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Standard Guide for Design of Ground-Water Monitoring Systems in Karst and Fractured-Rock Aquifers[1]

This standard is issued under the fixed designation D 5717; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ϵ^1 NOTE—Paragraph 1.5 was added editorially October 1998.

INTRODUCTION

This guide for the design of ground-water monitoring systems in karst and fractured-rock aquifers promotes the design and implementation of accurate and reliable monitoring systems in those settings where the hydrogeologic characteristics depart significantly from the characteristics of porous media. Variances from government regulations that require on-site monitoring wells may often be necessary in karst or fractured-rock terranes (see 7.3) because such settings have hydrogeologic features that cannot be characterized by the porous-media approximation. This guide will promote the development of a conceptual hydrogeologic model that supports the need for the variances and aids the designer or governmental reviewer in establishing the most reliable and efficient monitoring system for such aquifers.

Many of the approaches contained in this guide may also have value in designing ground-water monitoring systems in heterogeneous and anisotropic unconsolidated and consolidated granular aquifers. The focus of this guide, however, is on unconfined karst systems where dissolution has increased secondary porosity and on other geologic settings where unconfined ground-water flow in fractures is a significant component of total ground-water flow.

1. Scope

1.1 *Justification*—This guide considers the characterization of karst and fractured-rock aquifers as an integral component of monitoring-system design. Hence, the development of a conceptual hydrogeologic model that identifies and defines the various components of the flow system is recommended prior to the design and implementation of a monitoring system.

1.2 *Methodology and Applicability*—This guide is based on recognized methods of monitoring-system design and implementation for the purpose of collecting representative ground-water data. The design guidelines are applicable to the determination of ground-water flow and contaminant transport from existing sites, assessment of proposed sites, and determination of wellhead or springhead protection areas.

1.3 *Objectives*—The objectives of this guide are to outline procedures for obtaining information on hydrogeologic characteristics and water-quality data representative of karst and fractured-rock aquifers.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Referenced Documents

2.1 *ASTM Standards:*

[1] This guide is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

Current edition approved April 15, 1995. Published June 1995.

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 5092 Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers[3]

D 5254 Practice for Minimum Set of Data Elements to Identify a Ground-Water Site[3]

3. Terminology

3.1 *Definitions:*

3.1.1 For terms not defined below, see Terminology D 653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *aliasing*—the phenomenon in which a high-frequency signal can be interpreted as a low-frequency signal or trend because the sampling was too infrequent to characterize the signal.

3.2.2 *conduit*—pipe-like opening formed and enlarged by dissolution of bedrock and that has dimensions sufficient to sustain turbulent flow under ordinary hydraulic gradients.

3.2.3 *dissolution zone*—a zone where extensive dissolution of bedrock has occurred; void size may range over several orders of magnitude.

3.2.4 *epikarst*—a zone of enhanced bedrock-dissolution immediately beneath the soil zone; characterized by storage of water in dissolutionally enlarged fractures and bedding planes, and that may be separated from the phreatic zone by a relatively waterless interval locally breached by vertical vadose flow.

3.2.5 *fractured-rock aquifer*—an aquifer in which flow of water is primarily through fractures, joints, faults, or bedding planes that have not been significantly enlarged by dissolution.

3.2.6 *karst aquifer*—an aquifer in which all or most flow of water is through one or more of the following: joints, faults, bedding planes, pores, cavities, conduits, and caves, any or all of which have been significantly enlarged by dissolution of bedrock.

3.2.7 *karst terrane*—a landscape and its subsurface characterized by flow through dissolutionally modified bedrock and characterized by a variable suite of surface landforms and subsurface features, not all of which may be present or obvious. These include: sinkholes, springs, caves, sinking streams, dissolutionally enlarged joints or bedding planes, or both, and other dissolution features. Most karsts develop in limestone or dolomite, or both, but they may also develop in gypsum, salt, carbonate-cemented sandstones, and other soluble rocks.

3.2.8 *overflow spring*—a spring that discharges generally intermittently at a ground-water stage above base flow (compare with underflow spring).

3.2.9 *rapid flow*—ground-water flow with a velocity >0.001 m/s.

