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Assessing flow systems in carbonate aquifers using scale effects in hydraulic conductivity

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Abstract Counter to intuition, small-scale measurements of hydraulic conductivity do not average to regional values. Instead, mean hydraulic conductivity increases with measurement scale up to a critical distance termed the range, beyond which a constant regional value prevails. Likewise, variance in log hydraulic conductivity increases with separation distance between measurement points as the spatial correlation decreases. As dissolution proceeds in carbonate aquifers, heterogeneity and the volume necessary for an equivalent homogeneous medium (EHM) both increase. As these variables increase, the range of scale increase in both mean hydraulic conductivity and variance increases proportionately. Consequently, the range in scale effects is a reliable measure of the degree of secondary dissolution. By correlating the numeric value of range with independently measured hydraulic properties, the prevalent type of flow system, diffuse, mixed or conduit can be determined.

Key words Carbonate aquifers · Diffuse flow · Conduit flow · Karst · Scale effects

Introduction

The difference between karst and nonkarst behavior in carbonate aquifers can be an important but subtle distinction. The distinction is important because concentrated recharge and rapid transmittal of water make karst aquifers inherently susceptible to chemical degradation. It is nevertheless sometimes a difficult distinction to make. Carbonate aquifers have pore systems in a continuum between granular and large conduits. Moreover, some carbonates have little or no surficial geomorphic expression of karst but may yet have significant solution openings at depth.

Analysis of karst aquifers with conduit flow is complicated by non-Darcian behavior with channeling, turbulent flow, and complex flow paths. Predicted solute migration paths and velocities may be seriously flawed if normal monitoring techniques and Darcian analyses are used. The crux of the issue then is how to place a given carbonate aquifer into its proper position in the spectrum of pore types and resultant hydraulic behavior.

Karst indicators

Quinlan and others (1991) summarized the primary geomorphic features of karst terranes that are reliable indicators of conduit-type groundwater flow. In a carbonate terrane with any of the following—sinkholes, dry valleys, sinking streams, or karren—the aquifer is karstic, and conduit flow will prevail or at least be present. However, the premise and conclusion cannot be reversed. Absence of such surficial features does not disprove conduit flow, although that possibility may be likely. Therefore, hydraulic criteria are also necessary to evaluate the occurrence of conduits.

Obviously, one of the most important questions is how much enlargement of joints is necessary to constitute a conduit. This is a contentious issue with answers ranging from subjective evaluation of "significant enlargement" to precise numeric values of dissolution widths. A premise of this paper is that the boundary should be placed at apertures that allow the beginning of turbulent flow under common hydraulic gradients in hydraulically connected joints/openings.

White (1988) combined the Darcy-Weisbach equation with empirically derived values for surface roughness and friction factor to produce a graph showing the transition from laminar to turbulent flow for various hydraulic radii and gradients. Typically, regional hydraulic gradients vary between 0.01 and 0.001, and for this range the transition

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to turbulent flow would begin in joints with apertures between approximately 0.5 and 0.7 cm. For the same range in gradient, flow would be fully turbulent in joints with apertures greater than 1–4 cm. Consequently, aquifers with joints less than 0.5 cm wide would have dominantly diffuse-type flow, meaning that Darcian conditions would prevail.

Unfortunately, without direct observation of numerous exposures or rock cores, joint widths cannot be evaluated. Therefore, researchers have sought other hydrologic criteria that are less expensive and easier to measure, but still indicative of conduit flow. Shuster and White (1971) first correlated the type of flow (diffuse or conduit) to variability in chemistry and flow parameters. Of all factors, turbid flow is the most reliably associated with geomorphic karst, and it clearly indicates conduit flow. Variations in carbonate phase concentrations are also reliable criteria. Diffuse flow systems have coefficients of variation (CVs; standard deviation divided by mean, expressed as percentage) of hardness and bicarbonate of < 5.0. Conduit systems, in contrast, have CVs > 10.0 (Table 1, Fig. 1).

Quinlan and Ewers (1985) and Quinlan and others (1991) summarized several additional criteria for distinguishing conduit flow. Because of rapid recharge and transit, water-level hydrographs in aquifers with conduit flow are highly erratic, with fluctuations up to 30 m recorded in mature karst terranes. Due to short residence times, hardness in conduit systems is typically < 100 ppm, while concentrations in aquifers with slower diffuse flow are typically > 300 ppm. Similarly, springs fed by conduit systems are flashier, with peak-to-base-flow ratios of $> 10{:}1$. In contrast, springs fed by diffuse flow have ratios $< 3{:}1$. These various criteria are summarized in Table 2.

One of the vexing problems with existing criteria is that their application requires long-term monitoring and/or intense geotechnical investigation. Moreover, the monitoring would often have to be done over wide regions and on property that is inaccessible. The following section introduces a new methodology for evaluating the type of flow in carbonates. This method has a distinct advantage in that it can be completed with common hydrogeologic techniques and data collected over relatively small areas.

Table 1 Classification of flow and vulnerability of carbonate aquifers[a]

Diffuse ——→ CV		Mixed ——→	Conduit CV		
n	Range	Avg	n	Range	Avg
6	0.96–10.2	3.6	7	9.1–23.2	18.6

Slightly sensitive → Moderately sensitive → Very sensitive → Hypersensitive

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[a] CV designates coefficient of variation in concentration of major carbonate phases. Equation between the flow type (top) (White 1969) and vulnerability (bottom) (Quinlan and others 1991) is approximate only, based on author's experience and judgment. CV values characteristic of flow types are from Shuster and White (1971)

