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OCCURRENCE, FREQUENCY, AND SIGNIFICANCE OF CAVITIES IN FRACTURED-ROCK AQUIFERS NEAR OAK RIDGE NATIONAL LABORATORY, TENNESSEE[1,2]

Gerald K. Moore
University of Tennessee, Knoxville, Tennessee

Environmental Sciences Division
Oak Ridge National Laboratory
Bldg. 1503, MS 6352
P.O. Box 2008, Oak Ridge, Tennessee 37831-6352

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By Gerald K. Moore[2]
Environmental Sciences Division
Oak Ridge National Laboratory
Bldg. 1503, MS 6352
P.O. Box 2008, Oak Ridge, TN 37831-6352
(615) 574-7339

ABSTRACT

The main problem resulting from waste-storage practices and spills near Oak Ridge National Laboratory (ORNL) over a 45-year period has been the mobility of contaminants in groundwater. In the area near ORNL, groundwater occurs in regolith, bedrock fractures, and a few larger cavities. More than 1500 wells have been drilled within a 5-km radius, and more than 400 hydraulic conductivity values have been determined from slug tests. These data can be used to determine the potential for rapid groundwater movement through cavities.

Virtually all wells drilled into bedrock intercept a water-bearing fracture, but cavities occur only in areas underlaid by limy rocks. Multiple cavities are common in wells in the Conasauga and Knox Groups but are rare in the Rome Formation and the Chickamauga Group. The geometric mean height (vertical dimension) of the cavities is 0.59 m, the geometric mean depth is 14 m, the average lateral spatial frequency is 0.16, and the

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[2]Research Associate in Hydrology, The University of Tennessee, Knoxville.

average vertical spatial frequency is 0.019. Differences in cavity parameter values are caused partly by geologic factors such as lithology, bed thickness, and spatial fracture frequency. However, hydrologic factors such as percolation rate, recharge amount, aquifer storage capacity, and differences between lateral and vertical permeability may also be important.

Tracer tests show that groundwater velocity in some cavities is in the range 20-300 m/d, and relatively rapid flow rates occur near springs. In contrast, wells that intercept cavities have about the same range in hydraulic conductivity as wells in regolith and fractured rock. The hydraulic conductivity data indicate a flow rate of less than 1.0 m/d. This difference cannot be adequately explained, but rapid groundwater movement may be much more common above the water table than below. Rapid groundwater flows below the water table might be rare except near springs in the Knox Group.

INTRODUCTION

Radionuclides and other wastes have been stored in shallow burial grounds near Oak Ridge National Laboratory (ORNL) since 1943. The main problem resulting from waste-storage practices and accidental spills has been the entrainment and mobility of contaminants in groundwater. This mobility is determined by the hydrologic and geochemical properties of the uppermost aquifers.

More than 1500 observation wells have been drilled within a 5-km radius of ORNL since 1949. The data from these wells show that groundwater occurs in regolith, in bedrock fractures, and in a few larger cavities. Virtually all wells drilled into bedrock intercept a water-bearing fracture, but only about 12% of the wells intercept a cavity. Also, most cavities are reported to be filled with clay, gravel, or other detritus. Nevertheless, rates and quantities of groundwater flow may be large in cavities. For example, one tracer test showed a mean linear velocity of 0.17 m/d for shallow fractures (Davis et al. 1984, p. 77), whereas a velocity of 190-360 m/d was calculated for a tracer test in a cavity system about 3 km away (Ketelle and Huff 1984, pp. 131-135). Thus, an understanding of the hydrologic significance of cavities is necessary for a correct interpretation of groundwater occurrence and movement in the aquifers. This report describes the occurrence, size, depth, spatial frequency, and hydrologic significance of cavities in the fractured-rock aquifers. All cavities, except for a few occurrences of piping, are in limestone or other limy rocks, and most of the results are not applicable to areas underlaid by shale and sandstone.

BACKGROUND

The study area is a part of the Oak Ridge Reservation of the U.S. Department of Energy. It is about 11 km southwest of the City of Oak Ridge in the Valley and Ridge Province of eastern Tennessee. Average annual precipitation is about 1300 mm, and mean annual runoff is about 570 mm (McMaster 1967, p.9). Annual groundwater discharge may be about 150-250 mm of water.

