (1977) presented the following expression (after Rorabaugh, 1964):

$$\log(Q_1/Q_2) = \frac{T}{S} (t_2 - t_1) \frac{1.071}{L^2} \quad (7)$$

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. 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 previous analysis estimates T in base flow conditions which are more representative of the slower diffuse (continuum) flow than the more rapid conduit flow.

Results

Applicability of the Hydrograph Analysis Technique

Table 1 lists the data and calculated slopes for the three line segments from the 1992 storms I and III in GW-734 (Fig. 2). The values for t and Y in Table 1 are from the first point (the maximum water level) in each line segment listed. From equation (1), the ratios of the theoretical flows can be calculated, where Q_1 represents the conduit flow at position Y_1 and time t_1 , Q_2 represents fracture flow, and Q_3 represents dominantly diffuse, matrix flow. From the data from the first storm at GW-734 in 1992, $Q_1/Q_2 = 1.284$, $Q_2/Q_3 = 1.308$, $Q_3/Q_4 = 1.174$, and $Q_1/Q_4 = 1.972$.

Next, equations (2) through (6) are used to calculate the AS_y/Q ratios, and these ratios are calculated and reported in reference to Q_1 in Table 1. The value of AS_y/Q_1 in the first column refers to the value of AS_{y_1}/Q_1 for the first storm, the value in the second column refers to the value of AS_{y_2}/Q_1 for the first storm, etc. If recharge to all three flow domains (conduit, fracture, matrix) occurs over the same area, then a constant drainage area can be assumed. Assuming drainage area A is constant, it can be eliminated from the expression. The resulting S_y ratios between the individual segments appears in Table 1.

An estimate of the distance between the well (discharge area) and the ground-water divide is required to obtain a value of T/S from equation 7 for the continuum. The distance between GW-734 and the crest of Chestnut Ridge to the south is ≈ 463 m. Values for the T/S ratios are obtained from equation 7 by substituting values for the Q ratios obtained previously and the distance (L) to the ground-water divide (Table 1).

The average continuum S_y for the Knox aquifer (which includes both the Ccr and the Cmn) is about 3.0×10^{-3} (Moore and Toran, 1992). The continuum value is most appropriately associated with combined flow conditions represented by the baseflow (segment 3) portion of the hydrograph. The first listings of T (m^2/d) values in Table 1 are calculated by multiplying the T/S ratios of Table 1 by the assumed value of $S_y = 3 \times 10^{-3}$. The estimated T value for the third segment of the hydrograph of 2.4 to 2.6 m^2/d is very similar to that calculated for the continuum T of 1 to 7 m^2/d for the Knox aquifer (Moore and Toran, 1992). This shows that segment 3 is representative of the behavior of the continuum whereas the other two segments show greater influence from fractures and conduits. Assuming that the S_y value of 3×10^{-3} is reasonable for the continuum, the values of apparent S_y for the other portions of the hydrograph can be estimated using the previously obtained S_y ratios (Table 1). Using these S_y values necessarily results in the T for each portion of the hydrograph being set equal to the value of the continuum T (second listing of T , Table 1).

The previous procedure was used to calculate T/S , S_y and T from three storm hydrographs in GW-734 in 1992 and 1994, and these values appear in Table 2. Three storms were monitored in 1994, yet two of them had incomplete recession curves due to subsequent storms and data from the third line segment are unavailable. More distinct slopes are observed in the 1992 storms which did not overlap with one another to the extent that the 1994 storms did, and for which a sharper precipitation pulse was obtained. Nevertheless, three slopes are clearly identified from each of the storms with complete recessions. The responses in this well clearly show the effects of successive drainage of the conduit, fracture, and matrix portions of the aquifer. There were apparent changes in SC and $Temp$ during the 1994 storms in GW-734. However, a datalogger or Hydrolab probe malfunction resulted in lost data during critical times. Hence, no quantitative evaluation of these parameters can be made from the available data. The existing data do show, however, that water flow to this well, and not simply a pressure pulse, can occur quite rapidly following a rain storm.

The two 1992 storms previously discussed, and the second storm from 1994 are used to determine the values for T in the continuum near GW-734. Table 2 shows results of the calculations of T . The 1992 storms indicate a value of $T = 9.8 \pm 0.6 \text{ m}^2/\text{d}$, similar to that obtained in previous studies of the Knox aquifer (Moore and Toran, 1992). However, the values of T_3/Sy_3 , T , and K from the 1994 storm are 3.8, 2.4, and 2.4 times greater, respectively, than those from the 1992 storms. The higher values for the 1994 storm probably result because this storm pulse was much less sharp than those in 1992, had a higher total precipitation (59.2 mm, versus 36.6 and 23.4 mm in 1992), and resulted in a larger water level rise in the well (3.2 m, versus 1.6 m and 0.68 m in 1992). Because the T in an unconfined aquifer is a function of the changing thickness of the aquifer, and the aquifer thickness during the 1994 storm was slightly larger, it is reasonable to assume that the calculated T from the 1994 storm would be somewhat larger than that obtained in 1992. Based on the data that follow, the T value of $23.3 \text{ m}^2/\text{d}$ is probably an upper estimate for the GW-734 well.