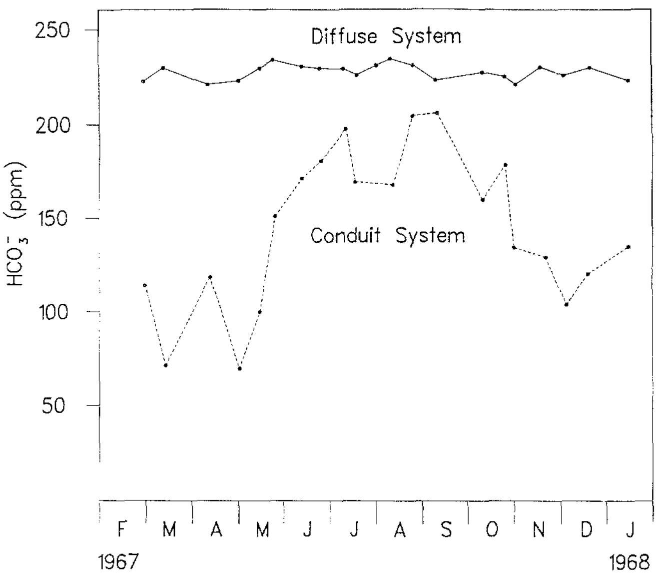

Fig. 1 Variation in bicarbonate concentration for diffuse and conduit flow systems. Variations were measured at spring discharge points. Modified from Shuster and White (1971)

Table 2 Geomorphic and hydraulic parameters for distinguishing between diffuse and conduit flow[a]

Parameter	Diffuse ——→	Mixed ——→	Conduit
Geomorphic landforms	lacks geomorphic karst		sinkholes, karren, dry valleys, sinking streams
Turbidity	none		high
CV	< 5.0		> 10.0
Hardness (ppm)	> 300		< 100
Groundwater level fluctuations (m)			up to 30
Peak-to-base-flow ratio (Springs)	$< 3{:}1$		$> 10{:}1$
Joint apertures (cm)	< 0.5		> 1.0

[a] Mixed flow conditions would have intermediate values. Based on Shuster and White (1971), Quinlan and Ewers (1985), and Quinlan and others (1991)

The initial premise is that in karst aquifers with conduit flow, hydraulic properties are extremely sensitive to the scale of measurement, whereas in nonkarst aquifers they are not. Furthermore, the degree of sensitivity to measurement scale is proportional to the degree of karstification and aquifer vulnerability. This premise is verified by evaluating various carbonate units in different stages of dissolution using the geomorphic and hydrologic criteria of Table 2. The extended analysis will show that mean hydraulic conductivity and variance in log hydraulic conductivity increase indefinitely with measurement scale in aquifers with conduit flow. In contrast, such increases are limited in range over small distances where conduits are absent. Furthermore, the range of scale increase is proportional to the degree of dissolution, and thus provides a convenient quantitative measure of the degree of karstification.

Scale effects

Different techniques of hydraulic conductivity measurement test different volumes of aquifer. For this paper, tests are grouped into three categories: local (slug and pressure-injection tests) with radius of influence (R_i) < 10 m, intermediate (pumping tests) with R_i between 10 and 1000 m, and regional (digital model calibration and baseflow recession analysis) with R_i > 1000 m. Numerical values of R_i for regional tests can be estimated simply as the square root of the study area. The R_i for the intermediate pumping tests are estimated using a form of the Cooper-Jacob distance-drawdown equation:

$$R_i^2 = \frac{2.25\,Tt}{S} \qquad (1)$$

where: T is the transmissivity (measured hydraulic conductivity (L^2/t) multiplied by thickness of tested interval), t is the time duration of test (t), and S is the storage coefficient (dimensionless).

Thus, reasonable estimates of the storage coefficient are required. Alternatively, the R_i can be determined directly from a semilog distance-drawdown plot, if multiple observation wells are used. Finally, the R_i of the local-scale pressure-injection and slug tests can also be estimated using equation 1, or the slug test value can be estimated independently using either the type curves or regression equations of Guyonnet and others (1993).

Intuitively one would expect that regional tests of hydraulic conductivity would be the most consistent and that smaller-scale tests would be more erratic, with both higher and lower values. Presumably the erratic values from the small-scale tests would average to regional values if enough tests were performed, but this seems to be incorrect. Mean hydraulic conductivity tends to increase with measurement scale even if hundreds of small-scale tests are averaged (Bradbury and Muldoon 1990; Rovey and Cherkauer 1994c). Rovey and Cherkauer (1994c) further showed that the magnitude of the scale increase varies with the nature of the medium.

1. In unconsolidated granular and jointed clay-rich media, hydraulic conductivity increases with scale to a test radius (range) between approximately 4 and 15 m (Fig. 2A).
2. In carbonates, the range of scale increase depends on the degree of dissolution. In mature karst aquifers with conduit flow the range is >1000 m (Fig. 2B) and will generally exceed the maximum dimensions of the study area.
3. Variance of log hydraulic conductivity, measured at successively greater separation (lag) distances, increases in a manner similar to hydraulic conductivity (Fig. 2C). Where both have been measured at the same site, the ranges in the two parameters are nearly identical.

The correlation between the increase in mean hydraulic conductivity and variance is explained as follows: If measurements at a given scale do not test at the scale of an equivalent homogeneous medium (EHM), they will not reach the maximum range in hydraulic conductivity.