3.2.10 *secondary porosity*—joints, fissures, faults, that develop after the rock was originally lithified; these features have not been modified by dissolution.

3.2.11 *sinkhole*—a topographic depression formed as a result of karst-related processes such as dissolution of bedrock, collapse of a cave roof, or flushing or collapse, or both, of soil and other sediment into a subjacent void.

3.2.12 *slow flow*—ground-water flow with a velocity <0.001 m/s.

3.2.13 *swallet*—the hole into which a surface stream sinks.

3.2.14 *tertiary porosity*—porosity caused by dissolutional enlargement of secondary porosity.

3.2.15 *tracer*—a substance added to a medium, typically water, to give it a distinctive signature that makes the medium recognizable elsewhere.

3.2.16 *underflow spring*—a spring that is at or near the lowest discharge point of a ground-water basin and that usually flows perennially (compare with overflow spring).

4. Significance and Use

4.1 *Users*—This guide will be useful to the following groups of people:

4.1.1 Designers of ground-water monitoring networks who may or may not have experience in karst or fractured-rock terranes;

4.1.2 The experienced ground-water professional who is familiar with the hydrology and geomorphology of karst terranes but has minimal familiarity with monitoring problems; and

4.1.3 Regulators who must evaluate existing or proposed monitoring for karst or fractured-rock aquifers.

4.2 *Reliable and Efficient Monitoring Systems*—A reliable and efficient monitoring system provides information relevant to one or more of the following subjects:

4.2.1 Geologic and hydrologic properties of an aquifer;

4.2.2 Distribution of hydraulic head in time and space;

4.2.3 Ground-water flow directions and rates;

4.2.4 Water quality with respect to relevant parameters; and

4.2.5 Migration direction, rate, and characteristics of a contaminant release.

4.3 *Limitations*:

4.3.1 This guide provides an overview of the methods used to characterize and monitor karst and fractured-rock aquifers. It does not address the details of these methods, field procedures, or interpretation of the data. Numerous references are included for that purpose and are considered an essential part of this guide. It is recommended that the user of this guide be familiar with the relevant material within this guide and the references cited. This guide does not address the application of ground-water flow models in the design of monitoring systems in karst or fractured-rock aquifers. The use of flow and transport mode at fractured-rock sites summarized in Ref **(1)**[4] provide a more recent comparison of fracturent and transport modeling.

4.3.2 The approaches to the design of ground-water monitoring systems suggested within this guide are the most appropriate methods for karst and fractured-rock aquifers. These methods are commonly used and are widely accepted and proven. However, other approaches or methods of ground-water monitoring which are technically sound may be substituted if justified and documented.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

[4] The boldface numbers given in parentheses refer to a list of references at the end of the text.

5. Special Characteristics of Karst and Fractured-Rock Aquifers

5.1 Karst and fractured-rock aquifers differ from granular aquifers in several ways; these differences are outlined in 5.2. Designing reliable and efficient monitoring systems requires the early development of a conceptual hydrogeologic model that adequately describes the flow and transmission characteristics of the site under investigation. Section 5.3 outlines various approaches to conceptualizing these systems and 5.4 contains subjective guidelines for determining which conceptual approach is appropriate for various settings.

5.2 *Comparison of Granular, Fractured-Rock, and Karst Aquifers*—Table 1 lists aquifer characteristics and compares the qualitative differences between granular, fractured-rock, and karst aquifers. This table represents points along a continuum. For this guide a karst aquifer is defined as an aquifer in which most flow of water is through one or more of the following: joints, faults, bedding planes, pores, cavities, conduits, and caves, any or all of which have been significantly enlarged by dissolution of bedrock (**2**). For this guide a fractured-rock aquifer is defined as an aquifer in which the flow is primarily through fractures that have not been significantly enlarged by dissolution. Fracture is "a general term for any break in rock, whether or not it causes displacement, due to mechanical failure by stress. Fractures include cracks, joints, and faults" (**3**). The following factors must be evaluated to properly characterize an aquifer's position in the continuum.