Three short duration injection tests were conducted at GW-734 in 1994, and these data are used to calculate continuum T and S_y by more traditional means. The computer model AQTESOLV (Duffield and Rumbaugh, 1991) was used to calculate T and S_y from unconfined solutions for slug tests (Bouwer and Rice, 1976), recovery tests (Theis, 1935), and pumping tests (Theis, 1935; Cooper and Jacob, 1946). Values of T from the slug test solutions are $5.87 \times 10^{-4} \pm 1.93 \times 10^{-4} \text{ m}^2/\text{s}$ (assuming a 99.1 m aquifer thickness), those from the recovery tests $4.9 \times 10^{-5} \pm 2.18 \times 10^{-5} \text{ m}^2/\text{s}$, and those from the traditional pumping tests $6.12 \times 10^{-5} \pm 1.7 \times 10^{-5} \text{ m}^2/\text{s}$. The slug test results are probably not as reliable as the others noted given that the water level responses used in the solution were not produced by a sharp, instantaneous injection or withdrawal of water. Hence, taking the average of the other results leads to an estimated T for the continuum of $5.81 \times 10^{-5} \pm 1.75 \times 10^{-5} \text{ m}^2/\text{s}$ (or $5.0 \pm 1.5 \text{ m}^2/\text{d}$). This value compares well with previous data (1 to $7 \text{ m}^2/\text{d}$) obtained from pumping tests at other localities in the aquifer (Moore and Toran, 1992). The estimated continuum T based on the new hydrograph analysis technique is approximately $9.8 \text{ m}^2/\text{d}$ (Table 2), indicating that realistic values can be obtained with this method. This value, which corresponds to a hydraulic conductivity (K) of $9.89 \times 10^{-2} \text{ m/d}$, is within the lower to middle of the range expected for typical karst limestones (Freeze and Cherry, 1979).

Also note that Table 2 lists T/S_y , and estimated S_y values based on assumptions that the continuum S_y value is 0.003. These data show that the S_y of the conduit portion of the aquifer (average of 0.0006) is less than that consisting of fractures (≈ 0.0014), which is less than the matrix, or continuum value of 0.003. Greater amounts of storage in intergranular porosity is expected in comparison to storage in conduits. In addition, T/S_y values for the line segments assumed to represent the conduit dominated portion of the recession curves are the greatest, and the third line segment is the least. This is reasonable given that T is much higher, and S_y much lower, in conduit dominated portions of an aquifer than in portions of the aquifer dominated by porous flow.

Well Hydrographs

Hydrographs were obtained from several wells, some of which were dominated by conduit flow, whereas others were not. Only one well in Picket W, and five wells in Picket J had recession curves with three line segments. Other wells showed no evidence of quickflow through conduits. A summary of observed responses in all monitored wells to precipitation events appear in Table 3, and these results are discussed in greater detail below.

Figs. 3-6 show examples of the responses expected from wells monitoring different portions of the aquifer. The different wells are grouped into three groups in Table 3 where the first group represent wells in a portion of the aquifer dominated by conduit flow where water levels showed the typical flashy responses to precipitation. The second group exhibit three slopes, yet their slopes are more nearly equal to one another than those in the first group and conduits in this group are less important (and probably smaller) than those in the first group. Group 3 lists wells for which there is no evidence for conduit flow.

Recession curves were plotted for each storm response as the natural logarithm of water level versus elapsed time since recession began. From these plots, breaks in slopes could be identified, with one, two and three slopes being noted depending on the well, storm event, and whether recession was complete before the next storm event. Other data in Table 3 includes delay to water level rise from the start of precipitation, duration of the peak water level, and total water level change as a result of a storm. These data are useful to qualitatively determine if the well taps a quickflow zone. Long delays in water level rises, and long, broad peaks suggest a well does not monitor a quickflow water zone. The following discussions include one example of a well exhibiting characteristics from each of the three groupings of wells.

Group 1

Precipitation and water level data for GW-715 are illustrated in Fig. 3, and SC and Temp data are plotted in Fig. 4. Water level changes during the storms ranged from 0.79 to 2.0 m, which are the largest changes observed in Picket W. GW-715 is a shallow well (TD = 13.6 m) and is known to contain cavities in its completion interval. Delays to the start of water level rises from the initiation of precipitation varied from 1.0 to 23.5 hours. The longest delay of 23.5 hours occurred during storm 3 in which the beginning of the precipitation event was of very low intensity. Hence, during the early times of storm 3, insufficient precipitation occurred to produce a water level rise, which is reasonable given that cavities are associated with this well. The timing and magnitude of water level rises correlate with precipitation amount, duration, or intensity. The highest precipitation (28.9 mm) corresponds with the largest water level change (1.52 m), whereas the smallest precipitation (17 mm) corresponds to the smallest water level change (0.39 m). The duration of the peaks during all storms was short (0.0 to 1.5 hrs). This is indicative of very rapid drainage of the conduit portion of the aquifer following cessation of precipitation, which is reasonable given that this well intersects cavities. Plots show storms 1, 2 and 3 exhibit three distinct slopes,

suggesting that conduits drain rapidly (slope 1), fractured portions (slope 2) drain less rapidly than the conduits, but more rapidly than the intervening matrix blocks (slope 3). Data from storm 1 appear to be the most reliable because this storm appears to have a complete recession curve, whereas the other storms do not.