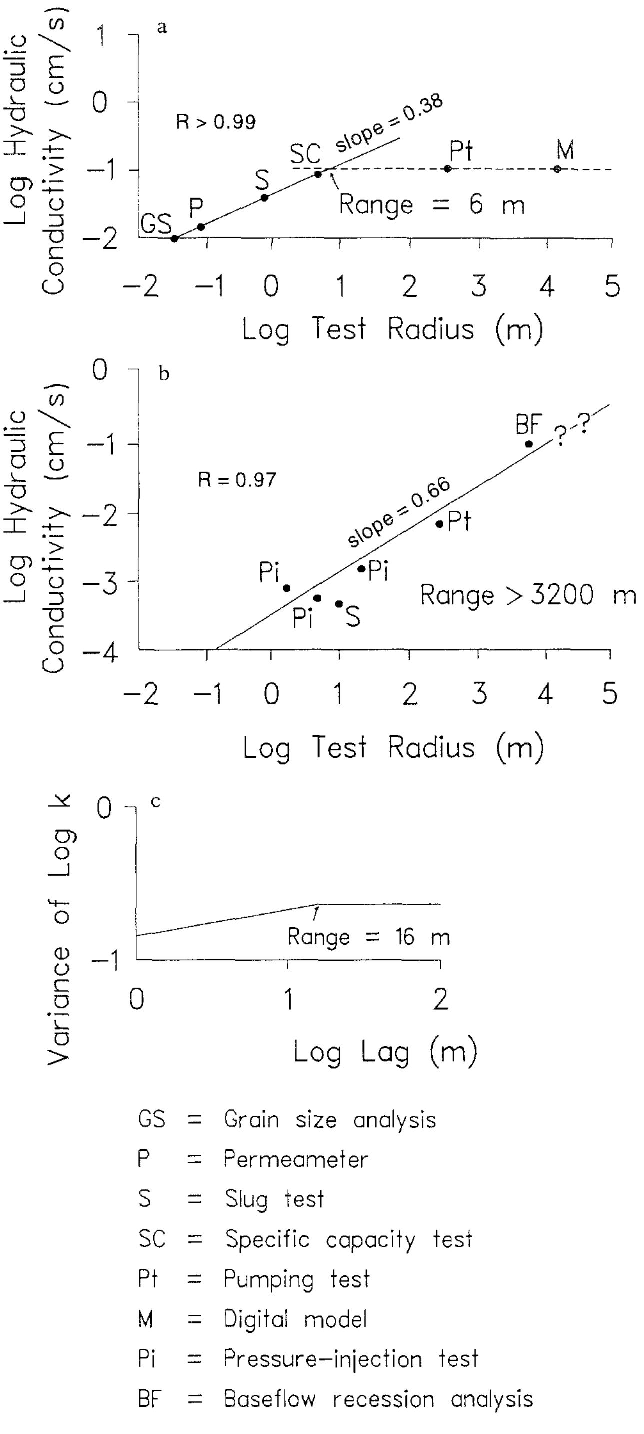

Fig. 2a–c Dependence of hydraulic parameters on measurement scale: **a** Geometric mean hydraulic conductivity of an outwash sand, central Wisconsin. Source: Rovey and Cherkauer (1994c) after Bradbury and Muldoon (1990). The range is the radius of influence, beyond which mean hydraulic conductivity is approximately constant. **b** Hydraulic conductivity in a karstic limestone. Modified from Sauter (1991) using field test values only. The hydraulic conductivities shown are the midpoints of the "common range" in the original. **c** Variance of log hydraulic conductivity in outwash sand versus separation distance (lag) between measurement points. Data are from Cape Cod, Massachussets, taken from the modeled isotropic variogram with nugget effect using flowmeter data in Hess and others (1992). See Isaaks and Srivastava (1989) for techniques and computational formulas for variogram construction

Therefore, measurements at greater separation (lag) distances will reach a greater range in hydraulic conductivity and return greater values of variance until the EHM scale is reached.

Under certain conditions which apparently prevail in geologic media, the increase in variance will also correlate with an increase in mean hydraulic conductivity. Those conditions are that the chances of a small-scale test being influenced by an extremely rare high-conductivity heterogeneity are disproportionately small relative to the degree with which that heterogeneity raises regional conductivity. Thus, as test radius and variance increase, higher conductivity values in the ever-rarer heterogeneities are averaged into and increasingly dominate the test measurements until an EHM is reached. It follows that if different media require different scales to reach an EHM, then the range in scale effects will vary.

White (1988), Ford and Williams (1989), and Smart and others (1991) have noted that karst aquifers have larger possible ranges in hydraulic conductivity than other media. Hydraulic conductivity may range from $<10^{-8}$ cm/s in the matrix of fine-grained, well-cemented carbonates to "practical infinity" within large conduits.

Karst flow systems also tend to be hierarchic (Sauter 1991; Teutsch and Sauter 1991). As scale increases, larger but rarer conduits increasingly dominate the percentage of groundwater flow. Therefore, the greater degree of heterogeneity and its hierarchic spatial distribution in karst aquifers should cause scale increases in mean hydraulic conductivity and variance distinctly greater than in other types of media.

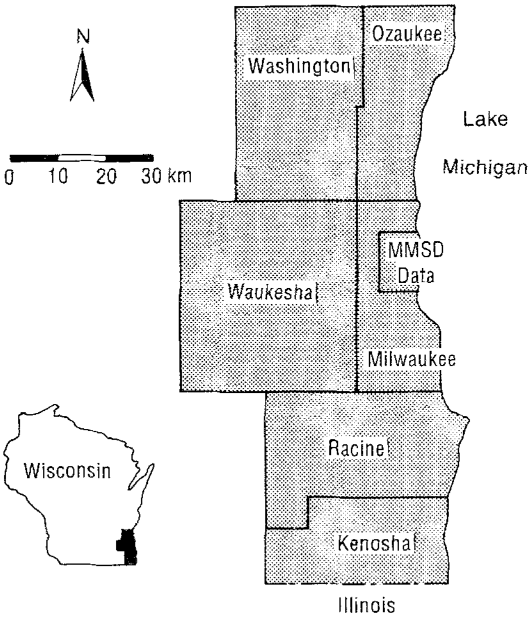

Fig. 3 Location of dolomite aquifer, southeast Wisconsin

Site investigations

Southeast Wisconsin

The dolomite aquifer of southeast Wisconsin (Fig. 3) is one of the most intensely studied aquifers of the midcontinent. Numerous hydraulic conductivity measurements have been made within various stratigraphic units using slug, pressure-injection, and single- and multiwell pumping tests and finally with calibrated digital models.

Rovey and Cherkauer (1994a,b) divided the aquifer into nine major hydrostratigraphic units by correlating hydraulic conductivity from pressure-injection tests with stratigraphic intervals (Fig. 4). With several minor exceptions not relevant here, these units have regionally consistent hydraulic conductivities, based on identical measurement techniques. However, each unit has a systematic increase in mean conductivity between local and regional test methods.

