Designation: D 5717 – 95$^{\epsilon 1}$

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:*

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]

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[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.

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

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

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.

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

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

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.

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)**.

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

5.2.3 *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

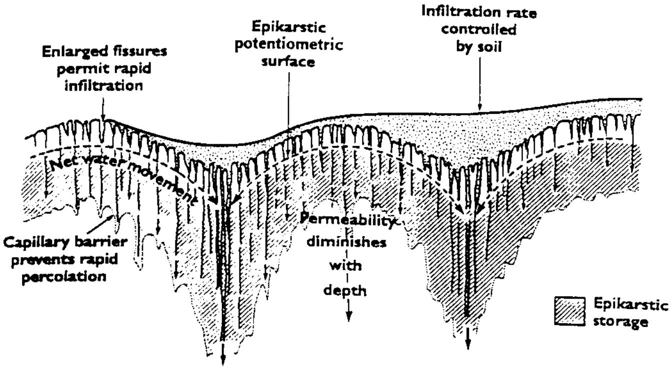

FIG. 1 Cross-Section Illustrating Epikarstic Zone in Carbonate Terrane (14)

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 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 to the relationships between stratigraphy and structure and the distribution of lineaments, fracture patterns, karst landforms, sinkhole alignments, and hydrologic features such as seeps or springs.

6.2.3 *Stratigraphy*:

6.2.3.1 In any layered rock sequence, either sedimentary rocks or layered volcanics, stratigraphy can be a controlling factor in the development of zones of enhanced flow of ground water. Bedrock outcrops, including quarries and caves, should be examined in order to determine the stratigraphic position of

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

springs, seeps, caves, zones of dissolution, or zones of intense fracturing.

6.2.3.2 In fractured carbonate terranes, the development of conduits and dissolution zones is most commonly controlled by bedding plane partings rather than vertical fractures. Dissolution preferentially develops along bedding planes with substantial depositional unconformities, planes with shale laminae or thicker partings, and planes with nodules or beds of chert **(14)**. The relationship of shale beds or other low-permeability units to hydrologic features should be noted. These units cannot be assumed to provide effective barriers to ground-water flow because in fractured-rock and karst terranes they are frequently breached by fractures or shafts **(32)**. In carbonate terranes, interbedded shales are frequently calcareous and hence subject to dissolution; in addition, shale beds may enhance dissolution, because of oxidation of included sulfides and production of sulfuric acid **(9)**.

6.2.3.3 In layered volcanic terranes, interbedded basalts and pyroclastic deposits have different hydrologic properties. Pyroclastic deposits can range greatly in terms of primary porosity and hydraulic conductivity due to differences in welding and the development of secondary fractures. In general, ash-flow tuffs in the upper portions of flows exhibit high values of porosity and permeability **(33)**. In flood basalts, the interflow zones (top of one flow and bottom of overlying flow) tend to be zones of high porosity and high conductivity due to primary depositional features such as "flow breccias, clinkers, shrinkage cracks, flow-top rubble, and gas vesicles" **(33)**. In flood basalt terranes, tubes or conduits (lava caves) should be suspected, and although these features will usually be influential only in the shallow zone, they could cause preferential flow similar to a conduit system in a karst terrane. Springs are also common in volcanic rocks; their location is determined by topography, structure, and depth to ground water.

6.2.3.4 In regions with no quarries, accessible caves, and few bedrock outcrops, geologic characterization will have to be based on information obtained from drilling. Core drilling provides a good record of both subsurface stratigraphy and fracture distribution in areas of good core recovery. However, core recovery often fails in zones of poor rock quality or in areas with extensive voids. An alternative approach for such situations is to drill destructively (without coring) and then log the hole with applicable geophysical techniques (that is, gamma, resistivity, or conductivity for stratigraphy; and caliper and television for fractures). While vertical boreholes provide useful information about horizontal fractures and dissolution zones, angle drilling with collection of oriented core can be used to better characterize vertical and near-vertical fracture systems, and steeply dipping beds **(34)**. A review of existing well logs, including geophysical logs, should note stratigraphic zones where circulation was lost during drilling, where enhanced yields were obtained during well development or aquifer tests, and where open or mud-filled cavities or fractures were encountered.

6.2.4 *Structure*:

6.2.4.1 Structural features commonly associated with concentration of ground-water flow include anticlines, synclines, and faults. Anticlines are important because extension of joints along their crests can favor development of joint-controlled conduits. Synclines tend to concentrate flow, usually with down-dip inputs to a conduit located close to the base of the trough **(14)**. Faults, especially faults formed by extension, can concentrate ground-water flow, provided that they have not been filled by secondary mineralization **(14)**. Faults can also provide barriers to ground-water flow if secondary mineralization or fault gouge is extensive or if a low-permeability fault block truncates an aquifer.

6.2.4.2 In dipping carbonate rocks (that is, 2 to 5° or more), initial ground-water flow is commonly downdip with eventual discharge along the strike of the beds. In these settings there is substantial evidence that strike-aligned flow is common, and can extend up to tens of kilometres. When designing monitoring systems in these settings, discharge points along the strike must be located even if they are several kilometres away from the site to be monitored. In dipping carbonate strata, depth of ground-water circulation is influenced by fissure frequency, down-dip resistance to flow, ground-water basin length, and angle of dip **(9, 14)**.

6.2.4.3 In crystalline rocks, fractures are typically most abundant near the land surface; fracture density diminishes with depth. However, high-permeability fractures have been found at depths greater than 1500 m **(35)**. Water-table configuration and hence ground-water flow direction in these settings appears to be topographically controlled **(36)**. Enhanced well-yields indicate that the zones of enhanced ground-water flow occur along fracture traces, at the intersection of fracture traces and in valley bottoms which are probably fracture-controlled **(36 and 37)**. Reference **(37)** also notes that "sheet joints", subparallel to the land surface at shallow depths and horizontal at greater depths, may play an important role in ground-water movement in plutonic rocks.