The parallel ridges and valleys are a result of differential erosion, which has been affected by the underlying structure of folds and faults. The strike of the rocks generally parallels the axes of the ridges and averages about N56°E; the dip is spatially variable but commonly averages 30-40°SE (Stockdale 1951, p. 16). Cavities have been intercepted by wells in the Rome Formation, the Conasauga Group, the Knox Group, and the Chickamauga Group of Cambrian and Ordovician ages.

The Rome Formation consists mainly of siltstone, shale, and sandstone (McMaster 1962); it is a relatively resistant unit that forms some of the ridges in the study area. The Conasauga Group is mainly shale and siltstone but includes two thin-bedded limestone formations in the lower part of the group and a massively bedded limestone in the upper part (Davis et al. 1984, pp. 15-18); the Conasauga units form valleys and hillocks. The Knox Group generally consists of cherty dolomite in thin to massive beds (McMaster 1962); residual chert in the regolith is resistant to erosion and forms ridges and hillslopes. The Chickamauga Group is a shaley and cherty limestone with thin to medium beds (McMaster 1962); it forms cross-valley slopes and low hillocks. The regolith in most areas consists of sandy, silty clay, but the lowermost part may include a rock-fragment layer or saprolite. The Knox regolith consists of a mixture of chert fragments and clay. With the exception of areas underlain by the Knox Group, The geometric mean thickness of regolith in observation wells is 3.1 m. The Knox regolith is 3 to 6 m thick at low elevations and up to 45 m thick atop the ridges.

In bedrock, essentially all groundwater occurs in fractures and in a few larger cavities. Most fractures are short, a few centimeters to 1 m in length, but various joint sets form intersecting systems (Sledz and Huff 1981, p. 12). Many fractures are bedding-plane parallel or strike parallel; both sets occur in some areas. A less common, orthogonal fracture set is parallel to the dip of the beds. A fracture system consisting of these two or three sets may be presumed to occur in any locality, and other sets may also be present. Most fractures are steeply dipping (R. B. Dreier, ORNL, personal communication to author, 1988).

The cavity data analyzed in this report are from drillers' and geologists' logs compiled during the drilling of 351 recent piezometer wells and from records of 451 other observation wells in nearby areas (Haase and others, 1987). Some interpretation of these records was required. A cavity was noted wherever logs use the words "cavity" or "void", but not where logs use the words "fracture," "soft," or "break." A cavity was also noted wherever the logs record an interval of unconsolidated material below the top of bedrock and where a zone of high water velocity or lost circulation was described. Cavities were included in the analysis regardless of whether or not they are water bearing or reported as filled and regardless of whether they are above or below the water table.

STATISTICAL ANALYSIS OF THE DATA

Probability graphs were used to determine the distribution of numerical data for purposes of analysis. This method was fully described by Sinclair (1976) but is not widely used in hydrology. Basically it consists of plotting sorted data values on cumulative probability paper; the data points are those that would be used for a cumulative histogram. If a straight line can be fitted to the data points, this line defines the cumulative density distribution of the population. Cavity parameters in the ORNL area proved to be lognormally distributed and to have a very large range. Thus the natural logarithms of the sorted data values were plotted on arithmetic probability paper (Figs. 1-3). The 50% probability value of the fitted line on one of these graphs represents the geometric mean of the population; it can be calculated from e^x, where x is the value determined from the line. Similarly, the geometric mean minus one standard deviation and the mean plus one standard deviation can be calculated from the 16% and 84% probability values of the straight line.

ORIGIN AND OCCURRENCE OF CAVITIES

Cavities in bedrock are formed by solution, abrasion, and a combination of these two processes. Enlargement of fractures begins with slow solution, but openings enlarged above some critical size permit turbulent groundwater flow. Physical erosion by abrasion then increases the rate of cavity enlargement while turbulent flows remove at least part of the resulting detritus. Any remaining detritus accumulates at the bottom of the cavity and partially protects this rock surface against further erosion. Thus, most larger cavities develop mainly by abrasion and by upward stoping.

Some rock layers and lithologies along a groundwater flow path are more easily eroded than others, and the cross-sectional area of a cavity may change considerably from one location to another. Mean groundwater velocity is less in the larger sections, especially near cavity walls, and solution may again become the dominant process in further enlargement of these reaches.