In southeast Wisconsin the dolomite aquifer has no geomorphic expression of karst. There are also no bedrock springs. Groundwater naturally discharges to Lake Michi-

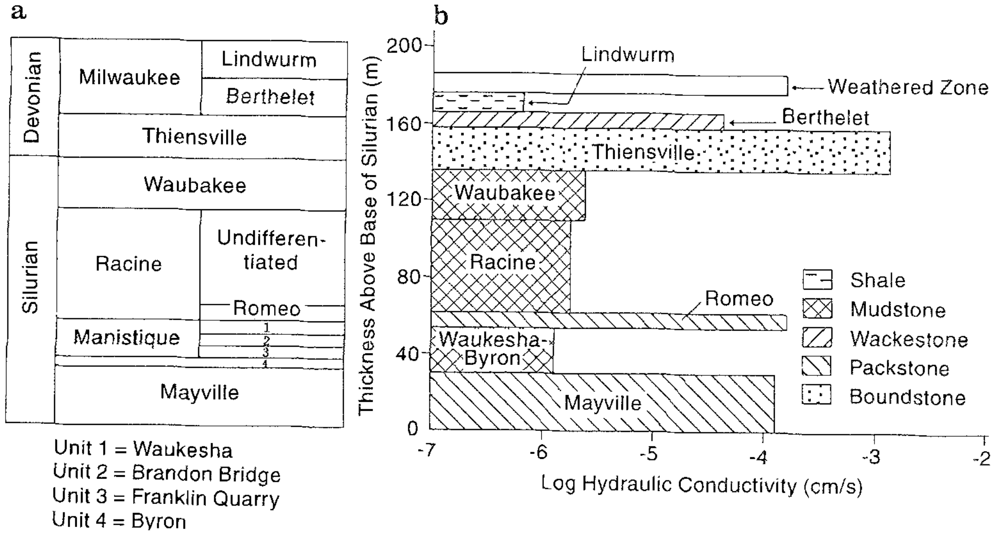

Fig. 4a,b Stratigraphy and hydrostratigraphy of dolomite aquifer, southeast Wisconsin: **a** Stratigraphy. Primary subdivision is at the formation level. Member subdivisions are informal except within the Milwaukee Formation. **b** Geometric mean hydraulic conductivity measured by pressure-injection tests. Each bar is the average thickness of a particular unit and extends to the geometric mean hydraulic conductivity. Patterns depict the dominant texture of each unit. Based on Rovey and Cherkauer (1994a) gan in patterns consistent with diffuse-type flow, but not conduit. Discharge rates, as measured with seepage meters at numerous sites, decrease exponentially away from the shoreline or from high-conductivity anomalies in the lake bed sediment (Cherkauer and Nader 1989; Cherkauer and Mikulic 1992). These patterns are typical of porous media and Darcian conditions (McBride and Pfannkuch 1975), not karstic behavior where discharge points would be controlled by the location of conduits.

Around the perimeters of eight active local quarries (approximately 20 km of exposure), there are no conduits or karren. The upper 6 m of rock, however, do contain some dissolution effects, such as numerous small vugs and nominal (< 0.5 cm) solutional widening along joints. Additionally, several minor paleoweathering surfaces are present within the Thiensville Formation. Therefore, if any rare karst effects are present, they would most likely be within the discrete upper weathered zone and secondarily within the Thiensville.

The Milwaukee Metropolitan Sewerage District (MMSD) has also performed numerous geotechnical and hydraulic tests for the design of several deep sewer tunnels. MMSD (1984) logged joint apertures for approximately 1900 m of core from 38 boreholes through the aquifer. Of 2451 logged joints (fractures and bedding plane breaks) four or 0.16% had apertures >0.5 cm. Additionally, a bit drop of approximately 25 cm was recorded within the Thiensville at one location. For comparison, at a site with surficial karst, an average 35% of the joints to a 240 m depth exceeded 0.5 cm (Degirmenci 1993).

Fig. 5a–c Water levels and bicarbonate concentrations in the dolomite aquifer, southeast Wisconsin. Raw data are from MMSD (1984) and unpublished