Peaks in SC and Temp also occurred as a result of the storms (Fig. 4). Modest increases in Temp occurred (between 0.12 and 0.16 °C), whereas decreases in SC varied from -8 to -39 $\mu\text{mhos/cm}$, with the largest change occurring during storm 4. These parameters began to change between 1 and 25 hours following the initiation of precipitation, with the fastest response occurring during the most intense storm (storm 4). The beginning of change in these parameters began 0 to 9.5 hrs after the beginning of water level rise, depending on the storm. During intense storms, such as storm 4, precipitated water may undergo rapid recharge and flow to the position of GW-715 in as little time as one hour indicating flow can be quite rapid. Water level peaks precede those of Temp and SC, as expected, showing that the pressure pulse arrives at GW-715 prior to the recharge water. Temperature began to increase before SC began to decrease for each of the monitored storms. This phenomenon results because of the different gradients in SC and Temp. Higher temperature water is introduced into lower temperature aquifer waters, and the driving gradient is from the recharge water to the aquifer water (i.e., in the direction of flow). The concentration of the recharge water is less than that in the aquifer, resulting in a concentration gradient from aquifer waters toward recharge waters (ie. opposite to the direction of recharging flow). Hence, in less intense storms in which flow rates are slower, or in storms in which recharge is from a greater distance, the SC is expected to lag the Temp pulse at a particular monitoring point.

Another feature of importance to note from the GW-715 data is that each storm caused two peaks in water level. Two peaks in SC and Temp were also observed during storms 1, 2, and 3, with the Temp peaks being more distinct. Storms 2, 3, and 4 each had two periods of relatively high precipitation separated by a short period of low precipitation. The double peaks from these wells may reflect very rapid changes in the well's water level in response to rapid changes in precipitation conditions. However, there was no lull in precipitation during storm 1, yet two water level, Temp and SC peaks also occurred during this storm (Fig. 3 and 4). These double peaks likely resulted because the water level in the conduit intersected by GW-715 responded to water level changes occurring at different times in two upgradient conduits which feed into the one at GW-715 (see Ashton, 1966).

Given the previous observations, it is clear that GW-715 taps a quickflow water zone which responds rapidly to precipitation. The conduit drains rapidly following a storm, and additional water level declines are a result of slower drainage from surrounding fractures and matrix blocks which likely have higher S_y , but much lower T . Temperature and SC recessions are much more rapid than WL recessions because the changes in these parameters reflect conditions in the conduits only, whereas those of WL show the combined effect of conduits, fractures, and matrix intervals. The data from all wells in Picket W

indicate that rapid conduit flow occurs at this picket, but may be restricted to relatively shallow levels. The deeper wells show no influence of quickflow.

Group 2

Precipitation and water level data from GW-604 (Picket J) are illustrated in Fig 5. Water level changes during the storms ranged from 0.24 to 1.55 m. Delays to the start of water level rises from the initiation of precipitation varied from 7.5 to 12 hours, which is identical to that observed in GW-603. The storm (storm 2) with the highest total precipitation and greatest intensity had the most rapid initiation of WL rise in GW-604 as well as the largest water level increase. The duration of the peaks during the storms was relatively short (0.5 to 1.5 hrs) for storms 2 and 3. The responses in GW-603 and GW-604 are nearly identical suggesting these two wells intersect zones with similar hydrologic characteristics and may be hydrologically connected.

The time delay between peak precipitation and peak water levels varies between 15 to 25 hours; however, there is no correlation between these lag times and precipitation amount or intensity. Each storm had recessions which were probably not complete prior to the initiation of the next storm event. Plots suggest that only storm 2 exhibits three distinct slopes, suggesting conduits may be draining rapidly and that poorly fractured portions (slope 2) may drain more rapidly than the intervening matrix blocks (slope 3). Conduit flow is indicated by the hydrograph data, yet the importance of this type of flow is less than in the Group 1 wells in light of the relative long delay times observed in the GW-604 well.

Group 3

Precipitation and water level data for GW-710 are illustrated in Fig. 6. Water level changes during the storms ranged from 0.15 to 1.0 m for precipitations between 17.0 and 29.0 mm. Delays to the start of water level rises from the initiation of precipitation varied from 8.0 to 11.5 hours. The timing and magnitude of water level rises correlate with precipitation amount, duration, or intensity. The highest precipitation (29.0 mm) corresponds with the largest water level change (1.0 m), whereas the smallest precipitation (17.0 mm) corresponds to the smallest water level change (0.15 m).

All responses to storms are relatively slow, and plot as broad, smooth curves reflecting a pressure pulse being transmitted through a unit with low storage. The time delay between peak precipitation and peak water levels varies between 44.5 and 49 hours, and the shortest time occurred during the largest precipitation event (storm 5). Each storm had relatively long recessions, which in most cases were not complete prior to the initiation of the next storm event. Plots of this hydrograph suggest slight changes in slope, yet the differences between slopes 1 and 2 are minimal (i.e., -1.50×10^{-3} and -2.73×10^{-3} , storm 1) and are not significant. Hence, the recessions suggest only one slope and not three as would be expected in wells exhibiting a quickflow component through fractures or conduits.