5.2.1 *Porosity*—The type of porosity is the most important difference between these three types of aquifers. All other differences in characteristics are a function of porosity. In a granular aquifer, effective porosity is primarily a consequence of depositional setting, diagenetic processes, texture, and mineral composition while in fractured-rock and karst aquifers, effective porosity is a secondary result of fractures, faults, and bedding planes. Secondary features modified by dissolution comprise tertiary porosity.

TABLE 1 Comparison of Granular, Fractured-Rock, and Karst Aquifers (3)

Aquifer Characteristics	Aquifer Type		
	Granular	Fractured Rock	Karst
Effective Porosity	Mostly primary, through intergranular pores	Mostly secondary, through joints, fractures, and bedding plane partings	Mostly tertiary (secondary porosity modified by dissolution); through pores, bedding planes, fractures, conduits, and caves
Isotropy	More isotropic	Probably anisotropic	Highly anisotropic
Homogeneity	More homogeneous	Less homogeneous	Non-homogeneous
Flow	Slow, laminar	Possibly rapid and possibly turbulent	Likely rapid and likely turbulent
Flow Predictions	Darcy's law usually applies	Darcy's law may not apply	Darcy's law rarely applies
Storage	Within saturated zone	Within saturated zone	Within both saturated zone and epikarst
Recharge	Dispersed	Primarily dispersed, with some point recharge	Ranges from almost completely dispersed- to almost completely point-recharge
Temporal Head Variation	Minimal variation	Moderate variation	Moderate to extreme variation
Temporal Water Chemistry Variation	Minimal variation	Minimal to moderate variation	Moderate to extreme variation

5.2.2 *Isotropy*—Fractured-rock and karst aquifers are typically anisotropic in three dimensions. Hydraulic conductivity can frequently range over several orders of magnitude, depending upon the direction of measurement. Ground water in anisotropic media does not usually move perpendicular to the hydraulic gradient, but at some angle to it (**4 and 5**).

5.2.3 *Homogeneity*—The variation of aquifer characteristics within the spatial limits of the aquifer is frequently large in fractured-rock and karst aquifers. Hydraulic conductivity differences of several orders of magnitude can occur over very short horizontal and vertical distances.

5.2.4 *Flow*—Flow in fractured rocks that are not significantly soluble is dependent upon the number of fractures per unit volume, their apertures, their distribution, and their degree of interconnection. Aquifers with a large number of well-connected and uniformly distributed fractures may approximate porous media. In these settings, the equations describing flow in granular media, based on Darcy's law, are sometimes applicable. Fractured-rock aquifers that have a few localized highly transmissive fractures, or fracture zones that exert a dominant control on ground-water occurrence and movement, are not accurately characterized by the porous-media approximation; they more closely resemble karst aquifers. Ground water moves through most karst aquifers predominantly through conduits formed by dissolution and fractures enlarged by dissolution that occupy a small percentage of the total rock mass. Ground-water flow in the rock mass is both intergranular and through fractures that have not been significantly modified by dissolution. Such flow is usually only a small percentage of the volume of water discharging from the aquifer, though it provides most of the storage (**6**).

5.2.4.1 It was formerly thought, after the work of Shuster and White (**7**), that conduit flow was dominant in some aquifers, and diffuse flow was dominant in others. The diffuse-flow dominated regime was thought to be characterized by low variation in hardness, turbidity, and discharge—as measured at a spring. It is now recognized that the variations of these parameters are due to the aquifer boundary conditions, such as the number of sinking stream inputs or whether the spring is an underflow or overflow spring (**8-10**).

5.2.4.2 The terms *rapid flow* and *slow flow* should be used rather than *conduit flow* and *diffuse flow*. The latter terms are ambiguous when used in reference to karst aquifers because they have been used to describe types of flow within an aquifer, types of recharge, and types of spring-flow as affected by recharge events, as well as flow hydraulics, and water chemistry. Rapid flow takes place in conduits >5 to 10 mm in diameter (**11**) where velocities generally exceed 0.001 m/s. The swallet-flow component of karst aquifers typically yields flow in conduits >0.001 m/s (**10**). Such rapid flow can also occur in open fractures. Flow in the rock matrix and through fractures that have not been significantly modified by dissolution is typically slow (<0.001 m/s). However, flow in conduits and fractures can also be slow.