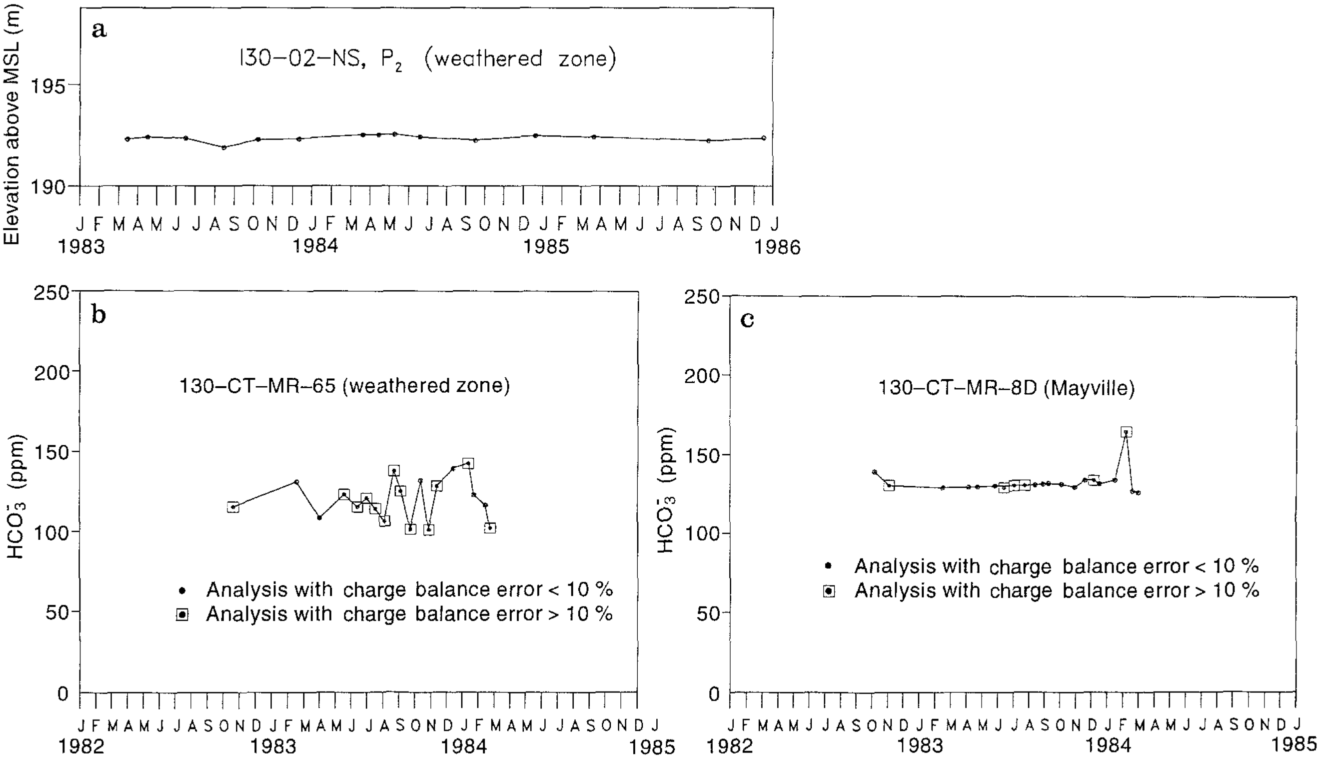

Table 3 Coefficient of variation (CV) for bicarbonate concentrations in monitoring wells in the dolomite aquifer[a]

Wells below weathered zone					Weathered zone				
Well No. and stratigraphic unit	*n*	*x*	*s*	CV	Well number	*n*	*x*	*s*	CV
1-D (Racine)	9	133	3.5	2.7	1-S	11	125	3.6	2.9
4-D (Waubakee)	13	183	6.2	3.4	2-S	17	333	15.7	4.7
6-D (Waukesha)	9	238	5.7	2.4	3-D	5	174	29.0	16.5
7-D (Mayville)	12	232	16.2	6.9	3-S	15	243	22.3	9.2
8-D (Mayville)	16	132	3.3	2.5	4-S	10	279	19.2	6.9
			Avg. =	3.6	5-S	13	212	14.6	6.9
					6-S	6	124	11.1	7.9
					7-S	7	378	28.6	7.6
					8-S	9	144	10.5	7.3
								Avg. =	7.8

[a] "*n*" denotes number of analyses; "*x*" arithmetic mean, "s" standard deviation. Statistics are calculated using only those analyses with charge balance errors <10%. Raw data are from MMSD (1984)

Table 4 Summary of geomorphic and hydraulic parameters of aquifers discussed in text[a]

	Dolomite aquifer, southeast Wisconsin[b]	Burlington limestone, Weldon Spring, Missouri[c]	Swabian Alb[d]
Geomorphic			
Sinkholes	Absent	Present	Present
Karren	Absent	—	—
Dry valleys	Absent	Absent	—
Sinking streams	Absent	Present	Present
Caves	Absent	Present	Present
Hydraulic			
Turbidity	None	Present	Present
CV	7.8 (weathered zone); 3.6 (below weathered zone)	—	—
Hardness (ppm)	375 ppm	—	—
Groundwater fluctuation (m)	<1	—	10–30
Peak-to-base-flow ratio (springs)	No springs	50:1	>20:1
Joint apertures >0.5 cm (%)	0.16	Many	—
Measured groundwater velocity (m/d)	1	1000	4800

[a] Dashes indicate that no data are available for that particular parameter

[b] MMSD (1981, 1984, and unpublished)

[c] (Kleeschulte and Emmett (1991), Garstang (1991), Price (1991), and Carman (1991)

[d] Teutsch and Sauter (1991) and Sauter (1991)

Considering the low frequency of enlarged joints in the dolomite aquifer at this location, it is unlikely that any with significant solutional widening would be hydraulically connected. This conclusion is consistent with unpublished field notes taken during construction of the actual sewerage tunnels. In rare instances, workers recorded measurable, but rapidly declining, flows of water into the tunnels from discrete joints, possibly solutionally widened. However, the declining flow rates would indicate the lack of hydraulic connection with any other enlarged joints.