6.3 *Field Mapping and Site Reconnaissance*—In areas where the surficial materials are thin or absent, high-angle fractures and the location of large karst features can sometimes be mapped from topographic maps and aerial photographs. Most fractures and many karst features are not recognizable on topographic maps or air photos and field mapping will be necessary to locate them. Field reconnaissance, completed early in the project, is an important component of site investigation and is essential for the identification of open fractures, swallets, small sinkholes, springs, and cave entrances. (A detailed discussion of fracture-mapping methods can be found in Ref **(38)**. Fractures and karst features will have a large impact on the subsurface hydrology, even if their surface expression is slight. Field mapping can provide detail on the distribution of karst features and on fracture orientation and density. However, it gives little information about the distribution of fractures or conduits at depth.

6.4 *Determination of Ground-water Flow Directions, Velocities, and Basin Boundaries*—Water-table or potentiometric-surface maps, or both, are used to estimate the direction and rate of ground-water and contaminant movement in granular aquifers. Such estimates are complicated in fractured-rock and karst aquifers. Even porous-medium-equivalent fractured-rock aquifers frequently exhibit significant horizontal anisotropy, which can make prediction of ground-water flow directions difficult. Some fractured-rock aquifers respond rapidly enough to recharge events that temporary ground-water mounding may develop and lead to reversals of flow directions. The concept of a "water-table" becomes less clearly defined in those fractured-rock and karst systems where there are discrete high-permeability zones in a much lower-permeability matrix. In these settings, the fractures and conduits respond quickly to recharge events and may spill over into empty, higher-lying conduits or fractures while the lower-permeability portion of the aquifer remains unsaturated.

6.5 *Variation of Hydraulic Head*:

6.5.1 *Potentiometric-Surface Mapping*—Constructing a potentiometric-surface map with water levels from existing wells assumes the following: vertical hydraulic gradients are not significant, and the well intersects enough fractures or conduits to provide a representative water level for the aquifer. If significant vertical gradients are present, construction of a potentiometric-surface map will require screening out of apparent anomalies in water levels resulting by measuring water levels from wells cased at different depths in an aquifer's recharge and discharge zones **(39)**. The elevation of base-level springs, lakes, and streams should be regarded as possible data points for a potentiometric map, provided it can be established that they are not perched.

6.5.1.1 When constructing a potentiometric map based on field-measured water levels, it is necessary to measure water levels in all representative accessible wells over a short time-interval. Data from existing wells may be adequate, provided well-construction information is available, and the water-levels are evaluated with respect to the length and depth of the open interval. Depending on the nature of the investigation and the level of detail required, it may be necessary to install additional wells.

6.5.1.2 It is difficult to state a universal rule that unambiguously specifies the appropriate contour interval or the density and distribution of data points that are needed for construction of a potentiometric map. The steepness of the hydraulic gradient guides the choice of contour interval and the data density should be such that, on average, no more than two to three contour lines are interpolated between data points.

6.5.1.3 Contaminants in karst terranes can quickly travel several kilometres or more. Therefore, it is necessary to extend potentiometric maps significantly beyond property boundaries in order to determine the likely extent and direction of contaminant travel, and to increase the accuracy of the map.

6.5.2 *Vertical Distribution of Hydraulic Head*:

6.5.2.1 The vertical component of flow should be considered in the delineation of ground-water flow direction. Ground-water flow systems typically have a downward flow component in recharge areas that gradually becomes horizontal before changing to upward flow in discharge areas. In granular and porous-media equivalent aquifers, vertically nested or closely spaced piezometers along the flow path are sufficient to describe these gradients.

6.5.2.2 In karst aquifers, the matrix, fractures, and conduits each have very different vertical flow regimes which can be difficult to characterize. For some karst aquifers, recharge is concentrated at very specific points (for example, at sinkholes and swallets of sinking streams) that feed a complex network of conduits. Whether flow is predominantly horizontal or vertical at various points along the flow path is controlled by hydraulic head, the geometry of the conduit system, and location of the discharge point. The degree of connection between the fractured and matrix portions of the aquifer and the conduits will be a function of fracture density, primary porosity, extent of dissolution, and hydraulic gradient. Characterization of the vertical component of flow in conduit-dominated aquifers requires locating point inputs and point discharges, determining the vertical component of flow in the fractured and matrix portions of the aquifer, and evaluating the degree of connection between the fractured and matrix portions of the aquifer and the conduits.

6.5.3 *Temporal Changes in Hydraulic Head*:

6.5.3.1 The response of springs or wells to recharge events is useful for characterizing an aquifer. On the continuum from porous-media-equivalent aquifers to discrete fracture or conduit-dominated aquifers, head variations in the latter tend to increase in magnitude; lag times to the hydrograph peak after the recharge event tend to decrease. In brief, flow in aquifers with numerous direct surface inputs (point recharge) and discrete fractures or conduits is more flashy than in those aquifers where direct surface inputs are minimal. Individual well-responses to recharge events can be used to indicate the degree of connection between the well and the fracture or conduit system.

6.5.3.2 Complex responses to recharge events commonly occur in fractured-rock and karst aquifers. Flow-system configurations can change dramatically in response to recharge events. In karst aquifers, as deeper conduits fill, ground water may spill over to higher conduits and discharge to a different ground-water basin than it does during low-flow conditions **(30, 40)**. Moderately permeable fractured-rock aquifers may also exhibit such ground-water flow reversals if temporary ground-water mounds develop **(40)**.

6.5.3.3 Investigators working in fractured-rock and karst aquifers need to assess whether temporal changes in hydraulic head can lead to changes in ground-water flow direction or the position of ground-water basin boundaries. The frequency of water-level measurements needs to be determined by the variability of the system rather than by reporting requirements. Continuous water-level records on representative wells are recommended in the early phase of the investigation; after monitoring the response of an aquifer to several recharge events, the measuring frequency can then be adjusted.