5.2.5 *Storage*—In most aquifers, ground water is stored within the zone of saturation (phreatic zone); however, karst aquifers can store large volumes of ground water in a part of the unsaturated (vadose) zone known as the epikarst (subcutaneous zone) **(12-14)**. The epikarst, the uppermost portion of carbonate bedrock, commonly about 10 to 15 m thick, consists of highly-fractured and dissolved bedrock (see Fig. 1). Highly permeable vertical pathways are formed along intersections of isolated vertical fractures. The epikarst behaves as a locally saturated, sometimes perennial, storage zone that functions similarly to a leaky capillary barrier or a perched aquifer, but it is commonly not perched on a lithologic discontinuity. Flow into this zone is more rapid than flow out of it, as only limited vertical pathways transmit water downward.

5.2.6 *Recharge*—In granular aquifers, recharge tends to be areally distributed and an aquifer's response to a given recharge event tends to be damped by movement of the recharging water through the unsaturated zone. Generally there is some temporal lag between a recharge event and a resultant rise in water-table; water-table fluctuations in granular aquifers rarely range more than a few meters. By contrast, in karst and fractured-rock aquifers with minimal unlithified overburden, recharge tends to be rapid; water-levels may rise within minutes of the onset of the storm and water-table fluctuations may range up to many tens of meters. Karst and fractured-rock aquifers with thick unlithified overburden may have a long temporal lag similar to that of granular aquifers. Recharge may be distributed through an areally extensive network of fractures or through soil (*dispersed recharge*), or it may be concentrated at points that connect directly to the aquifer (*point recharge*). The percentage of point recharge of an aquifer strongly influences the character and variability of its discharge and water quality **(10, 14)**.

5.3 *Conceptual Models of Ground-Water Flow in Fractured-Rock and Karst Aquifers*:

5.3.1 Three conceptual models of ground-water flow can be used to characterize fractured-rock and karst aquifers: continuum, discrete, and dual porosity. A hydrogeologic investigation must be conducted to determine which model applies to the site of interest.

5.3.2 The continuum model assumes that the aquifer approximates a porous medium at some working scale (sometimes called the "equivalent porous-media" approach). In this approach, the properties of individual fractures or conduits are not as important as the properties of large regions or large volumes of aquifer material. The porous-medium approximation implies that the classical equations of ground-water movement hold at the problem scale, that knowledge of the hydraulic properties of individual fractures is not important, and that aquifer properties can be characterized by field and laboratory techniques developed for porous media. The discrete model assumes that the majority of the ground water moves through discrete fractures or conduits and that the hydraulic properties of the matrix portion of the aquifer are unimportant. Measurement of the hydraulic characteristics of individual fractures or conduits are used to characterize ground-water movement. The dual-porosity model of ground-water flow lies somewhere between that of the continuum and discrete models. A dual-porosity approach attempts to characterize ground-water flow in individual conduits or fractures as well as in the matrix portion of the aquifer.

5.3.3 These theoretical models are useful tools for conceptualizing ground-water flow in fractured-rock and karst aquifers. However, the design of a ground-water monitoring system must be based on empirical data from the site to be monitored. It is important to realize that standard hydrogeologic field techniques may not be valid in fractured-rock and karst aquifers, because many of these techniques are based on the continuum model. The following section provides subjective guidelines for determining which conceptual approach will best characterize ground-water flow in the aquifer under investigation.

5.4 *Subjective Guidelines for Determining the Appropriate Conceptual Model*:

5.4.1 The question of which conceptual approach is most suitable for a given aquifer is somewhat a question of scale. Implicit in the porous-medium approximation is the idea that aquifer properties, such as hydraulic conductivity, porosity, and storativity, can be measured for some representative elementary volume (REV) of aquifer material and that these values are representative over a given portion of the aquifer. For granular aquifers and some densely-fractured aquifers, the REV is likely to be encompassed by standard field-monitoring devices such as monitoring wells. In such aquifers, the continuum approach is appropriate for site-specific investigations provided aquifer heterogeneity is adequately characterized. The porous-medium approximation is not a valid conceptual model for those fractured-rock and karst aquifers where flow is primarily through widely-spaced discrete fractures or conduits, **(14-16)**.