If abundant detritus is available over time, a profile may develop in which a small open cavity overlies a wedge of detritus. Because most fractures are steeply dipping but not vertical, one well may intercept a cavity filled with detritus, another well a short distance away may intercept an open cavity, and a third well a short distance in the other direction may intercept a slightly enlarged section of the original fracture. The wedge of detritus is commonly thicker than the open part of the cavity, and thus most cavities are reported as filled. Cavity-fill material in this area has been described as consisting of clay, mud, mixed clay and gravel, sand, chert, limestone chips, rounded gravel, or limestone pebbles and cobbles; twigs were recovered from one cavity.

So-called solution cavities in the Chickamauga Group were first described by Stockdale (1951, p. 41). Since then, cavities have been reported in all other rock units with limy layers. A general principle of cavity occurrence is that if everything else is equal, the largest cavities are found in the purest and most massively bedded limestones. This principle is generally applicable to rock units in the ORNL area. Cavities in the Conasauga Group have been reported only in the Maryville Limestone, Nolichucky Shale, and Maynardville Limestone. All three of these formations contain limestone layers, and the cavities are presumed to occur in these layers. Similarly, two cavities in Rome Formation bedrock may occur in dolomite layers, which have been described in the upper part of this formation (Stockdale 1951, p. 17).

A few cavities in the study area have been reported as zones of high water velocity (which washed away sandpack material) in regolith, just above top of bedrock. Apparently this is a form of piping which occasionally occurs in unconsolidated sediments near a point of groundwater discharge. Two cavities in the Rome Formation and three cavities in the Conasauga Group are of this type. The piping at the base of the regolith may occur along upward extensions of enlarged fractures in the bedrock.

The records of 802 wells in the study area show that only 97 wells (12%) intercept a cavity, and most of the smaller number intercept only one cavity. However, there are some distinctive differences in cavity occurrence among the geologic units (Table 1). None of the wells in the Rome Formation and only one (8%) in the Chickamauga Group intercept more than one cavity. In the Conasauga Group, 27 wells (46%) intercept more than one cavity, but only 11 wells (19%) intercept more than two cavities, and none intercept more than four cavities. More Knox wells (48%) intercept two cavities than one or any larger number. A total of ten cavities were reported in one Knox well, but only four wells (19%) intercept more than three cavities. Thus, multiple cavities are rare except in the Conasauga Group and the Knox Group, and more than three cavities are uncommon in these units.

SIZE AND SHAPE

Only the vertical dimension of cavities (called "height" for the purposes of this report) can be obtained from well records. A cumulative probability graph of these data (Fig. 1) is somewhat irregular, mainly