6.6 *Determination of the Directions and Rates of Ground-Water Flow*:

6.6.1 *Flow Directions*—Water-table and potentiometric-surface maps are valuable guides for predicting ground-water flow directions. However, the predicted flow directions will be correct only if the assumption of two-dimensional flow is valid and anisotropic aquifer characteristics, if present, are taken into account. In some fractured-rock aquifers and most karst aquifers, the assumption of two-dimensional flow is probably not valid and anisotropy ratios are frequently unavailable for site-specific scales **(15, 18)**. In some settings the potentiometric surface can provide a reasonable first approximation for the delineation of ground-water flow directions and basin boundaries, but this approximation must be confirmed with tests that are not dependent on the assumption of two-dimensional flow. Such confirmation can be provided by properly conducted tracer tests performed on both sides of a proposed boundary, as shown by Quinlan and Ewers **(40)** and discussed by Quinlan **(30, 31)**.

6.6.2 *Flow Rates*—It is usually inappropriate to use water-table or potentiometric surface-maps to predict regional or local ground-water flow rates in fractured-rock and karst aquifers. Such calculations assume that the porous-media approximation is valid, flow is two-dimensional, and the hydraulic conductivity distribution is relatively homogeneous. While these conditions might be met over very short distances, they are rarely, if ever, met for site-specific or larger areas. See 6.9 for a discussion of aquifer characteristics. Flow rates are directly determined from the results of aquifer-scale or site-scale tracer tests.

6.7 *Use of Tracer Tests*:

6.7.1 Tracer tests are a valuable tool for characterization of fractured-rock and karst aquifers. They can yield empirical determinations of ground-water flow directions, flow rates, flow destinations, and basin boundaries. The results of these tests depend on the conservative nature of the tracer, its unambiguous detectability, proper test design and execution, and correct interpretation.

6.7.2 Two broad classes of tracers have been used: labels and pulses, both of which can be usefully subdivided into natural and artificial tracers. The purpose of the labels is to enable identification of the investigator's water which serves as a surrogate for a pollutant. The purpose of pulse-tracing is to be able to send an identifiable signal through the ground-water system. A partial outline of tracers that has been used can be found in Table 2.

6.7.3 The various types of tracers have different advantages and disadvantages and they yield different types of information about a hydrogeologic system. As the level of sophistication of an investigation increases, comparison of the results obtained with different tracers can often yield additional information about the system properties.

6.7.4 An ideal tracer has the following properties. It is:

6.7.4.1 Nontoxic to people and the ecosystem;

6.7.4.2 Either not naturally present in the system or present at very low, near-constant levels;

6.7.4.3 In the case of chemical substances, soluble in water with the resulting solution having approximately the same density as water; (care should be taken, in the design of tracer tests, to address concerns that may arise when the pollutants of concern are light or dense non-aqueous phase liquids);

6.7.4.4 Neutral in buoyancy and, in the case of particulate tracers, with a sufficiently small diameter to avoid significant losses by natural filtration;

6.7.4.5 Unambiguously detectable in very small concentrations;

6.7.4.6 Resistant to adsorptive loss or to chemical, physical, or biological degradation, or all of the aforementioned;

6.7.4.7 Capable of being analyzed quickly, economically, and quantitatively;

TABLE 2 Types of Tracers (43)

- *Labels:*
  - Natural
    - Flora and fauna (chiefly, but not exclusively microorganisms)
    - Ions in solution
    - Environmental isotopes
    - Temperature
    - Specific conductance
  - Introduced
    - Dyes and dye-intermediates
    - Radiometrically detected substances
    - Salts and other inorganic compounds
    - Spores
    - Fluorocarbons
    - Gases
    - A wide variety of organic compounds
    - Biological entities (bacteria, viruses, yeasts, phages)
    - Effluent and spilled substances
    - Organic particles, microspheres
    - Inorganic particles (including sediment)
    - Temperature
    - Specific conductance
    - Exotica (eels, ducks, marked fish, etc.)
- *Pulses Significantly Above Background or Base-Flow Levels:*
  - Natural
    - Discharge (change in stage or flow)
    - Temperature
    - Turbidity
  - Introduced
    - Discharge
    - Temperature

6.7.4.8 Easy to introduce to the flow system; and

6.7.4.9 Inexpensive and readily available.

6.7.5 Nontoxicity is the most important tracer characteristic. Few tracers satisfy all of these criteria, but several of the fluorescent dyes meet most in many situations. For most settings, dyes are the most practical tracers. Toxicity studies indicate that most fluorescent dyes are not harmful in the concentrations conventionally employed in tracer tests. It has been determined that a concentration of one part per million of the most commonly used fluorescent dyes, over an exposure period of 24 h, poses no threat to human or ecosystem health **(41)**.

6.7.6 Tracer tests are appropriate when:

6.7.6.1 Flow velocities are likely to be such that results will be obtained within a reasonable period of time, usually less than a year;

6.7.6.2 The consequences of existing or possible future ground-water contamination must be determined;

6.7.6.3 It is necessary to delineate recharge areas or ground-water basin boundaries; or

6.7.6.4 It is necessary to design or test a ground-water monitoring system, or both.

6.7.7 Tracer tests can be classified in several ways which are outlined in Table 3. Techniques for tracing ground water, with emphasis on the use of fluorescent dyes, are described and discussed in Ref **(43)**.

6.7.8 Tracing techniques and approaches that an investigator might use vary greatly in levels of sophistication. For example, the question "Is the septic system of this house connected to the nearest sewer main?" can sometimes be adequately answered with a few pennies worth of dye and a few minutes of someone's time. Similarly, questions about the internal connections in some caves can often be answered with

TABLE 3 Classifications of Tracer Tests (43)

- *A. Degree of Quantification:*
  - Qualitative
  - Semi-quantitative
  - Quantitative
- *B. Degree of Alteration of Hydraulic Gradient:*
  - Natural gradient
  - Forced gradient, accomplished by:
    - Injection (input raises potentiometric surface)
    - Discharge (pumping lowers potentiometric surface)
- *C. Type of Injection Site:*
  - Natural
    - Sinkhole or swallet
    - Cave stream
  - Artificial
    - From a well or other man-made contrivance
- *D. Type of Recovery Site:*
  - Natural discharge site
    - Spring, cave stream, etc.
  - Artificial discharge site
    - Monitoring well
    - One or more domestic wells

about the same level of resources and time. In contrast, questions about the regional-scale dispersal of pollutants from a major Superfund site in a densely populated karst terrane require a considerably greater investment of time, resources, and effort.