5.4.2 The discrete approach is most appropriate for those aquifers where there is a great contrast between matrix and fracture or conduit hydraulic conductivity. The dual-porosity approach is most appropriate for those aquifers where the matrix is relatively permeable and yet there are discrete zones of higher conductivity such as dissolution zones, fractures, or conduits.

5.4.3 Determining which conceptual model is appropriate for a given aquifer requires that an investigator determine the influence of fractures and conduits on the flow system. Existing data may provide valuable information. However, relevant and

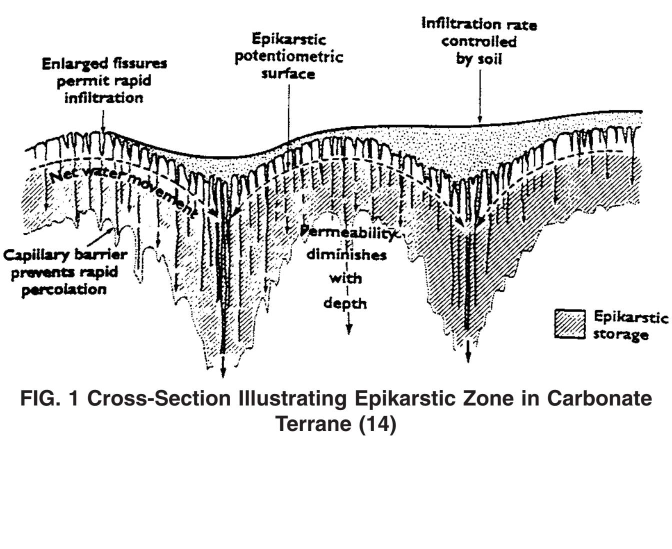

FIG. 1 Cross-Section Illustrating Epikarstic Zone in Carbonate Terrane (14)

appropriate site-specific field investigations are necessary to fully characterize the flow system.

5.4.4 Below is a list of subjective criteria that can be used to help determine which conceptual ground-water flow model is appropriate for use at a given site. Reference **(3)** lists several criteria for determining whether the continuum approach is appropriate for a fractured-rock aquifer; these are summarized in 5.4.1-5.4.5. Additional criteria for determining the applicability of the porous-medium approximation in karst aquifers (5.4.8) are provided by Ref **(2)**. All of these guidelines are subjective because fractured-rock and karst aquifers range from porous-medium-equivalent to discrete fracture or conduit-dominated systems. The decision as to which conceptual model is most appropriate will always require professional judgment and experience.

5.4.5 *Ratio of Fracture Scale to Site Scale*—For porous-medium-equivalent aquifers, the observed vertical and horizontal fractures should be numerous, the distance between the fractures should be orders of magnitude smaller than the size of the site under investigation, and the fractures should show appreciable interconnection.

5.4.6 *Hydraulic Conductivity Distribution*—In porous-medium-equivalent settings, the distribution of hydraulic conductivity, as estimated from piezometer slug tests or from specific capacity analyses, tends to be approximately log-normal. In aquifers where the hydraulic conductivity distribution is strongly bimodal or polymodal, the porous-medium approximation is probably not valid. It is also possible to obtain a log-normal distribution of hydraulic conductivity for wells in those aquifers that do not fit the porous-medium approximation (see 6.5) because most wells are preferentially completed in high-yielding zones. In addition, hydraulic conductivity values vary with the scale of measurement **(16-19)** and slug tests completed in open boreholes will yield averaged hydraulic conductivities that do not represent the full variability in hydraulic conductivity.

5.4.7 *Water-Table Configuration*—For porous-medium-equivalent aquifers, a water-table map should show a smooth and continuous surface without areas of rapidly changing or anomalous water levels. In particular, the water table should not have the "stair-step" appearance that can occur in sparsely fractured rocks with large contrasts in hydraulic conductivity between blocks and fractures, nor should the map exhibit contours that appear to "V" upgradient, where no topographic valley exists. In such settings, flow within a conduit may be affecting the configuration of the water table. Although the "stair-step" or "V-shaped" anomalies (for an example, see Ref **(20)** clearly indicate a failure of the porous-medium approximation, a smooth water table does not prove a porous-medium-equivalent setting because the density of measuring points may not be sufficient to detect irregularities in the water-table configuration (see section 6.3.1.1).