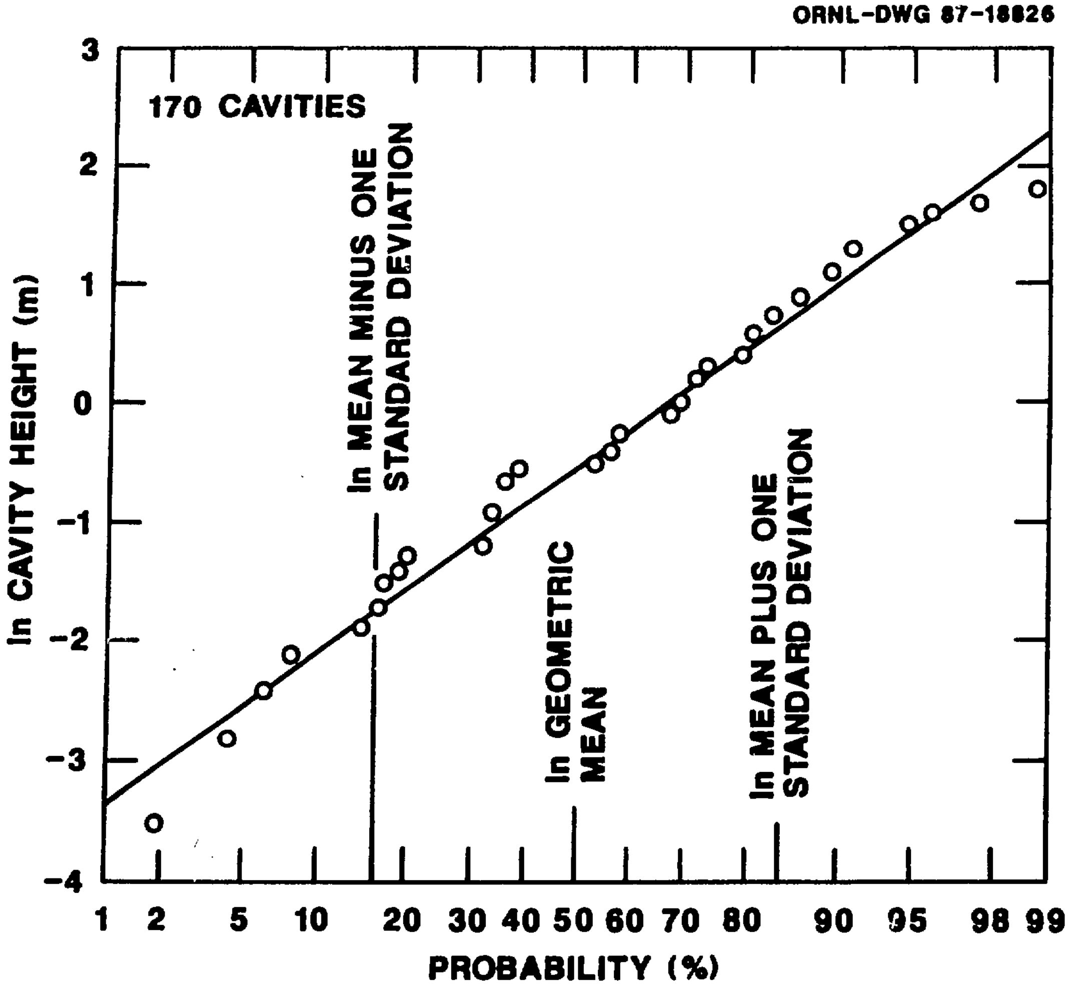

Fig. 1. Cumulative probability graph of cavity heights (vertical dimension of cavities).

because many cavity heights were recorded as integers rather than decimal numbers. Nevertheless, a single straight line can be satisfactorily fitted to the data points. This fit shows that cavity heights represent a single lognormally distributed population and suggests that all cavities were formed by the same processes. The geometric mean of cavity height is 0.59 m, and the range from the mean minus one standard deviation to the mean plus one standard deviation is 0.18-2.0 m.

A grouping of cavity heights by geologic unit (Table 2) shows some interesting differences. The cavity with the largest height is in the Knox Group, and, although large cavities also occur in the Conasauga and Chickamauga Groups, the geometric mean height of cavities in the Knox Group is almost twice as large as that in the Conasauga Group. One-tail Student's *t*-tests of log-transformed (normalized) data show that the geometric mean height of cavities in the Knox Group is statistically larger than the mean height both in the Conasuaga Group and in the population at the 5% level of significance. There are no statistically significant differences in the geometric mean heights of the other units.

The shape of cavities in the study area is unknown. Elsewhere in the limestone region of Tennessee, many cavities have a semicircular (domed upward) section; this is also the stable shape for piping. However, circular to rectangular (with elongation in the direction of the controlling fracture) sections have also been observed.

Table 1. Number of cavities in wells by geologic unit

Geologic unit	Number of wells	Number of wells with one or more cavities				
		One cavity	Two cavities	Three cavities	Four cavities	Five or more cavities
Chickamauga Group	13	12	1	0	0	0
Knox Group	21	5	10	2	3	1
Conasauga Group	59	32	16	9	2	0
Rome Formation	4	4	0	0	0	0
Total Population	97	53	27	11	5	1

Table 2. Distribution of cavity heights by geologic unit

Geologic unit	Number of wells	Height of cavities (m)				
		Geo-metric mean	Mean minus one standard deviation	Mean plus one standard deviation	Minimum value	Maximum value
Chickamauga Gpoup	14	0.90	0.25	3.3	0.061	6.9
Knox Group	53	1.0	0.34	3.1	0.030	8.5
Conasauga Group	99	0.51	0.16	1.7	0.030	5.9
Rome Formation	4	0.81	NA*	NA*	0.30	1.5
Total population	170	0.59	0.18	2.0	0.030	8.5

*Not applicable because of small number of wells.