6.7.9 Dye-detection techniques range from visual detection, to detection by fluorometer, to instrumental analysis of water samples using a scanning spectrofluorophotometer or (rarely) high performance liquid chromatography (HPLC). The use of simple visual detection of dyes is now considered usually unacceptable in a major project, but it can still be a very effective demonstration of a connection in some settings.

6.8 *Geophysical Techniques*:

6.8.1 Geophysical techniques can be used in a number of ways to aid subsurface investigations and to characterize some subsurface features of karst or fractured-rock aquifers **(29, 44)**. Surface geophysics can provide general information over a large area and can also be used to provide detailed, site-specific data. Borehole logging techniques provide localized information within and immediately around a borehole or well. Some borehole or hole-to-hole techniques can be used to detect fractures and karst features. The method or methods to be used must be selected to meet both project objectives and site conditions. Interpretations based upon surface and borehole geophysical data should be verified by other data and require experienced field crew and interpretation.

6.8.2 *Surface Geophysical Techniques*—Surface geophysics provides a means of characterizing subsurface conditions by making measurements of some physical parameter (acoustical properties, electrical properties, etc.) at the surface. Surface geophysical methods can help characterize subsurface features such as depth to rock, depth to water table, or to locate buried channels. Large structural features such as dip, folds, and faults can be located and mapped. Fracture orientation and areal variations in water quality can also be determined. Surface geophysical methods can sometimes be used to detect conduits directly if they are shallow and large enough **(29, 44)**. Effectiveness of surface geophysical methods diminishes as the feature of interest occurs at an increasing depth and with decreasing size of the feature. Fractures or conduits that are deeper than can be detected by surface geophysical methods, can sometimes be located indirectly by using near-surface indicators **(29, 45)**. Geophysical methods are often used to indicate anomalous conditions caused by a fracture or conduit. The anomalous conditions can then be investigated further by boreholes where the borings are focused into the anomalous area(s) and have a much better probability of encountering the fracture or conduit than a randomly placed borehole.

6.8.2.1 Surface geophysics may be a good reconnaissance tool that can be used to determine areas in need of further study. Several of the following methods may be applicable in fractured-rock and karst settings, including ground-penetrating radar, electromagnetic or electrical resistivity surveys, natural potential (SP), and or microgravity. Such methods as electromagnetics **(46-48)** azimuthal resistivity **(48, 49)**, and azimuthal seismic measurements **(50)** can be applied to determine dominant fracture orientations.

6.8.3 *Borehole Logging Methods*—Borehole logging can be used to identify strata (for example, shale versus limestone) and to correlate stratigraphy between boreholes. These methods are particularly useful for investigation of fractured-rock aquifers because they provide detailed information about rock properties in the immediate vicinity of borehole walls. They are useful for determining water-bearing zones within a borehole and for determining hydraulic properties of inclined and horizontal fractures (see Ref **(51)** for general borehole logging techniques applied to ground water investigations).

6.8.3.1 Borehole logs most commonly used to correlate stratigraphy include natural gamma, gamma-gamma, resistivity (or conductivity), and spontaneous potential. Borehole methods particularly useful for locating and characterizing fractures and conduits include video, temperature, caliper, acoustic televiewer, flow meter, borehole fluid logging, and cross-hole tomography **(29, 44)**. When budget limitations preclude the use of multiple logging techniques, it is recommended that video logging be used to determine the location and orientation of fractures and conduits to aid in the placement of monitoring well screen. Tomography carried out by radar and attenuation of higher frequency acoustic signals can be used to detect fractures and conduits.

6.8.3.2 Borehole methods are often used in conjunction with each other. Borehole diameter, well construction, and proper well development can affect the results and usefulness of borehole logs.

6.9 *Aquifer Characteristics*—One of the special problems of monitoring in fractured-rock or karst aquifers is that aquifer characteristics such as aquifer thickness, porosity, hydraulic conductivity, and storativity can be difficult to quantify.

6.9.1 *Aquifer Thickness*—In aquifers with mainly primary porosity, the thickness of the aquifer can frequently be defined by lithologic or stratigraphic boundaries. In fractured-rock aquifers, fracture density and aperture frequently decrease with depth and it is difficult to determine at what depth the fractures are no longer capable of transmitting significant amounts of water. Examination of cores and borehole logging data may be helpful in identifying the “productive” portion of the aquifer. Karst aquifers present similar problems in that karstification may decrease with depth or be confined to very specific zones or beds within the carbonate rock. While it is often difficult to determine the base of karstification, Worthington **(9)** suggests that stratal dip and length of ground-water basin can be used to estimate the mean depth of flow. Reference **(52)** suggests that packer tests at successively lower depths can be used for estimates of depth of karstification.

6.9.2 *Porosity*—Primary porosity can be measured on the scale of a hand sample or a core sample; secondary and tertiary porosity need to be measured at a scale that statistically represents the distribution of heterogeneities in the aquifer. For densely-fractured rock, the sample volume may be relatively small and encompassed by borehole geophysical measurement techniques, while for aquifers with widely spaced heterogeneities (that is, sparsely fractured rock or conduit systems) the huge volume of rock needed prohibits meaningful evaluations of porosity.

6.9.3 *Hydraulic Conductivity and Storativity*—Hydraulic conductivity values vary with the scale of measurement **(16, 17, 53)**. The range of hydraulic conductivities and associated ground-water velocities for karst aquifers is illustrated in Fig. 2. Hydraulic conductivity values from lab and field tests (Methods A through D) are compared to velocities of ground-water flow in conduits (Method E). The presence of conduits in a karst aquifer requires a dual-porosity approach to aquifer characterization, or at least a discrete-porosity approach, rather than a porous-medium approximation because the hydraulic conductivity would be grossly underestimated with the porous-medium approach.