The MMSD has also conducted several tracer tests

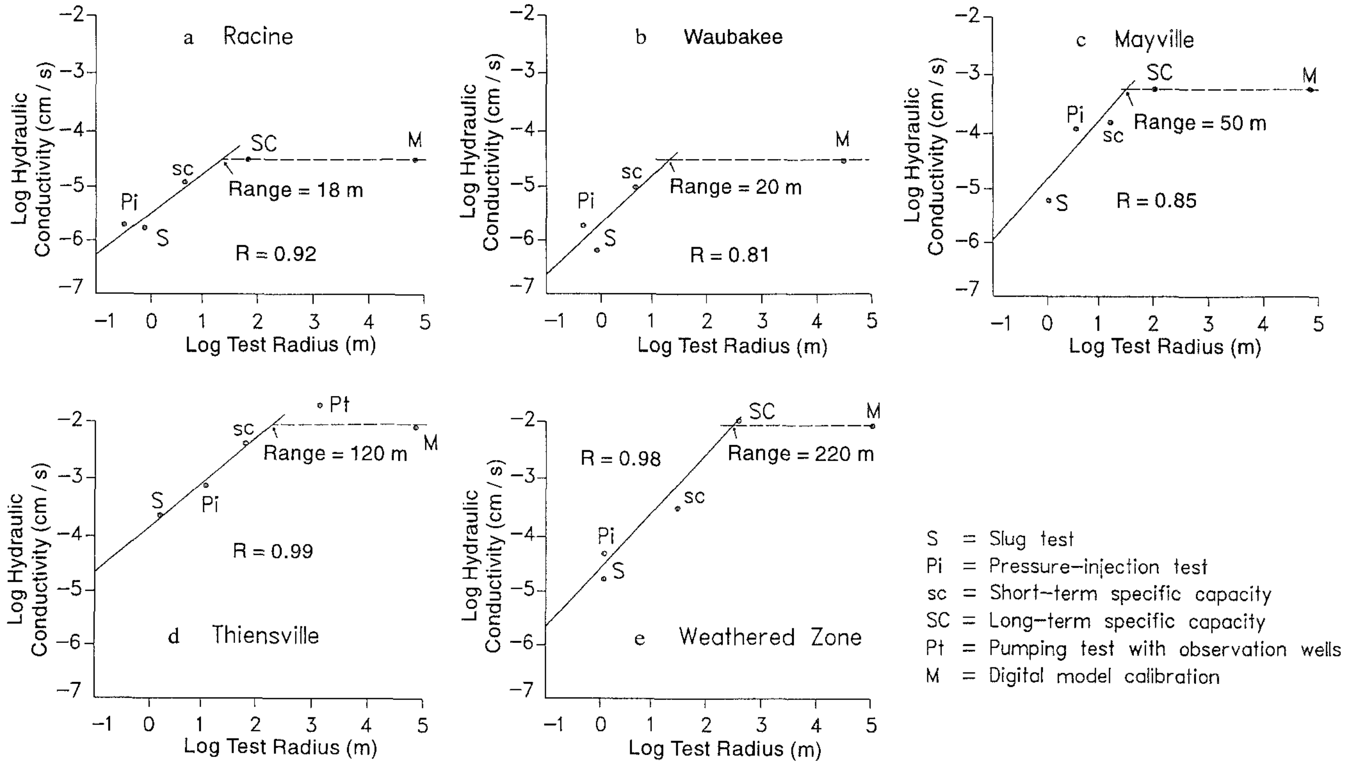

Fig. 6a–e Relation between geometric mean hydraulic conductivity and effective test radius, dolomite aquifer. Solid lines are linear regressions between three or more points; dashed lines are fit by hand. The measured range listed is the test radius beyond which hydraulic conductivity is approximately constant. See Rovey and Cherkauer (1994c) for raw data and discussion of test methods

and monitored water levels and chemical parameters over several years. The measured velocities are low and, when expressed in terms of the regional hydraulic gradient, would be approximately 1 m/d. Water level hydrographs occasionally do have wide fluctuations (up to 10 m), but only for wells near industrial centers where the aquifer is heavily but intermittently pumped. Wells away from pumping centers generally have < 1 m variation over two-year monitoring periods (Fig. 5A). Moreover, the groundwater is generally hard, averaging 375 ppm, and the concentration of carbonate phases is relatively constant within a given monitoring well. Wells below the weathered zone have an average CV in bicarbonate concentrations of 3.6 (Table 3, Fig. 5C) indicating diffuse flow. Wells in the upper weathered zone have higher CVs, averaging 7.8 (Table 3, Fig. 5B). The greater variance is consistent with the observed solutional effects in the weathered zone and is characteristic of the mixed flow category (Tables 1 and 2).

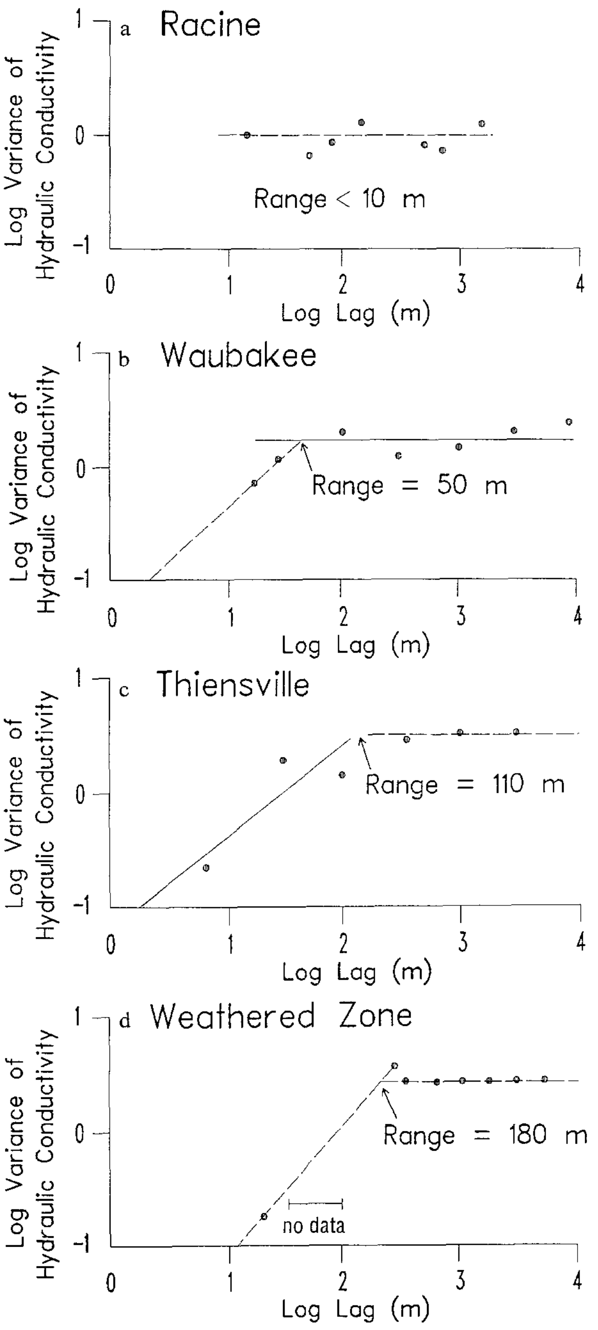

Fig. 7a–d Hydraulic conductivity variograms, dolomite aquifer, Wisconsin. Graphs show the (semi)variance in log hydraulic conductivity for different lags or separation distances between measurement points. Variograms are generated using local-scale pressure-injection tests. Solid lines are linear regressions between three or more points; dashed lines are fit by hand. The measured range listed is the separation distance beyond which variance is approximately constant, and therefore, the scale at which the aquifer is statistically homogeneous. Lag tolerance is 0.5 log units. See Rovey and Cherkauer (1994c) for further discussion

Based on both geomorphic and hydraulic criteria (Table 4), it is clear that the majority of the aquifer is within the diffuse flow category. The upper 6 m, however, and possibly portions of the Thiensville, have some characteristics of mixed flow. Qualitative observations of the pore systems prevailing within the various units are now used to further subdivide the units along the dissolution continuum and to correlate the degree of dissolution with the range of scale effects.