DEPTH

The depths of cavities in the well records were denoted as the midpoints of the open intervals. A probability graph of cavity depths (Fig. 2) shows that a single straight line can be satisfactorily fitted to these points. This fit shows that the data can be considered to be samples from a single population. Thus, cavity depths are lognormally distributed with a geometric mean depth of about 14 m and a 5.8- to 32-m range from minus one to plus one standard deviation.

An analysis of cavity depths by geologic unit (Table 3) shows that the geometric mean depth of cavities in the Knox Group is much larger than those in the Rome Formation, the Conasauga Group, and the Chickamauga Group. This result was expected because of the larger regolith thickness in the outcrop area of the Knox Group. The similarity of geometric mean values for the depths of cavities in the other geologic units was not expected. Apparently, the factors that determine cavity depth are nearly the same over the entire area underlaid by these three units. The other statistical indices suggest that the curvature of data points near the center of Fig. 2 may be caused by the fact that only 16% of cavities in the Conasauga and Chickamauga Groups are deeper than 16 m and only 16% of cavities in the Knox Group are shallower than 21 m.

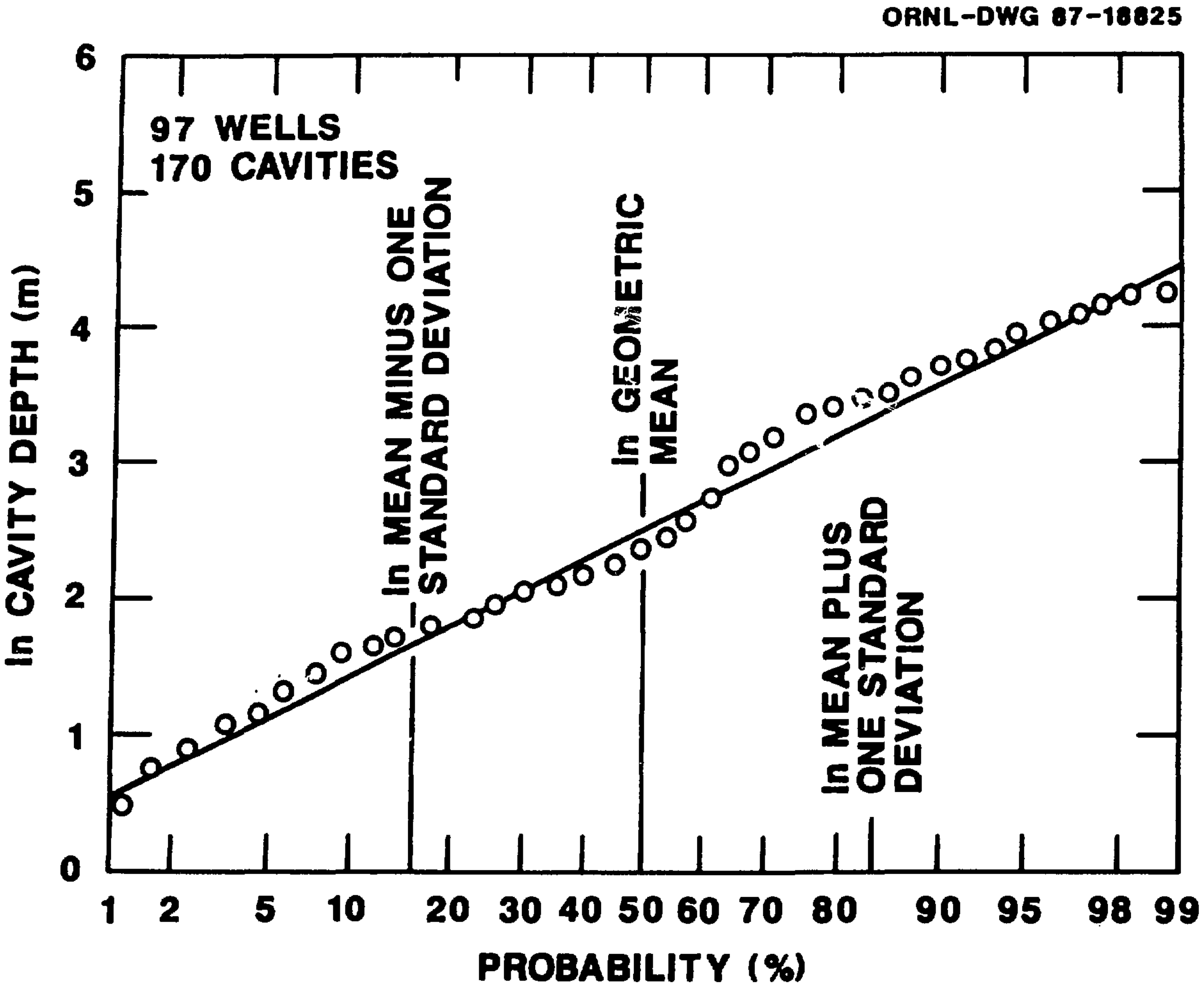

Fig. 2. Cumulative probability graph of cavity depths below land surface.