6.9.3.1 Hydraulic conductivity in granular media is frequently evaluated by single-well or multiple-well pumping tests. Results of such tests performed in fractured-rock and karst aquifers should be interpreted with respect to the portion of the aquifer that responds and the measurement-scale effects, illustrated in Fig. 2 should be recognized. The discrete nature of high-conductivity zones in fractured-rock and karst aquifers can yield hydraulic conductivity values ranging over several orders of magnitude at a specific measurement scale. Fig. 3 illustrates the range of hydraulic conductivity values measured from slug tests (borehole-scale) at a small site in horizontally-bedded fractured dolomite. Significant errors can occur when aquifer characterization tests are designed, conducted, or interpreted without regard to the portion of the aquifer being tested.

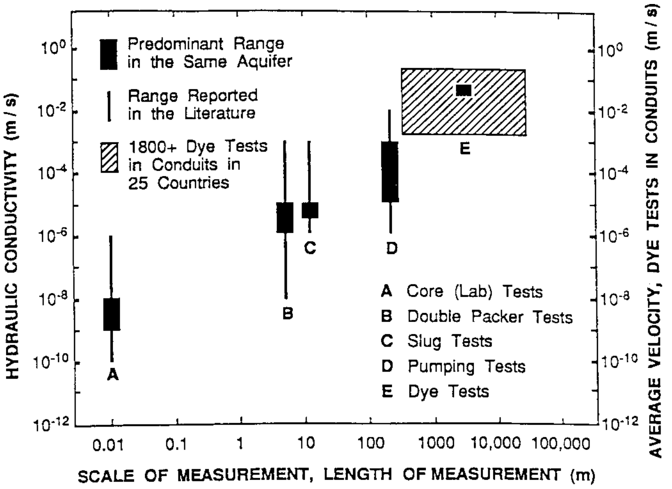
6.9.3.2 Site-specific investigations may require detailed information on the transmissivity of specific zones within the aquifer. In fractured-rock and karst aquifers, borehole packers can be used to segregate specific zones within the borehole. Slug tests and single-well pumping tests can then be performed to determine transmission characteristics of different portions of the aquifer. Borehole-fluid logging in a pumping well **(24)** can also help to characterize the producing zones within fractured-rock aquifers.

6.9.3.3 Measurements of transmissivity and storativity averaged over a ground-water basin in karst aquifers can be estimated from discharge rates at springs **(32, 52)**. Such averaged parameters may be appropriate for regional assessments of ground-water resources but they are less appropriate for site-specific investigations.

7. Developing a Reliable Monitoring System

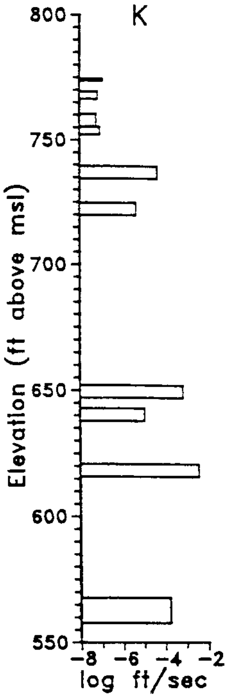
7.1 *Applicable Monitoring Points*:

7.1.1 Determination of applicable monitoring points will depend on which conceptual approach most accurately describes the setting under investigation. If the aquifer deviates



NOTE 1—The data represented by heavy bars are from a Jurassic karst aquifer in the Swabian Alb of Germany, as described by Sauter **(69)**. The hatchured box represents velocity data from more than 1800 dye traces from sinking streams to springs (that is, in conduits) from 25 countries (modified after **(16, 69)**).

FIG. 2 Range in Hydraulic Conductivity and Ground-Water Velocity in Karst Aquifers as a Function of Scale of Measurement



NOTE 1—Elevation is on the vertical axis (land surface is 800 ft (243.84 m) above msl), thickness of bar indicates length of open interval, length of the bar indicates measured hydraulic conductivity. Hydraulic conductivity values range over five orders of magnitude (compiled from data in Ref **(17)**).

FIG. 3 Range of Hydraulic Conductivity Values from Slug Tests (Borehole-Scale) at a Site in Fractured Dolomite

significantly from the porous-medium approximation, monitoring wells probably will not yield representative ground-water samples unless it is demonstrated by properly designed tracer studies and hydraulic tests that the monitoring points are connected to the site to be monitored. Alternative monitoring points (such as springs, cave streams, and seeps) are usually more appropriate in karst terranes. These natural discharge points intercept flow from a larger area than a monitoring well and, as a result, they are more likely to capture drainage from a site. Monitoring sites that integrate drainage from a large area are likely to show more dilute concentrations of contaminants than monitoring sites that intercept drainage from a small area. Monitoring of alternative sampling points requires evaluation of the significance of dilution of contaminants. Designers of a monitoring system must weigh the desirability of analysis of diluted waters that are known to drain from a site versus analysis of waters that are not demonstrably derived from the site.

7.1.2 Current ground-water monitoring practices utilize both upgradient and downgradient-monitoring points in order to meet regulatory requirements. In fractured-rock and karst aquifers, rapid variations in hydraulic head can lead to changes and even reversals in ground-water flow directions (see 6.5). In these settings, determination of flow-directions from water-table or potentiometric maps may not be adequate to determine placement of monitoring points. Samples for background water-quality should be collected at springs, cave streams, and wells that yield water that is geochemically representative of the aquifer. These monitoring points might be located in an adjacent ground-water basin **(30, 31, 54)**.

7.2 *Methods of Testing Applicability of Monitoring Points*—Tracing studies and hydraulic tests should be used to demonstrate whether or not sampling sites are connected to the site being monitored. “Downgradient” monitoring-points cannot be assumed to intercept drainage from a site unless a positive connection from the site to the monitoring point is demonstrated.