The relationship between hydraulic conductivity and scale of measurement is plotted on log-log coordinates for units that have at least four independent methods of measurement (Fig. 6). The range over which hydraulic conductivity increases varies considerably, but systematically, among units. Hydraulic conductivity in the Waubakee and Racine Formations is controlled by unenlarged joints and increases with measurement scale to approximately 20 m. The Thiensville and Mayville Formations both contain complex pore systems. The Mayville contains both intergranular and secondary porosity as interconnected solution-enlarged molds of fossil grains. The Thiensville also contains intergranular porosity but has horizons of nonselective dissolution beneath several minor paleoweathering profiles. Hydraulic conductivity increases with scale to 50 and 125 m in the Mayville and Thiensville, respectively, coinciding with the greater degrees of dissolution effects. The weathered zone, with the greatest degree of dissolution, has the greatest range of scale effects, 220 m. Summarizing, the range of scale increase correlates precisely with the extent of secondary dissolution porosity.

Variograms (plots of variance, technically semivariance) in log hydraulic conductivity versus lag distance, are also shown for four units with an adequate number of tests (Fig. 7). There is a high correlation between the range of the variograms and the earlier plots of hydraulic conductivity. Like mean hydraulic conductivity, variance in log hydraulic conductivity increases to greater lag distances in units with greater dissolution effects.

Weldon Spring, Missouri

Data from a mature karstic aquifer are available from Weldon Spring, Missouri (Fig. 8, Table 4) (Price 1991; Carman 1991; MK-Ferguson and Jacobs 1990; Kleeschulte

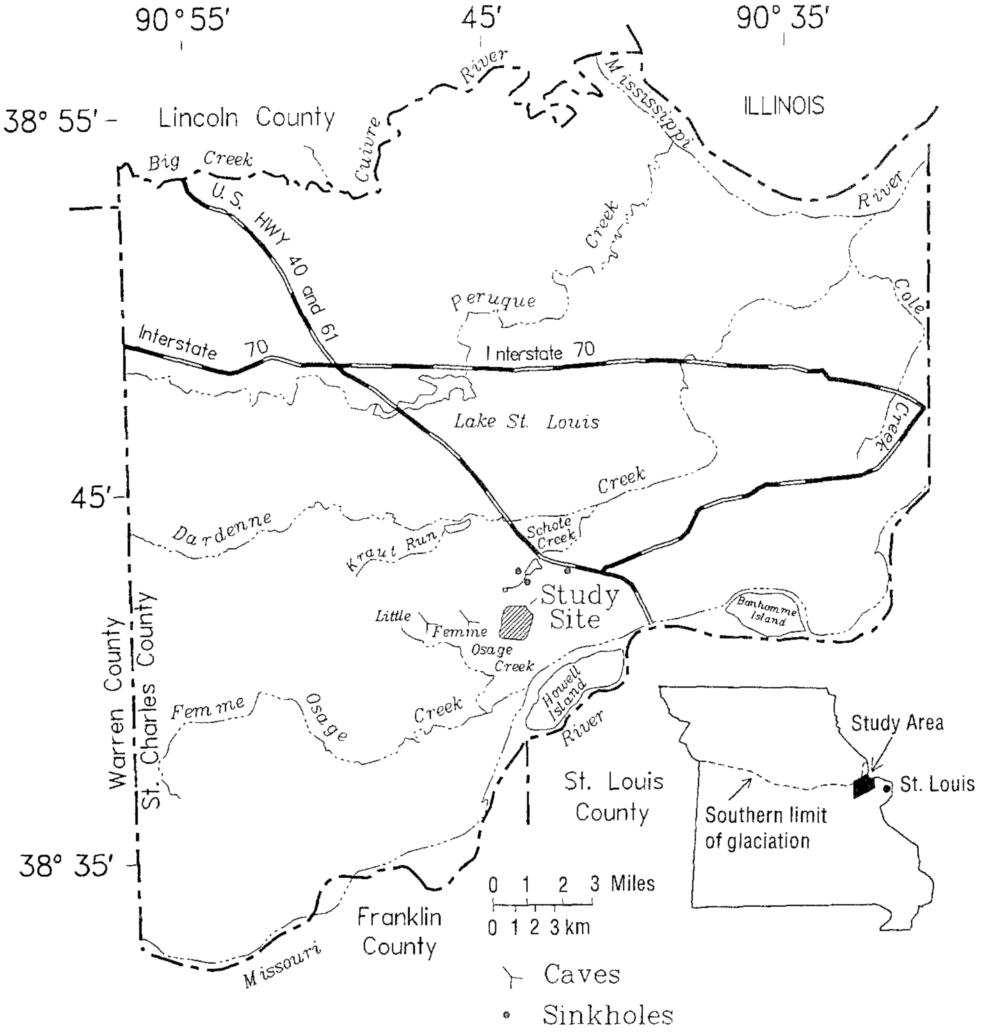

Fig. 8 Weldon Spring site, east-central Missouri. Adopted from Kleeshulte and Emmett (1987) and Garstang (1991)

and Emmett 1987). The site is located in east-central Missouri where the Burlington Formation, a tightly cemented crinoidal grainstone, is at the ground surface. The Burlington is particularly susceptible to karstification, and wherever it is exposed in Missouri there are karst features and cave networks.

Geomorphically, the site is within several kilometers of several large sinkholes, numerous springs, and two known cave systems (Garstang 1991). Dye traces have confirmed conduit connections between local streams, with recorded velocities of approximately 1000 m/d, assuming straight-line travel paths (Price 1991).

Other hydraulic data are consistent with the presence of conduit flow. During monitor-well installations, drops of the drill bit up to 1.5 m were recorded, implying conduits (MK-Ferguson and Jacobs 1990). Finally, the ratio of peak to base flow at a nearby spring system is approximately 50:1 (Kleeschulte and Emmett 1987).