Table 3. Distribution of cavity depths by geologic unit

Geologic unit	Number of values	Depth of cavities (m): Geometric mean	Mean minus one standard deviation	Mean plus one standard deviation	Minimum value	Maximum value
Chickamauga Group	14	9.7	5.7	16	4.8	21
Knox Group	53	34	21	53	19	96
Conasauga Group	99	8.3	4.3	16	1.2	71
Rome Formation	4	12	NA*	NA*	6.1	26
Total population	170	14	5.8	32	1.2	96

*Not applicable because of small number of values.

Table 4. Spatial frequency of cavity occurrence by geologic unit

Geologic unit	Number of wells	Lateral spatial frequency	Vertical spatial frequency
Chickamauga Group	175	0.13	0.018
Knox Group	50	0.43	0.058
Conasauga Group	552	0.12	0.012
Rome Formation	25	0.11	0.011
Total population	802	0.16	0.019

SPATIAL FREQUENCY OF OCCURRENCE

The vertical spatial frequency of cavities (Table 4) was determined by dividing the total height of cavities in any group of wells by the total length of borehole in rock. The lateral spatial frequency of the cavities could have been estimated by dividing the number of wells that intercept one or more cavities by the total number of wells in any group. However, deep wells are more likely to intercept cavities than shallow wells, and results might have been biased by differences in the average depth of wells that intercept cavities and the average depth of wells that do not. Instead, each well was assigned a weight based on its depth and on the probability (Fig. 2) of its intercepting a cavity at any level above this depth. For example, a well 20 m deep (ln 20 = 3.0) was given a weight of 0.73 based on the relationship shown by the fitted line on Fig. 2. Lateral spatial frequency was then calculated by dividing the total weight of wells that intercept one or more cavities by the total weight of all wells in the group. A lateral spatial frequency of 0.12, for example, means that if wells in the Conasauga Group were drilled deeply enough to intercept all possible cavities, 12% of these wells would intercept one or more cavities.

Lateral and vertical spatial frequencies of cavity occurrence are related but are not simply different measures of the same parameter. Vertical spatial frequency (V) is directly proportional to lateral spatial frequency (L), mean cavity height (h), and mean number of cavities (n) in each well that intercepts cavities; it is inversely proportional to mean cavity depth (d). Thus,

$$V = Lhn/d \ .$$

If a value of 1.8 is used for mean number of cavities per well and population values from Tables 2-4 are used for the other parameters, vertical spatial frequency is 0.012. This result is reasonably close to the value of 0.019 calculated by the method described previously.

An analysis of the spatial frequency of cavity occurrence by geologic unit (Table 4) shows that cavities in the Knox Group are three to five times as common as cavities in the other geologic units. The only other significant differences between the units is that cavities in the Chickamauga Group have about 1.5 times the vertical spatial frequency of cavities in the Conasauga Group. This difference might be caused by the larger geometric mean height (Table 2) of cavities in the Chickamauga Group, even though multiple cavities are more likely to occur in wells in the Conasauga Group.

HYDROLOGIC SIGNIFICANCE OF RESULTS

The contribution of cavities to rates and quantities of groundwater flow is difficult to determine from well logs. Many cavities are reported to be filled, but some types of fill material may have a large permeability. The detailed records on 28 recent piezometer wells describe a fill material for the cavities in 14 wells (50%) but do not mention fill in the other cavities. Slug tests have been run on 25 wells in this group and have produced two of the smallest and four of the largest hydraulic conductivity values in a group of 413 test results. One large hydraulic conductivity value (5.7 m/d) is from a presumably open cavity about 1.0 m in height, but another large hydraulic conductivity value (7.6 m/d) was obtained from a well that intercepts a mud-filled cavity with a height of about 1.4 m. The smallest value (0.0001 m/d) is from a well that intercepts a presumably open cavity about 0.4 m in height. Thus, a physical description may not be a reliable indicator of the water-bearing potential of a cavity.