Discussion

The previously discussed hydrographs, as well as those from several other wells, provide significant insight into the behavior of flow in different portions of the karst Cmn. The data presented allow several types of interpretations and conclusions to be made. For instance, the presence of two conduits feeding into one was indicated at GW-715, and karst features are locally more well developed in some areas.

Referring again to Table 3, the Group 3 wells did not show three distinct slopes, but showed only one or two. In some cases, it is believed that insufficient recession time occurred for the second slope to become apparent. In other cases in this table, 1 or 2 is indicated if there was a slight break in slope, yet slopes 1 and 2 are not appreciably different from one another. Group 3 wells show no evidence of contributions from conduit flow, but suggest there may be two forms of storage, fracture and matrix. Table 3 generally shows that longer delay times from the start of precipitation to the start of water level rise occur in Groups 2 and 3 than in Group 1. The slightly shorter minimum delay time in Group 3 in comparison to Group 2 reflects the effects of a variety of different types of wells represented in this list. GW-167 has a short delay time because it is a shallow (9.1 m) well which would be expected to respond relatively rapidly to precipitation, yet would not necessarily show evidence of conduit flow. The delay times for GW-711, GW-713 and GW-714 are likely to be relatively short because of low storage capacity in these portions of the aquifer. Relatively small increases in water being added to areas with low storage should result in a fairly rapid pressure pulse being transmitted. Maximum delay times to start of water level rises are progressively longer for Groups 1 through 3. Other summary parameters in Table 3 also show consistent trends. The delays between peak precipitation and peak water level increase with group, with the wells influenced by conduit flow being most rapid. Conduit-influenced areas also show very short peak durations and water levels fall very soon after the end of the precipitation event. This flashy water level response is characteristic of rapidly draining conduits. Group 3, in contrast, show relatively long durations of the peaks because conduits do not influence flow in these areas, and this trend reflects the slower responses expected from the lower K fractures and matrix intervals. Durations of the recessions vary somewhat, in part because many recessions were not complete. However, the average time of the recession curves is similar for all three groups (≈ 120 or 160 hours). The similarity in recession times between conduit dominated and matrix dominated portions of the aquifer is reasonable, because the recession duration is controlled by the time required to drain the matrix. In addition, similar ranges in WL rises are observed showing that the magnitude of WL rise can not be used as an indicator of conduit influence. The largest WL rise did occur in a conduit well (GW-734), yet the second largest occurred in a well dominated by slow flow (GW-167). The magnitude of WL rise is a function of the precipitation amount, intensity and storage coefficient in the aquifer.

Table 4 lists the estimates of continuum T calculated using all storms for all wells showing three distinct line segments on their recession curves for at least one storm event. Only 6 of the 15 wells

monitored thus far have had three slopes on their recession curves. The data and results from some of the storms appear anomalous (GW-715 storm 4, GW-604 storm 3, and GW-735 storm 3). In each of these cases, the slope of the second line segment in the recession is greater than or equal to that of the first segment. The recession for the fourth storm in GW-715 is not complete, and the brief, sharp decrease observed at the end of the record (Fig. 3) may result from datalogger or transducer malfunction. Hence the results from storm 4 are not considered reliable. The recessions from the third storm in GW-604 and GW-735 were also not complete prior to termination of data collection. Because the first and second slopes are nearly equal to each other, the break in slope selected may not be accurate, and perhaps only the first slope is represented by the data. Hence the calculated continuum T from these two wells for the third storm and from GW-715, storm 4, may not be reliable, and the values are not represented in the calculated averages.

As expected, the T/S values for the conduit portion of the recession curve are greater than those of the fracture and matrix portions of the curve at all wells for all storm events, because conduit T is high and storage is low. These T/S values vary by storm, yet the highest intensity storms are not necessarily associated with the larger T/S values, or vice versa. For instance, storm 1 had an intensity of 2.44 mm/hr (total precipitation of 36.6 mm), storm 2 had an intensity of 3.48 mm/hr (total precipitation of 59.2 mm), and storm 3 had an intensity of 2.16 mm/hr (total precipitation of 27.9 mm), yet storm 1 had the highest T/S values for all three segments in GW-220 (Picket J).

The S_y expected for each portion of the recession curve is also noted in Table 4. Based on numerous studies on the Oak Ridge Reservation, the S_y value of $\approx 3.0 \times 10^{-3}$ for the third (continuum) segment is probably a reasonable estimate, and lower calculated values for the first two segments (conduit and fracture dominated) are likely to be realistic averages for the Y-12 area. Based on these calculations, the S_y for the conduit dominated portions of the aquifer are expected to be on the order of 1 to 8×10^{-4} , and the fractured portions on the order of 1×10^{-3} , with these values varying somewhat with position within the aquifer.