7.2.1 *Tracer Tests*:

7.2.1.1 Tracer tests that monitor the presence or absence of tracer at monitoring points are usually sufficient for determining flow directions and validating monitoring points. Tracer tests in which tracer concentration is determined on samples collected at short-time intervals (that is, minutes to hours) can be used to determine optimum monitoring frequency that avoids aliasing; without this knowledge a large number of monitoring points might be sampled for contaminants more frequently or less frequently than is necessary for accurate characterization.

7.2.1.2 Measuring tracer concentrations and discharges at monitoring points can provide additional mass-balance data that will make the design or modification of a monitoring system more efficient. At sites where there are multiple flow-directions and discharges to numerous monitoring points, it is useful to know whether a majority of the site’s drainage is to one or just a few of the monitoring points, as contrasted with nearly equal discharge to all of them. This mass-balance data can also be used to assess the significance of contaminant dilution.

7.2.1.3 As a general principle, the cost-benefit ratio of measuring both tracer concentration and discharge rises as the number of potential monitoring points increases. If mass-balance tracing results are deemed necessary, qualitative traces should be performed first. This may eliminate the cost of sampling and analyzing monitoring points which do not receive tracers. For a discussion of mass-balance tracing techniques as applied to the design of ground-water monitoring plans, see Refs **(30, 43, 55, 56)**.

7.2.1.4 The mass-balance tracing technique described by Mull et al. **(55)**, would be useful (in some settings) for evaluating the possible consequences of a spill into an open sinkhole draining to a cave stream. However, this technique is incapable of evaluating leakage from a waste disposal site. Therefore, use of this method should be limited to settings where there is point recharge directly into a cave stream.

7.2.2 *Hydraulic Testing Methods*:

7.2.2.1 A variety of hydraulic tests can also be used to determine the relative “connectedness” of an individual monitoring point to the fracture-flow system, connections between monitoring wells, and connection to the site being monitored. Any hydraulic testing program requires careful design because of the discrete nature of high-conductivity zones in fractured-rock and karst aquifers. Ideally, monitoring wells should intersect the producing zones that are more likely to carry contaminants from the site. However, in some cases it may also be necessary to monitor the matrix portion of the aquifer.

7.2.2.2 Packer tests and borehole logging techniques can help locate both high-conductivity and low conductivity zones within the aquifer (see 6.8.3). Pumping tests can then be designed to test the connections between various parts of the system **(57)**. If possible, a pumping well could be placed at the source of contamination and the response of individual monitoring wells to pumping (both rate of response and overall drawdown) could be used to determine connection to the monitoring site. Sometimes more distant wells will respond more quickly than nearby wells, indicating that they are better connected to the pumping well. Any drawdown indicates that the monitoring point is connected to the pumping well; however, it is difficult to use drawdown to assess the degree of connection. Small drawdowns could indicate a weak connection or they could indicate that the connected zone is highly transmissive (and thus difficult to draw down).

7.3 *Monitoring Wells*—Monitoring wells are the method of ground-water monitoring required by federal and state regulatory agencies and should always be considered as possible monitoring points in a karst or fractured-rock aquifer. Boreholes drilled onsite or offsite to obtain geological information can be converted to piezometers since most ground-water monitoring plans include the installation of piezometers in order to determine the variation in hydraulic head. The piezometers can then be considered as temporary or surrogate monitoring wells. If any of the piezometers later prove to be capable of providing ground-water samples representative of the water draining from the site, they can be converted to, or replaced by, true monitoring wells that meet regulatory standards.

7.3.1 *Placement of Monitoring Wells*—Placement of monitoring wells should be guided by interpretation of the data gathered in the site characterization (see 6.3-6.9). If the aquifer is uniformly and densely fractured, monitoring well placement, construction, and development are similar to that for granular aquifers (see Practice D 5092 and Refs (**58** and **60**). Different placement and construction techniques are necessary for aquifers characterized by discrete high-permeability zones (enlarged fractures, dissolution zones, and conduits) that carry the majority of the water. Wells placed in these high-permeability zones are more likely to intercept drainage from a site than randomly placed wells or wells completed in low-permeability zones. In settings where the matrix blocks have appreciable porosity, it may also be important to monitor the blocks as well as the high-permeability zones because the blocks may function as storage reservoirs for pollutants.

7.3.1.1 Fracture lineaments and the intersection of vertical fractures are potential sites for monitoring wells, especially in crystalline rocks. However, in carbonate rocks, most conduits and high-permeability zones are developed along bedding planes; monitoring wells located on the basis of fracture-trace and lineament analysis are not likely to intercept major conduits. Horizontal zones of high permeability are important in determining placement of monitoring wells. If the site characterization has identified zones of enhanced permeability (that is, noted by borehole geophysical logs, loss of circulation when drilling, etc.), monitoring wells should be constructed so as to intersect these zones.

7.3.1.2 In most karst terranes, substantial flow occurs at the soil-bedrock interface and within the subjacent epikarst. Wells placed across this interface or within the epikarst may only be intermittently saturated. However, these wells are likely to intercept the early movement of contaminants from an overlying source.

7.3.1.3 Wells drilled to intersect cave streams may also function as good monitoring points. While most geophysical techniques are incapable of detecting the flow of water within conduits, the natural potential method (a type of spontaneous potential measurement) is the only geophysical method that can detect flowing water and it can sometimes be used effectively **(50, 60-62)**.

7.3.1.4 Monitoring wells are typically constructed within the boundaries of the site to be monitored. In fractured-rock and karst aquifers, the location of high-permeability zones should guide the placement of monitoring wells even if they are located offsite.

7.3.2 *Construction of Monitoring Wells*:

7.3.2.1 The presence of zones of enhanced dissolution can complicate construction of monitoring wells in karst and fractured-rock aquifers. Drilling methods and well construction techniques should be chosen so as to minimize loss of drilling fluids, cuttings, or construction materials to the formation. Air-rotary drilling is one possibility if circulation can be maintained and risk of partial plugging of fissures can be tolerated; rotary drilling with over-shot casing can effectively reduce loss of fluids to a formation.