Hydraulic conductivity values determined from slug tests are well fitted to a single line except for points at the lower and upper ends of the graph (Fig. 3). The data are mainly from wells in regolith and in fractured rock of several different lithologies, but 25 hydraulic conductivity values, scattered through these data, represent wells that intercept cavities. The geometric mean of the population line is 0.040 m/d, and the range from the mean minus one to plus one standard deviation is 0.0060-0.26 m/d. Three cavity wells are among the 33 data values that plot with a steeper slope at the lower end of the graph. Twenty one (64%) of these wells are deeper than the depth of the geometric mean plus one standard deviation (16.4 m) for all wells. This is fairly good evidence for a change in the distribution of hydraulic conductivities at deeper levels in the aquifers. Five cavity wells (42%) are among the 12 values that plot above the fitted line at the upper end of the graph. In considering these points, it is important that the anomalously large values constitute only about 3% of the population and that the anomalous values are not much larger than would normally be expected in the population, as is shown by the line extension on the graph.

The geometric mean of hydraulic conductivity for 25 cavity wells is 0.085 m/d. This is about twice as large as the geometric mean for all wells. However, a one-tail Student's *t*-test of the log-transformed data shows that the geometric mean of the cavity wells is not statistically larger than that of the population at the 1% level of significance. These

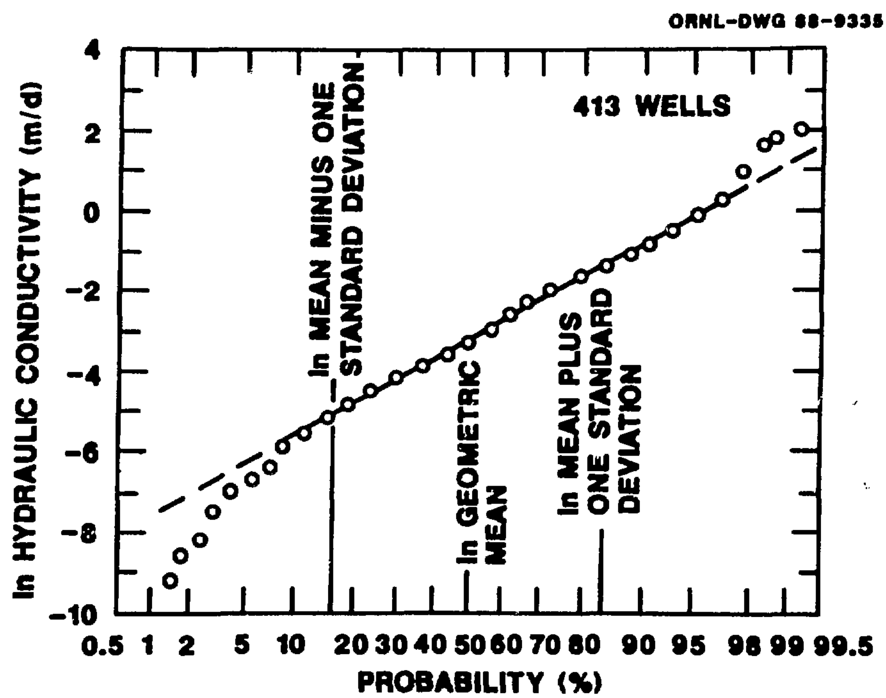

Fig. 3. Cumulative probability graph of hydraulic conductivity values determined by slug tests.

results do not contradict the interpretation of the probability graph. Cavity wells have hydraulic conductivities that are not much different than those of wells in regolith and fractured rock.

The coarse detrital material reported as fill in some cavities and the reported washing away of sand during construction of a few wells suggest large groundwater velocities in at least a few locations. A velocity of about 40 cm/s (3.5 km/d) is required to move sand with a particle diameter of 0.2-1 mm (Gregory and Walling 1973, pp. 238-239). One tracer test in the Knox Group, as mentioned previously, showed a water velocity of about 200-300 m/d between a swallow hole and a discharge point farther downstream. Another tracer test in the Chickamauga Group showed a groundwater velocity of about 20-80 m/d between an excavated cavity in limestone and a sump in a reactor building at ORNL. In contrast, low water velocities are indicated by the range of hydraulic conductivity values and by the hydraulic gradients that have been measured in the shallow aquifers. Velocity can be calculated by a form of Darcy's law:

$$\underline{V} = \underline{Ki} ,$$

where $\underline{V}$ is velocity, $\underline{K}$ is hydraulic conductivity, and $\underline{i}$ is hydraulic gradient. Typical lateral gradients in the study area are 0.005-0.05; if the gradient is 0.05, groundwater velocity near the cavity well that has the largest hydraulic conductivity (7.6 m/d) is only 0.38 m/d.