Additional data on recession curves are available from cross borehole tests in which water was injected into one well in a picket, and water level responses were monitored in surrounding wells (Shevenell et al., in review). Table 5 lists results of calculations made with the recession curves from these types of tests. GW-735 is the only well for which both hydrograph data and cross borehole testing data are available. Dramatically different T/S and S_y values are obtained with the cross borehole testing data. The differences are due, in part, because the cross borehole tests involved injecting water into a source well under pressure, thus creating artificial conditions. Also, the aquifer parameters represented in the cross borehole testing are only those between the injection and monitor well (GW-734 in this case), and not the aquifer as a whole. The lower S_{y1} in the cross borehole test results for GW-735 may indicate that low storage conduit flow is important between wells GW-734 and GW-735. Nevertheless,

calculations using both types of data indicate that continuum T near the GW-735 well bore is between about 20 and 40 m²/d. Data from the wells in other pickets show high continuum T can be expected near GW-694 and GW-725, with lower, more typical values of about 5 m²/d being associated the the GW-695, GW-704, GW-738 and GW-739 locations. Wells GW-603 and GW-604 have the same calculated T of about 10 m²/d, and both showed nearly identical responses to storms during each of the three monitored events. Generally higher continuum T were calculated for the first group of wells which show a greater influence from conduit flow. These results can be useful in conducting ground-water flow modeling because the data can be used to assign different T values in different portions of the aquifer system.

Limitations

The method of estimating S_y and continuum T using three slope recession curves from wells responding to flow through conduits, fractures and matrix blocks will provide useful information on aquifer characteristics, but has several limitations to its use.

- (1) Sharp storm pulses produce the best and most useful data. Long storms forming broad peaks tend to mask some of the quickflow characteristics expected in wells monitoring conduit areas.
- (2) Recession curves should be complete, because incomplete recessions may not contain the third slope in karst aquifers, and the method to calculate continuum T and the S_y values may not result in realistic estimates of continuum T because only the higher T portions of the aquifer (conduit and fracture) may be represented.
- (3) In the calculations, the logarithm of WL is used. Hence, the absolute WL elevation (e.g., meters above sea level) can not be used because identical responses in different wells at different elevations will yield dramatically different calculated T values. A consistent method of identifying WL is to use the WL above transducer, which in the studies here, was ≈ 1.5 m.
- (5) Following equation (6), it is assumed that the drainage area corresponding to volume changes represented by the three line segments are the same, and that the $AS_{y_i} / Q_1 = X_i$ expressions could be solved for Q_1 and equated. This limitation imposes the assumption that the area associated with the conduit, fracture and matrix responses are equal, yet this would not be true if a dominant source of the recharge to the conduit portion of the aquifer were through a sinkhole. The sinkhole area would be much smaller than the area comprising recharge to the matrix portions of the aquifer.

Conclusions

This paper describes the development of a method to quantitatively analyze well hydrographs in order to obtain estimates of non-conduit T, and S_y associated with karst dominated portions of an aquifer. Several wells intersect conduits which responds rapidly (30 minutes to 5 hrs) to precipitation events. The

hydrographs from these wells show three discrete line segments on recessions curves obtained during a number of storms. These segments are believed to represent drainage from the conduit, fracture and matrix dominated portions of the aquifer in the vicinity of the well bores.

Hydrographs from several wells in the karst Maynardville Limestone near Oak Ridge, Tennessee were used to estimate the S_y associated with the conduit, fracture and matrix portions of the aquifer. Continuum T were also estimated for different positions within the aquifer. Data from short injection tests at one well indicate continuum T at this well bore is $\approx 5 \text{ m}^2/\text{d}$, and tests at numerous other wells in the aquifer yield results between 1 and $7 \text{ m}^2/\text{d}$. The T estimated with well hydrographs from two storms indicates a T of $9.8 \text{ m}^2/\text{d}$ indicating that the use of hydrographs provides reasonable estimates of continuum T. In the study area near Oak Ridge, well developed conduit systems in which water levels in wells show a flashy response typically have shown S_y 's of about 1×10^{-4} , 1×10^{-3} , and 3×10^{-3} for conduit, fractured, and matrix portions of the aquifer. Less well developed conduit areas show more nearly equal S_y 's (8.6×10^{-4} , 1.3×10^{-3} , 3×10^{-3}). Areas with no evidence for the presence of conduits have only one, or in some cases two, slopes on the recession curve. In these cases, water level responses are slow. Recession curves with a single slope represent drainage from only the lower T matrix. Those with two slopes have an additional, more rapid response segment on the recession curve which represents drainage from the higher T, lower S_y , fractures in the system. Using easily obtainable and relatively inexpensive hydrograph data with the method described here provides reliable estimates of continuum T, and S_y of conduit, fracture and matrix intervals in many portions of the aquifer. Such information will be useful in constructing numerical, ground-water flow models.

Acknowledgments

This work was supported, in part, by a subcontract to the University of Nevada, Reno from Martin Marietta Energy Systems, Inc. under its U.S. Department of Energy contract DE-AC05-84OR21400. The author would like to thank G.K. Moore for discussions on this topic, and a review of an early draft of this work.

References

- Ashton, K. 1966. The analysis of flow data from karst drainage systems. Trans. Cave Research Group. v. 7, no. 2, pp. 161-203.
- Atkinson, T.C., 1977. Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain), J. of Hydrol. v. 35, pp. 93-110.
- Barnes, B.S. 1940. Discussion of analysis of runoff characteristics. Trans. ASCE. v. 105, pp. 106.
- Bouwer, H., and R.C. Rice. 1976. A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resour. Res. v. 12, no. 3, pp. 423-428.