7.3.2.2 The open interval of the monitoring well should be designed to intercept zones of high-permeability. If no such zones are present, the well should be cased to the depth where competent rock is encountered and left open below that. The annular space between the casing and the borehole wall should be sealed in such a way as to minimize loss of materials to the aquifer. It may be possible to use standard well construction techniques such as a bentonite slurry or grouting to set the casing if no high-permeability zones are present.

7.3.2.3 If discrete high-permeability zones are encountered, the wells should be constructed so as to be open to those zones. When smaller-diameter monitoring wells are placed within a larger-diameter borehole, a gravel pack should be installed around the screen and an annular seal placed above the gravel pack. The gravel pack should be constructed of materials that will minimize any chemical reactions with the ground-water. Bentonite chips and pellets are recommended for the annular seal because these materials are not as easily lost to the formation as are slurries of cement or bentonite.

7.3.2.4 All materials used in monitoring-well construction should meet federal regulations **(63)** and state guidelines. Practice D 5092 provides general recommendations for monitoring-well construction.

7.3.2.5 *Development and Maintenance*—Wells that intersect high-permeability zones frequently exhibit high turbidity if finer particles from the fractures, conduits, and other dissolution zones are drawn into the well. These wells will require more extensive development than most monitoring wells. In many wells, turbidity may be a persistent problem, particularly during and after storm events. If siltation is a persistent problem, routine maintenance to remove the accumulated sediment may be necessary.

7.3.3 *Alternative Monitoring Points*—When tracer studies and hydraulic tests do not indicate a connection between a monitoring well and the site being monitored, the well should be considered inadequate for its intended purpose; alternative monitoring points must be used. Monitoring water quality at seeps, springs, or cave streams shown to be connected to the site by tracing studies is one alternative **(31, 40, 54)** provided a waiver from existing federal or state regulations can be obtained (see 7.5). Regulators are increasingly recognizing springs and cave streams as viable, efficient, and reliable monitoring points that meet the intent of the laws, even though these features may be found offsite (see 7.5.3). However, whenever possible, the protocols of locating monitoring points at the site should be followed. Detection of contaminants prior to migration offsite, the desired monitoring goal, may not be possible if the only relevant monitoring sites are offsite. However, because cave streams and seeps are natural discharge points for ground water flowing through discrete, difficult-to-locate, high-permeability zones, monitoring at these offsite sampling points may be the only appropriate and practicable monitoring strategy.

7.3.3.1 When documenting monitoring points, horizontal and vertical coordinates should be noted (see Practice D 5254), and pertinent geologic information should be recorded. Pertinent geologic information would include such things as identifying the formation from which a spring is discharging and noting particular lithologic and structural descriptors (for example, spring issues at intersection of vertical joint in limestone and bedding plane of a shale bed).

7.3.3.2 In carbonate terranes, the ratio between maximum and minimum discharge of a spring and the shape of the hydrographs are indications of whether a spring is classified as an overflow or underflow spring **(64)**. In addition, Worthington **(9)** used the coefficient of variation of bicarbonate and sulfate to determine overflow/underflow springs. This classification is important in assessing the number of potential discharge points and monitoring points for a karst ground-water basin. If a spring is recognized as an overflow spring, it indicates the presence of underflow springs that carry some of the ground-water discharge, sometimes all of it when the overflow spring is not discharging. Both underflow and overflow springs must be included in a comprehensive ground-water monitoring network in karst terranes.

7.3.3.3 When collecting samples from alternative monitoring points, it is best to sample as close to a spring orifice or seep discharge as possible. Where possible, spring discharge should be measured and recorded whenever samples are taken. If the discharge cannot be accurately measured, stage height is an acceptable alternative, and even a visual estimate of discharge is better than no record at all. As in sampling a well, a visual description of the water sample should be recorded (for example, level of turbidity, coloration, presence of iron staining, presence of oil sheen, noticeable odors, etc.) and standard field parameters (for example, specific conductance, temperature, and pH) should be measured and recorded.

7.4 *Sampling Frequency*:

7.4.1 Water-quality parameters can be extremely variable in karst and fractured-rock aquifers. This is particularly true during and after recharge events that cause rapid changes in discharge at springs or rapid changes in hydraulic head at wells. Such events typically cause high-frequency, high-amplitude changes in water quality. These water-quality changes may be either in-phase or out-of-phase with discharge peaks or with each other. In order for samples to be representative of conditions in the aquifer, frequency of sampling should be selected to reflect this inherent variability rather than at pre-specified, fixed intervals as is often dictated by regulatory programs. A general discussion of sampling frequency is given in Ref **(65)**.

7.4.1.1 The correct interpretation of the variation of water-quality data for determining proper sampling frequency cannot be done with confidence unless it is known that the results were not subject to aliasing, a phenomenon in which a high-frequency signal can be interpreted as a low-frequency signal or trend because the sampling was too infrequent to accurately characterize the signal **(66)**.

7.4.1.2 The following discussion of sampling frequency assumes that properly designed and conducted tracer tests and hydraulic tests have identified representative downgradient monitoring points that are connected to the site and representative background monitoring sites that are not connected to the monitored site (see 7.2).

7.4.2 *Hydrographs and Chemographs*—The determination of an appropriate sampling frequency should be based on interpretation of the behavior of several physical and chemical parameters at springs and wells. Plots of spring discharge (or stage) and water quality as functions of time (hydrograph and chemograph analysis, respectively) have been used extensively in karst-aquifer studies **(14)** as tools for obtaining information about the ground-water flow dynamics of the karst system. (In aquifers where discharge is to subaqueous springs or seeps, monitoring is difficult, but possible—if they can be found.) Monitoring wells completed in fractured dolomite may also exhibit extreme temporal variations in hydraulic head and water-quality parameters and these variations can be used to characterize ground-water flow dynamics in similar aquifers **(17)**.