5.4.8 *Pumping Test Responses*—There are several criteria for determining how closely a fractured-rock aquifer approximates a porous medium by using an aquifer pumping test.

5.4.8.1 The drawdown in observation wells should increase linearly with increases in the discharge rate of the pumping well.

5.4.8.2 Time-drawdown curves for observation wells located in two or more different directions from the pumped well should be similar in shape and should not show sharp inflections, which could indicate hydraulic boundaries.

5.4.8.3 Distance-drawdown profiles that are highly variable (for example, distant points respond more strongly while nearby points have little or no response) indicate that the porous-media approximation is not valid.

5.4.8.4 A plotted drawdown cone from a pumping test using multiple observation wells should be either circular or near-circular (elliptical). Linear, highly elongated, or very irregular cones, in areas where no obvious hydraulic boundaries are present, indicate that the assumption of a porous medium is invalid.

5.4.9 *Variations in Water Chemistry*—Large spatial and temporal variations in the chemistry of natural waters can be observed in fractured-rock and karst aquifers because of the rapid movement of water through discrete fractures or solution conduits. The coefficient of variation of specific conductance (or hardness) of spring and well water is a function of the percentage of rapid versus slow recharge to an aquifer and can be used to infer that percentage except where anthropogenic influences will impact the conductivity of the recharging water **(8-10)**.

5.4.9.1 Many wells and springs, particularly those used for public water supply, are sampled on a regular basis for such parameters as temperature, pH, specific conductance, hardness, turbidity, and bacteria. If sampling results indicate large, short-term fluctuations in any of these parameters, the porous-medium approximation cannot be assumed.

NOTE 1—The last sentence of the preceding paragraph assumes that the short-term fluctuations (on the order of hours or days) are not a consequence of initiation of pumping or other withdrawal methods.

5.4.9.2 Water-supply wells and springs are often sampled on a monthly basis and while monthly variation in water-quality parameters may provide a general indication of whether the aquifer behaves as a porous medium, water-quality variations in response to recharge events are frequently a better test of the porous-medium approximation. In order to determine the validity of the porous-medium approximation at a monitoring point, observe and record at least two, and preferably all, of the following: spring discharge or hydraulic head, turbidity, specific conductance, and temperature, preferably a day before, during, and for several days or weeks after several major recharge events. If the water becomes turbid and the other parameters show rapid and flashy responses to the recharge event, the porous-medium approximation is most likely not valid. A bimodal or polymodal distribution of daily or continuous measurements of specific conductance **(14, 21)** also indicates that the porous-medium approximation may not be valid.

5.4.10 *Presence of Karst Features*—The presence in the same contiguous formation within several kilometres of a site of landforms such as sinkholes, sinking streams, blind valleys, and subsurface features such as caves and dissolutionally enlarged joints, indicates a degree of dissolutional modification that probably invalidates the porous-medium approximation and denotes a karst terrane. As a generalization, if there is carbonate rock, it is highly probable that there is both a karst terrane and a karst aquifer. If a carbonate aquifer has been or is presently subaerially exposed, and if total hardness is less than 500 mg/L, then a rapid-flow component and a karst aquifer are present **(10)**.

5.4.11 *Variations in Hydraulic Head*—Monitoring wells in granular media tend to exhibit predictable and minor changes in hydraulic head in response to recharge events. In fractured-rock and karst aquifers it is not uncommon to see large variations in head in immediate response to recharge events. The degree of response of hydraulic head in a given well is dependent upon the size of fractures or conduits encountered by the well and the directness of their connections to surface inputs.

5.4.11.1 Aquifers with a high contrast in hydraulic conductivity over short distances can exhibit non-coincident water levels in closely spaced wells that are screened or open over the same vertical interval. In Karst and fractured-rock terrane such non-coincident water levels indicate that the porous-medium approximation is probably not valid.

5.4.12 *Borehole Logging*—Several borehole logging techniques can help determine if high-permeability zones are present within a borehole. The presence of such zones suggests that the aquifer is not a porous-medium equivalent. Zones of high permeability are indicated by the following:

5.4.12.1 Presence of open fractures or dissolution features as indicated by a caliper log, borehole television logs (for example, Ref **(22)**), or acoustic televiewer **(23)**.