- Burdon, D.J., and N. Papakis. 1963. Handbook of karst hydrogeology. United Nations, Athens.
- Cooper, H.H., and C.E. Jacob. 1946. A generalized graphical method for evaluating formation constants and summarizing well field theory. *Am. Geophys. Union Trans.* v. 27, pp. 526-534.
- Duffield, G.M, and J.O. Rumbaugh, III. 1991. AQTESOLV, Aquifer test solver version 1.00 documentation. Geraghty and Miller Modeling Group, Reston, Virginia.
- Fetter, C.W. 1988. Applied Hydrogeology, Merrill Publishing, Columbus, OH.
- Freeze, R.A., and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
- Hatcher, R.D., Jr., et al., 1992, Status Report on the Geology of the Oak Ridge Reservation, ORNL/TM-12074
- Linsley, R.K., M.A. Kohler, and J.L.H. Paulhus. 1982. Hydrology for Engineers. McGraw-Hill Book Company, New York: 508 pp.
- Milanovic, P.T. 1981. Karst Hydrogeology. Water Resources Publications, Littleton, Colorado: 434 pp.
- Miller, R.L., and J.O. Fuller. 1954. Geology and oil resources of the Rose Hill district--The Fenster area of the Cumberland overthrust block, Lee County Virginia. *VA Geol. Survey Bull.* 71.
- Moore, G.K. 1992. Hydrograph analysis in fractured rock terrane, *Ground Water*. v. 30, no. 3, pp. 390-395.
- Moore, G.K., and L.E. Toran. 1992. Supplement to a hydrologic framework for the Oak Ridge Reservation, Oak Ridge, Tennessee. ORNL/TM-12191.
- Padilla, A., A. Pulido-Bosch, and A. Mangin. 1994. Relative importance of baseflow and quickflow from hydrographs of karst spring. *Ground Water*. v. 32, no. 2, pp. 267-277.
- Rorabaugh, M.I. 1960. Use of water levels in estimating aquifer constants in a finite aquifer. *Int. Assoc. of Sci. Hydrol.* v. 52, pp 314-323.
- Rorabaugh, M.I. 1964. Changes in bank storage, *Int. Assoc. of Sci. Hydrol., Publ.* v. 63, pp. 432-441.
- Shevenell, L. 1994. Chemical characteristics of waters in karst formations at the Oak Ridge Y-12 Plant, Y/TS-1001.
- Shevenell, L., B. McMaster, and K. Desmarais. (in review). Evaluation of cross borehole tests at selected wells in the Maynardville Limestone and Copper Ridge Dolomite at the Oak Ridge Y-12 Plant. Y/TS-1166.
- Theis, C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. *Am. Geophys. Union Trans.* v. 16, pp. 519-524.
- White, W.B. 1988. Geomorphology and Hydrology of Karst Terrains. Oxford University Press, New York: 464 pp.

LIST OF FIGURES

Figure 1. Generalized geologic map of the Oak Ridge Reservation. Modified from Hatcher, et al. (1992)

Figure 2. The natural logarithm of water level versus time for GW-734, 1992 data.

Figure 3. Water level and precipitation data versus time for the GW-715 well.

Figure 4. Specific conductance and temperature data versus time for the GW-715 well.

Figure 5. Water level and precipitation data versus time for the GW-604 well.

Figure 6. Water level and precipitation data versus time for the GW-710 well.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Table 1

Hydrologic parameters calculated from the 1992 GW-734 hydrograph
data and equations (1) through (7)

	Storm 1			Storm 2		
	Segment 1	Segment 2	Segment 3	Segment 1	Segment 2	Segment 3
t (hrs)	0	31.5	95	0	6.5	23.5
Y (m)	3.5	2.74	2.28	2.73	2.49	2.32
λ (hr ⁻¹)	1.19×10^{-2}	3.63×10^{-3}	1.49×10^{-3}	1.54×10^{-2}	4.27×10^{-3}	1.37×10^{-3}
AS _y /Q ₁	8.5	30	68	8.9	32	100
T/S (m ² /hr)	1143	3401	1391	14455	4004	1282
<u>Using S_y=3 × 10⁻³:</u>						
T (m ² /d)	20.8	6.1	2.6	27.0	7.5	2.4
<u>Using S_y ratios:</u>						
S _y	4.12×10^{-4}	1.35×10^{-3}	3×10^{-3}	2.93×10^{-4}	1.06×10^{-3}	3×10^{-3}
T (m ² /d)	10.2	10.2	10.2	9.4	9.4	9.4
S _{y1} /S _{y2}	0.305			0.277		
S _{y2} /S _{y3}	0.409			0.320		
S _{y1} /S _{y3}	0.125			0.089		

Table 2. Continuum transmissivity and specific yields estimated for the conduit, fracture, and matrix portions of the aquifer at GW-734 from three hydrograph recession curves.