7.4.3 *Conventional Parameters*—A suite of easily measured parameters has commonly been used to characterize the variability of water-quality in karst aquifers. These parameters include discharge or head, specific conductance, temperature, and turbidity and are recommended as a minimum set of data to be collected. They should be measured at representative monitoring points continuously, or near-continuously, for a period of several weeks to several months and at least until several major recharge events have occurred.

7.4.4 *Determining Sampling Frequency for Target Compounds*—When monitoring pollutant releases from a site in karst or fractured-rock aquifers, the inherent variability of the system must be considered. The natural variation of head or discharge, temperature, specific conductance, and turbidity can be used to select the appropriate sampling frequency for contaminant or target compounds. For a monitoring system, the most important question to be answered is whether the maximum concentration of the target compound exceeds an established background or regulatory-action value at the point of compliance.

7.4.5 A general procedure for determining the sampling frequency of target compounds is outlined below:

7.4.5.1 Plot discharge (stage) for a spring or head for a well, specific conductance, temperature, and turbidity against time (plot all of them on the same graph, using different vertical scales, so that they may be compared). The continuous or near-continuous measurement of these parameters is necessary in order to prevent aliasing of the data.

7.4.5.2 Determine which parameter varies the most.

7.4.5.3 Establish the correlation and time-lag (if any) between maxima and minima of discharge (stage) or head, specific conductance, temperature, and turbidity.

7.4.5.4 Determine a sampling frequency that will capture the variability of the most-variable parameter.

7.4.5.5 Sample for the target compound(s) at this sampling frequency both at the background and at the downgradient-monitoring points. Samples should be collected through at least one major recharge event. This recharge event should be near to or greater than the average annual maximum recharge event. Samples must also be collected during baseflow conditions.

7.4.5.6 Plot the concentration of the contaminant compound(s), discharge (stage) or head, specific conductance, temperature, and turbidity against time for both high-flow and baseflow conditions. Establish the correlation and lag-time between maximum target compound concentration and the maxima and minima of discharge (stage) or head, specific conductance, temperature, and turbidity. These correlations determine the subsequent sampling frequencies for the target compounds.

7.4.5.7 If the maximum target compound concentrations are measured under baseflow conditions, periodic samples collected during lowest flow conditions may achieve the monitoring goals. If maximum target compound concentrations occur during high-flow conditions, then subsequent samples for those compounds must be collected during high flow. High-flow sampling frequency should initially be based on 7.4.5.1-7.4.5.4 and modified as data are collected and interpreted.

7.4.6 This procedure may indicate an optimum storm-related sampling frequency ranging from minutes to hours for some systems; sampling at this frequency is necessary through at least one major recharge event. Analytical costs can be lessened by analyzing every third sample. If the contaminant concentration data plot smoothly, it may not be necessary to analyze the stored samples; if they do not, it will.

7.4.7 At the start of a recharge event, it is impossible to know how significant it will be. At its middle or end, it is too late to collect samples that will characterize its beginning. Accordingly, it is always necessary to commence sampling at the start of an event. After the event, the decision to analyze or not to analyze the samples should be based on professional judgment and evaluation of the significance of the event.

7.5 *Meeting Regulatory Goals*:

7.5.1 Regulatory agencies require ground-water monitoring wells as a means of detecting statistically significant changes in water quality resulting from releases to ground water by various operations. However, alternative monitoring points such as springs and cave streams, shown to be draining from the site, may provide the most representative ground-water samples in some settings, and have been required in some states (see 7.3.3).

7.5.2 *Current Federal Regulations*—The Code of Federal Regulations (CFR) that addresses ground-water monitoring and corrective action at hazardous-waste-disposal sites can be found in Ref **(67)** (40 CFR Subpart F §§ 264.90 to 264.101 and 40 CFR Subpart B § 270.14(c)). These regulations contain specific information on monitoring ground-water quality (§ 264) and reporting requirements based on a comprehensive site investigation (§ 270). Section 264.97 specifically lists ground-water monitoring requirements that must be met in order to satisfy the requirements of § 264.98, Detection Monitoring;§ 264.99, Compliance Monitoring; and § 264.100, Corrective Action. Section 270.14(c), *Additional Information Requirements*, provides for specific information to be compiled and submitted in order to meet the provisions required under §§ 264.90 through 264.101 **(66)**.

7.5.3 *Modifications of Current Regulations*—Recent program evaluations have shown that specifically requiring certain items (for example, monitoring wells) has led to the development of inadequate ground-water monitoring systems that are designed solely to meet regulatory guidelines. The U.S. EPA is currently considering new, more flexible guidelines/regulations that allow the use of seeps, springs, and cave streams as monitoring points to supplement a monitoring-well network. Alternative monitoring points would have to meet the performance criteria described in Ref **(67)** § 264.97 [for example, monitoring wells at the point of compliance Ref **(66)** § 264.97(a)(2)] and the use of such alternative monitoring points would be based on a site investigation designed to assess the hydrogeologic conditions of the site. These new procedures have been outlined in Refs **(63, 67, 68)**.

7.5.3.1 Alternative monitoring schemes have been proposed and implemented at some facilities regulated under the Resource Conservation and Recovery Act (RCRA), where hydrogeologic conditions did not conform to the porous-medium approximation. The reasoning behind such variances was that a monitoring system consisting solely of monitoring wells that are unable to provide ground-water samples representative of a given site would not meet the intent or spirit of the law. However, monitoring ground-water quality at alternative, off-site monitoring points, while violating the letter of the law (because the points are offsite), would meet the intent and spirit of the law. Such variances from RCRA regulations are considered acceptable for existing and interim status facilities. Variances have not been allowed for a new facility because § 264.97(a)(2) **(66)** stipulates that monitoring must be conducted at the point of compliance (for example, the unit boundary or facility boundary).

8. Keywords

8.1 carbonate aquifers; fractured-rock; ground water; ground-water monitoring; ground-water sampling; karst; springs

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