5.4.12.2 Significant variation in specific conductance or temperature as interpreted from borehole logs (for example, Ref **(24)**).

5.4.12.3 Significant variations in borehole fluid movement as measured by a flow meter in a pumped or unpumped well (for example, Refs **(25-28)**.

5.4.12.4 Significant increase in porosity within a rock unit that otherwise has a constant porosity as measured by a porosity (neutron-neutron) log; and

5.4.12.5 Significant decrease in density within a rock unit that otherwise has a consistent density as measured in a density (gamma-gamma) log.

6. Hydrogeologic Setting

6.1 Hydrogeologic characterization of fractured-rock and karst aquifers is complicated by the presence of high-permeability fractures, conduits, and dissolution zones that exert a controlling influence on ground-water flow systems. Locating and characterizing these high-permeability zones can be logistically difficult if not impossible, because conduits, dissolution zones, or subsurface fractures that transmit a large percentage of the flow may be as small as a few millimetres in size. Benson and Yuhr **(29)** note that borings alone are inadequate for subsurface characterization in karst settings. They provide some insights into the number of borings required for locating a subsurface cavity by noting the detection probabilities. The example they provide is that "if a 1 acre site contains a spherical cavity with a projected surface area of 1/10 acre (a site to target ratio of 10), 10 borings spaced over a regular grid will be required to provide a detection probability of 90 %. Sixteen borings will be required to provide a detection probability of 100 %...for smaller targets, such as widely spaced fractures, the site-to-target ratio can increase significantly to 100 or 1000, thus requiring 100 to 1000 borings to achieve a 90 % detection confidence level" **(29)**.

6.1.1 In granular media, the monitoring well is the standard measuring point for both obtaining representative ground-water samples and determining aquifer properties. However, the discrete and dual-porosity conceptual models require an investigator to identify sampling points and perform aquifer tests or tracer tests, or both, that do not rely on the porous-medium approximation (continuum approach). In karst and fractured-rock settings, an investigator cannot assume that a monitoring well will provide representative data either for water-quality or aquifer characteristics **(14, 30, 31)**. Tracer tests (see 6.7) are one of the more valuable tools for determining ground-water flow directions and velocities because the interpretation of these tests does not require the porous-medium approximation (continuum approach).

6.1.2 This section discusses the importance of understanding stratigraphic and structural influences on ground-water flow systems (see 6.2); location and characterization of fracture patterns and karst features (see 6.3); delineation of ground-water basin boundaries and flow directions (see 6.4); applicability of geophysical techniques (see 6.5); and measurement of aquifer characteristics (see 6.6).

6.2 *Regional Geology and Structure*—The design of a ground-water monitoring network should include a determination of how the site fits into the regional geologic setting because regional stratigraphic and structural patterns provide the constraints within which the local ground-water flow system is developed.

6.2.1 *Sources of Data*—Information on regional geology and hydrogeology, (that is, geologic maps, stratigraphic cross-sections, geophysical logs from nearby sites, cave maps, water-table or potentiometric-surface maps, long-term records of water levels or water quality in monitoring wells) can be obtained from both published and unpublished sources including federal and state publications, academic theses and dissertations, journal articles, and available consultants' reports. Additional information can be obtained from local land owners, quarry operators, highway departments, local construction firms, as well as geologic logs, drillers' logs, and well-construction reports from domestic wells. Data on the number, distribution, and construction of domestic wells are best obtained by house-to-house survey; state and federal files for most areas rarely include more than a small percentage of the wells that exist. The most information about caves can be obtained from consultation with the National Speleological Society[5] whose members compile information on a state-by state basis.

6.2.2 *Integrating Geologic Information With Flow-System Characteristics*—When reviewing the existing data, an investigator should take extra note of any information that indicates the presence of conduits or high permeability dissolution or fracture zones (see guidelines outlined in 5.4). The initial hydrogeologic characterization should include a survey of bedrock outcrops in the area. Special attention should be paid

[5] National Speleological Society, Cave Ave., Huntsville, AL 35810.