	T1/Sy1	T2/Sy2	T3/Sy3	Sy1	Sy2	Sy3 (Assumed)	T1 (m ² /d)	Saturated Thickness (m)	K (m/d)
1992	11143	3401	1391	4.12E-04	1.35E-03	0.003	10.2	99.1	1.03E-01
1992	14455	4004	1282	2.93E-04	1.06E-03	0.003	9.4	99.1	9.49E-02
1994	15410	10222	5082*	1.09E-03	1.64E-03	0.003	23.3*	99.1	2.35E-01*
Average:	13669	5876	1337	5.98E-04	1.35E-03		9.8		9.89E-02
Stdev:	14933	7113	1282	4.30E-04	2.90E-04		0.6		5.71E-03

Note: Transmissivities of the Knox aquifer based on previous tests are 1.0 to 7.3 m²/d (Moore and Toran, 1992).

Transmissivities based on injection tests into GW-734 from the 2 short injection tests are 5.0 m²/d.

• questionable results

Table 3. Comparison of responses to precipitation events in the three types of wells monitored.

	Picket	Well Depth (m)	Number of Slopes	Delay to start		Delay to Peak		Duration Peak		Duration	Recession	WL Rise	
				Min (hrs)	Max (hrs)	Min (hrs)	Max (hrs)	Min (hrs)	Max (hrs)	Recession (hrs)	Complete	Min (m)	Max (m)
Group 1													
GW-220	J	13.8	3	0	8	1.5	6	0	0	135.5	Y?	0.3	0.6
GW-715	W	13.6	3	4	23.5	5	7	0	0	174	Y	0.4	1.5
GW-734	J-1992	18.3	3	0	2	7	17	0	0	203	?	0.7	1.6
GW-734	J-1994	18.3	3	0	9.5	5	14.5	0	1	144.5	Y?	1.2	3.2
GW-735	J	25.3	3	3	10	8	8	0.5	1	145	Y	1.0	2.1
Average				1.4	10.6	5.3	10.5	0.1	0.4	160.4		0.7	1.8
Std. Dev.				1.9	7.9	2.5	4.9	0.2	0.5	27.9		0.4	1.0
Group 2													
GW-603	J	22.9	3	7.5	12	14.5	22.5	0.5	3.5	111	Y	0.2	1.7
GW-604	J	34.3	3	7.5	12	15	25	0	1.5	134	Y	0.2	1.6
Average				7.5	12.0	14.8	23.8	0.3	2.5	122.5		0.5	1.8
Std. Dev.				0.0	0.0	0.4	1.8	0.4	1.4	16.3		0.4	0.3
Group 3													
GW-710	W	226.9	1 or 2	8	24.5	22	51	1.5	9.5	250.5	Y?	0.1	1.0
GW-711	W	203.1	1 or 2	0	9	37.5	53.5	0.5	0.5	272	Y	0.2	1.1
GW-712	W	139.4	1 or 2	2.5	27	19	47.5	1.5	3	155.5	Y?	0.1	1.2
GW-713	W	96.1	1 or 2	2	27.5	36	41.5	1.5	12	129	N	0.2	0.9
GW-714	W	44.2	1 or 2	3	8	24	35	0.5	4	158	Y?	0.3	1.5
GW-733	J	78.2	1 or 2	6	13	20	37.5	1.5	4	130	Y?	0.0	1.3
GW-748	J	8.3	1 or 2	8.5	8.5	15.5	22.5	2	5	135	?	0.2	1.0
GW-750	J	22.2	1 or 2	4.5	8.5	13.5	24	0.5	1.5	128	N	0.7	1.0
GW-167	J	9.2	1 or 2	0.0	9.5	11.0	18.0	1.0	1.5	139.5	Y?	1.5	2.8
Average				3.8	15.1	22.1	36.7	1.2	4.6	166.4		0.4	1.3
Std. Dev.				3.3	8.2	9.9	14.9	0.6	3.4	62.4		0.4	0.6

Table 4. Estimates of specific yields and continuum transmissivities for wells which exhibited three distinct slopes on recession curves following precipitation events.