The contradictory evidence on groundwater velocities cannot be adequately explained at present. Parts of the flow paths for the two tracer tests were above the water table, but this fact explains neither the presence of cavities and coarse detritus below the water table nor the occurrence of large springs (McMaster 1967, pp. 19, 22, 25) near the base of ridges, especially those underlain by the Knox Group. It is possible that nearly all cavities are remnants of fossil flow paths. Terrace gravel is a common constituent of regolith near land surface, and cavities might have formed during the same period of geologic time that transported and rounded this gravel. It is clear that the hydraulic conductivities of tested cavities are about the same as those for water-producing fractures. It is hypothesized that any rapid transport of pollutants by groundwater is more likely to occur above the water table than below. It is also hypothesized that any rapid movement below the water table is more likely near the base of ridges in the Knox Group than in other topographic settings and geologic units, where rapid groundwater movement is rare in time, space, or both.

CONCLUSIONS

Cavities in the ORNL area have been reported only in rocks with limy layers, and the cavities are presumed to occur in these layers. An exception is the occurrence of five cavities in regolith, just above top of bedrock; these openings are a form of piping. Bedrock cavities originate by solution, which slowly enlarges fractures in the rocks. However, the larger cavities have developed mainly by abrasion and upward stoping. Open cavities are apparently are underlaid by a wedge of detritus, which is thicker than the open section. Thus, most cavities intercepted by wells are filled; the fill material ranges from clay to sand, gravel, and pebbles or cobbles.

Analysis of the number, size, depth, and spatial frequency of cavities in the study area shows both differences and similarities among the geologic units. Cavities in the Knox Group have more distinctive characteristics than cavities in any of the other units. Thus, geometric mean depth of cavities, lateral spatial frequency, and vertical spatial frequency are larger in the Knox Group than in the Rome Formation, the Conasauga Group, and the Chickamauga Group. Also, multiple cavities at any location are more likely in the Knox and Conasauga Groups, and the geometric mean heights of cavities in the Rome Formation, the Knox Group, and the Chickamauga Group are almost twice as large as mean cavity height in the Conasauga Group.

The similarities of cavity parameter values in two or more geologic units are as important as differences between units. Differences are probably caused by factors such as lithology, thickness of rock layers, and the spatial frequency of fractures in these layers. Other factors may explain the similarity of some parameter values, and these other factors are the same over large areas regardless of the underlying geologic unit. Cavities presumably occur at locations where there are or have been large flows of groundwater; factors that can produce large groundwater flows include relatively large infiltration rates, recharge amounts, and water-storage capacities, as was pointed out by McMaster and Waller (1965, pp. 6-8, 11). However, large flows of groundwater also require a convergence of flow paths and a point of discharge at a spring. The factors that cause convergence of flow paths may include contrasts in vertical versus lateral permeability and the lateral hydraulic gradients along optional flow paths.

Slug tests on 25 wells that intercept cavities show hydraulic conductivity values similar to those for wells completed in regolith and fractured rock; these hydraulic conductivity values indicate only slow rates of groundwater movement (less than 0.38 m/d). In contrast, two tracer tests on cavity systems have shown velocities of 20-300 m/d, and springs indicate relatively large rates of groundwater movement near these points of discharge. Also, large water velocities would be required to transport the coarse detrital fill in some cavities. These contradictions cannot be adequately explained. However, rapid groundwater movement may be much more common above the water table than below. Below the water table, at present, rapid groundwater flows may be rare except near the larger springs. Additional research is needed on the potential for rapid transport of pollutants above the water table, especially during periods of intense precipitation. Below the water table, pollutant transport probably can be modeled as slow seepage regardless of aquifer material and mode of groundwater occurrence in regolith, fractured bedrock, and cavities.

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