As shown in Fig. 9, both mean hydraulic conductivity and its variance increase beyond the maximum scale of investigation, more than 1000 m. This minimum range in scale effects is still much greater than those in the dolomite aquifer in southeast Wisconsin where the rock has only nominal solution effects.

Swabian Alb

Data from the final aquifer are summarized from Sauter (1991) and Teutsch and Sauter (1991) (Table 4). The aquifer is comprised of several Upper Jurassic limestones in the Swabian Alb of southwest Germany, an area well known for karst features, including sinkholes, springs, and caves. Some springs have turbid discharge with a peak-to-base-flow ratio of >20 and groundwater level fluctuations between approximately 10 and 30 m. Groundwater tracer velocities up to 4800 m/d have also been measured.

Results from this karstic aquifer were previously presented as Fig. 2B. Like the Weldon Spring site, mean hydraulic conductivity increases beyond the maximum scale of investigation, in this case approximately 3200 m.

Summary and applications

The range in scale effects within various carbonates is summarized in Table 5. The Racine and Waubakee formations are jointed but have insignificant dissolutional poros-

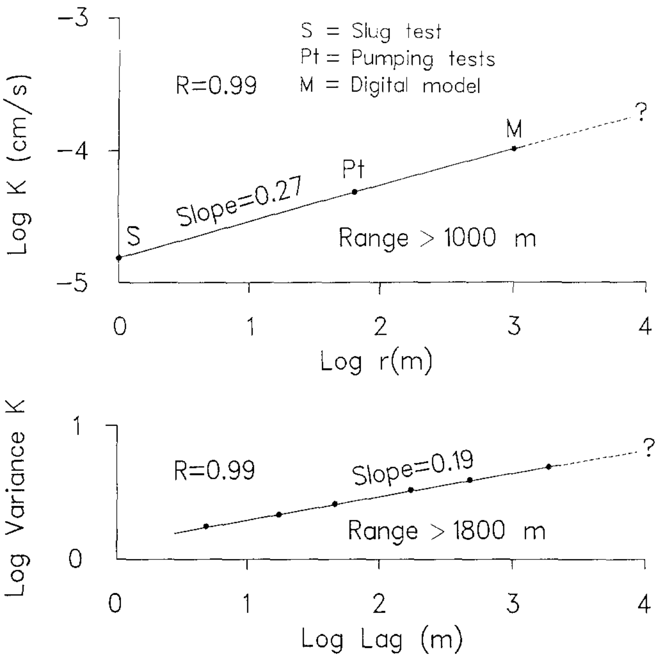

Fig. 9 Scale effects in mature karst aquifer at Weldon Spring, Missouri. Hydraulic conductivity plot (top) is generated using pumping test and model value from MK-Ferguson and Jacobs (1990) and Durham (1991). Slug test data are calculated from raw field data supplied by MK-Ferguson Company. The model conductivity is the area-weighted average of values from three separate modeled zones. Variogram (bottom) is generated from slug test values with a lag tolerance of 0.5 log units

ity. Hydraulic conductivity increases with R_i to about 20 m, while variance in log hydraulic conductivity is slightly more erratic, but much less than 100 m. The Mayville Formation has significant secondary porosity, but it is fabric selective. Fossil grains have been preferentially dissolved, producing enlarged and interconnected pore space, but joints are relatively unaffected. Too few tests have been completed to measure the range in variance, but mean hydraulic conductivity increases with R_i to approximately 50 m, a significantly greater range than in the Racine and Waubakee. The Thiensville Formation and upper weathered zone both have nonselective dissolution along joints associated with both modern and paleoexposure surfaces. These units in turn have even greater ranges in scale effects, approximately 100–200 m. Finally, the two carbonate units with observed conduit flow have the largest ranges, exceeding 1000 m.

The pattern is very clear: the range of increase in both mean hydraulic conductivity and variance in log hydraulic conductivity increases with the degree of dissolution. The range in scale effects for carbonates with purely diffuse flow is fairly well constrained at values less than 100 m. In the range 100–200 m, the aquifer may begin to exhibit characteristics of mixed flow, with localized channeling superimposed on a predominantly diffuse system. The boundary to fully turbulent conduit flow is not as well constrained. Pending additional data, 500 m is suggested as an initial approximation to this boundary.

These results are easily applied to site investigations even without expensive pumping tests or data-intensive modeling. With foresight, economical local-scale measurements (such as slug tests) can be completed in spatial arrangements conducive to variogram construction. One important qualification is that all tests used to construct a given variogram should measure exactly equivalent hydrostratigraphic horizons. In many terranes, a discrete, highly weathered upper zone of epikarst is present above a less weathered rock. If so, tests from the two zones should not be mixed.

If more extensive data are available, the scale dependence of mean hydraulic conductivity will provide the same results or can be used as confirmation. Based on the author's experience, a minimum of four independent measurement techniques, including at least one regional measurement, are generally required for adequate definition of the response curve. In the dolomite aquifer of southeast Wisconsin, the geometric mean values of the local-scale pressure-injection tests converge to within two times the final value in 7–15 tests, depending on the stratigraphic unit. Thereafter, mean conductivity changes very little, even with 100 or more additional tests. For pumping tests, three to four measurements are necessary for the same accuracy.

If the scale increase is well bounded at distances less than 100 m, the aquifer should have a diffuse flow system and normal monitoring and analysis may be used with confidence. At the other extreme, if the range is greater than 500 m or the maximum site dimensions, conduit flow should be suspected and monitoring techniques specific for

Table 5 Range of scale effects in carbonates, arranged in order of increasing dissolution effects

	Unenlarged Joints		Soution-enlarged molds	Nominal joint enlargement		Mature karst	
	Racine	Waubakee	Mayville	Thiensville	Weathered zone	Weldon Spring	Swabian Alb
Hydraulic conductivity	18	20	50	120	220	>1000	>3200
Variance in log hydraulic conductivity	<10	50		110	180	>1800	

[a] All values given in meters

karst terranes and conduit flow (Quinlan and others 1991, Quinlan and Ewers 1985) should be used.

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