	T1/Sy1	T2/Sy2	T3/Sy3	Sy1	Sy2	Sy3 (assumed)	T (m2/d)	Saturated Thickness (m)	K (m/d)
GROUP 1									
GW-220									
Storm 1	25423	6746	1648	1.94E-04	7.33E-04	3.00E-03	11	99.1	0.11
Storm 2	11435	1962	622	1.63E-04	9.50E-04	3.00E-03	4.2	99.1	0.04
Storm 3	8682	1731		1.68E-04	<i>8.42E-04</i>		3.25	99.1	0.03
Ave:	15180	3480	1135	1.75E-04	8.42E-04		6.2		0.06
+-	8977	2831	725	1.66E-05	1.09E-04		4.2		0.04
GW-715									
Storm 1	40238	2099	1014	5.93E-05	1.32E-03	3.00E-03	6.78	182.8	0.04
Storm 2	59579	7413	3800	1.48E-04	1.35E-03	3.00E-03	25.4	182.8	0.14
Storm 4	14814*	84998*		8.57E-03*	<i>1.49E-03*</i>		283*	182.8	1.55*
Ave:	49909	4756	2407	1.04E-04	1.33E-03		16.1		0.09
+-	13676	3758	1970	6.27E-05	2.05E-05		13.2		0.07
GW-734									
1992 - 1	11143	3401	1391	4.12E-04	1.35E-03	3.00E-03	6.4	99.1	0.06
1992 - 2	14455	4004	1282	2.93E-04	1.06E-03	3.00E-03	5.9	99.1	0.06
1994 - 1	16446	10706		6.19E-04	<i>9.51E-04</i>		13.2	99.1	0.13
1994 - 2	15410	10222	5082	1.09E-03	1.64E-03	3.00E-03	23.3	99.1	0.24
1994 - 3	18363	13545		7.01E-04	<i>9.51E-04</i>		16.7	99.1	0.17
Ave:	15163	8376	2585	6.23E-04	1.19E-03		13.1		0.13
+-	2674	4456	2163	3.06E-04	3.00E-04		7.3		0.07
GW-735									
1994 - 1	9047	5118		1.32E-03	<i>2.34E-03</i>		26.7	99.1	0.27
1994 - 2	9710	7668	5992	1.85E-03	2.34E-03	3.00E-03	40.1	99.1	0.40
1994 - 3	11841*	12144*		2.40E-03*	<i>2.34E-03*</i>		63.4	99.1	0.64
Ave:	9379	6393	5992	1.59E-03	2.34E-03		33.4		0.34
+-	469	1803		3.75E-04	0.00E+00		9.5		0.10
GROUP 2									
GW-603									
Storm 2	5856	4429	1508	7.72E-04	1.02E-03	3.00E-03	10.1	99.1	0.10
Storm 3	5068	4424		8.90E-04	<i>1.02E-03</i>		10.07	99.1	0.10
Ave:	5462	4427	1508	8.31E-04	1.02E-03		10.1		0.10
+-	557	4		8.34E-05	0.00E+00		0.0		0.00
GW-604									
Storm 2	5671	3881	1535	8.12E-04	1.19E-03	3.00E-03	10.3	99.1	0.10
Storm 3	3891*	3910*		1.19E-03*	1.19E-03*		10.35	99.1	0.10
Ave:	5671	3881	1535	8.12E-04	1.19E-03				0.10

The Sy2 values in italics are average values calculated from recession curves containing three slopes from other storms at the same well.

* indicates questionable results

Table 5. Calculated transmissivity based on the three slope recession method using cross borehole test recessions.

	T1/Sy1	T2/Sy2	T3/Sy3	Sy1	Sy2	Sy3 (assumed)	T (m ² /d)	Saturated Thickness (m)	K (m/d)
Picket W									
No suitable slopes observed for use with this method									
Picket A									
GW-683	63.7	8	4.2	2.00E-04	1.60E-03	3.00E-03	1.7	31.52	0.05
SS-5-1	1.3	1.1	0.5	1.10E-03	1.30E-03	3.00E-03	0.18	31.52	0.01
SS-5-2	1.8	1.1	0.3	4.75E-04	8.03E-04	3.00E-03	0.12	31.52	0.00
Picket B									
GW-694	1142	313	101	2.65E-04	9.65E-04	3.00E-03	40.5	64.9	0.62
GW-695	157	58	10	1.95E-04	5.27E-04	3.00E-03	4.1	64.9	0.06
GW-704	725	141	14.5	5.98E-05	3.09E-04	3.00E-03	5.8	64.9	0.09
Picket C									
GW-725	1484	119	90	1.82E-04	2.27E-03	3.00E-03	36.2	83.8	0.43
GW-738	108	9.8	3.8	1.04E-03	1.15E-03	3.00E-03	1.5	83.8	0.02
GW-739	39	14.5		1.11E-03	3.00E-03		5.8	83.8	0.07
Picket J									
GW-735-1	2709	87	54	6.00E-05	1.88E-03	3.00E-03	21.8	99.1	0.22
GW-735-2	2449	24	29	3.60E-05	3.66E-03	3.00E-03	11.8	99.1	0.12
GW-735 - from storm hydrographs									
1994 - 1	9047	5118		1.32E-03	2.34E-03		26.7	99.1	0.27
1994 - 2	9710	7668	5992	1.85E-03	2.34E-03	3.00E-03	40.1	99.1	0.40
1994 - 3B	11841*	12144*		2.40E-03*	2.34E-03*		63.4	99.1	0.64
Ave:	9379	6393	5992	1.59E-03	2.34E-03				0.34
+	469	1803		3.75E-04	0.00E+00				0.10

The Sy2 value in italics is the average value calculated from recession curves containing 3 slopes from other storms at the same well.

* indicates questionable results

DISTRIBUTION

DEPARTMENT OF ENERGY

G. W. Bodenstein
W. G. McMillan

HEALTH, SAFETY, ENVIRONMENT, AND ACCOUNTABILITY ORGANIZATION

W. K. Jago
S. B. Jones
S. W. Wiley
File-GWPP-RC

ENVIRONMENTAL RESTORATION PROGRAM

H. L. King (2)

ENVIRONMENTAL SCIENCES DIVISION

T. O. Early
R. B. Dreier
D. D. Huff
D. B. Watson

UNIVERSITY OF NEVADA, RENO

L. A. Shevenell (3)

HSW ENVIRONMENTAL CONSULTANTS

J. R. Walker

Y-12 Central Files

~~A. K. Lee/DOE-OSTI (2)~~