Quantitative Approaches in Characterizing Karst Aquifers

By Charles J. Taylor[1] and Earl A. Greene[2]
[1] U.S. Geological Survey, 9818 Bluegrass Parkway, Louisville, KY, 40299
[2] U.S. Geological Survey, 8987 Yellow Brick Road, Baltimore, MD, 21237

Abstract

Karst aquifers are an important ground-water resource and are highly vulnerable to contamination due to relatively fast transport and limited attenuation processes. Quantitative understanding of karst hydrologic functions is integral to managing water resources and developing protection or remediation strategies. However, traditional methods of aquifer characterization and testing, based on Darcian approaches, provide misleading or inadequate quantitative data when applied to karst settings. This difficulty is partly a problem of scale (volume of aquifer tested), and partly a problem of the complex nature of the typical karst aquifer system.

Early approaches to studying karst concentrated on describing geomorphic features and their hydrologic functions, or understanding singular elements of karst flow dynamics, such as spring discharge, or hydraulic properties of solutional conduits. However, proper understanding of karst aquifers requires a systems approach in which the hydrologic function of each primary component—vadose zone, epikarst, and conduit network—is considered separately and as an integrated part of the whole system. The major difficulty facing the hydrologist is that karst aquifers typically exhibit dual ground-water flow regimes, that is, fast (conduit-dominated) flow and slow (diffuse) flow. In selecting investigative techniques to characterize properties of a karst aquifer, it is therefore important to determine how the data obtained by a particular test method are influenced by the fast-flow regime, slow-flow regime, or both. With this point in mind, several quantitative methods that are particularly useful in investigating the hydraulic parameters of the karst aquifer system are briefly discussed here.

Quantitative water-tracing tests, conducted with fluorescent dyes, are among the most useful types of field methods that can be employed in the investigation of a karst aquifer. A common misconception is that dye-tracing methods are too expensive, difficult, or unreliable, to use in many karst investigations. This is simply not the case. Like any other type of aquifer-testing technique, dye-tracing tests require careful planning and implementation, and a proper understanding of the applicability and limitations of the techniques and the data. One great advantage is that tracer tests can be designed and implemented to any field scale, and another is that the movement of the dye tracer almost exactly replicates the movement of water (and many dissolved solutes) through the aquifer.

Quantitative water-tracing tests require careful measurement of dye concentration at frequent sampling intervals and discharge through the sampled part of the aquifer, usually a spring. It is advisable that qualitative, or point-to-point tracer tests, using passive dye detectors and less frequent sampling, be conducted first to delineate ground-water flow paths, ensure that all potential dye-resurgence sites are known and sampled, aid in selecting the proper sampling frequency and duration, and assess the possible interference of ambient fluorescent solutes with detection and measurement of the tracer dye. The use of dye-tracing tests to delineate ground-water flowpaths and basin boundaries in karst aquifers is demonstrated by Bayless, Taylor, and Hopkins (1994) and Taylor and McCombs (1998).

The principal tool for analysis of quantitative water-tracing tests conducted with fluorescent dyes is the dye hydrograph, a specialized tracer breakthrough curve. The time of travel of the dye, indicated by the first detection of dye at concentrations above background fluorescence levels, provides a direct measurement of average ground-water velocity. The shape of the dye-hydrograph curve provides an indication of the dispersion of the dye as it migrates through the aquifer (Greene, 1999). For example, multiple peaks on a dye hydrograph may indicate splitting of the dye along multiple flow paths (conduits), or intermittent flushing of dye from hydraulic dead zones. Dye hydrograph analysis is particularly useful in contaminant transport investigations, because the tracer dye can be used as a surrogate pollutant. Estimates of peak contaminant concentration, persistence at concentrations that exceed quality criteria (such as maximum contaminant level, or MCL), and contaminant loading can be easily calculated for karst springs (Mull and others, 1988).

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Data obtained from quantitative dye-tracing tests can also be used to calculate a variety of parameters related to the geometry and hydraulic properties of any type of conduit network system. A good demonstration of the application of these techniques was presented by Fountain (1993) in a study of subglacial conduit networks. Examples of physical properties that can be calculated include conduit diameter, surface area, and hydraulic depth (assuming open-channel flow conditions). Estimates of fluid dynamic parameters that can be determined include the Peclet number, Reynolds number, Froude number, and hydraulic head loss. A summary of these methods and a software program that greatly facilitates the calculations involved in dye-hydrograph analysis was recently published by Field (1999).

Traditional aquifer tests can be used to estimate rates of ground-water movement and hydraulic properties such as transmissivity and storativity if special consideration is given to the dual-flow nature of karst aquifers while interpreting the aquifer test data. Recognition must be given to the fact that the framework of the karst aquifer is composed of integrated networks of fractures and solutional conduits of different sizes and interconnection. The aquifer test data represents a measurement of the composite hydraulic response of families of fractures and solutional conduits having different hydraulic characteristics (Streltsova, 1988). The larger solutional openings act collectively as the initial source of water being pumped during an aquifer test. Typically, these larger solutional openings are hydraulically connected to smaller, more diffuse sets of fractures in the aquifer. As the pumping continues, the fluid pressure in the larger solutional openings is reduced, resulting in hydraulic gradients which allow water in the diffuse fractures to provide recharge to the larger solutional openings. Thus, in describing the hydraulic properties of the karst aquifer, four physical parameters must be described: T, the transmissivity of the solutional openings; S, the storativity of the solutional openings; S_f, the storativity of the network of diffuse fractures; and β, the rate of fluid exchange between the network of fractures and the solutional openings (Greene, Shapiro, and Carter, 1999).

As a tool for simulation of flow and transport in karst aquifers, numerical models are frequently used. At present, great difficulties exist in accurately simulating karst flow systems at the local or subregional scale because of the difficulty in developing numerical models that realistically represent boundary conditions for conduit networks. Nevertheless, numerical models are among the best quantitative tools for gaining a better understanding of the functioning of individual karst hydrology components and for predicting how the system works as a whole. The two most common types of approaches can be classified as either a black box (or lumped parameter) approach or a distributed parameter approach. The black box approach uses techniques such as recession analysis and transfer/kernel functions to simulate karst aquifers. Several examples are shown where recession analysis is used to estimate regional hydraulic parameters and the volume of available ground-water resources. In addition, we demonstrate the use of kernel functions to interpret and simulate karst responses to precipitation.

The limitations of the black box (or lumped parameter) model approach become apparent when a known heterogeneity that has a physical basis needs to be modeled. Tracer-test results (velocity, breakthrough times) often show that slow-flow or fast-flow dominates different parts of the aquifer, for example, as ground water moves from the epikarst to the conduit network. Each of these aquifer components represents a particular heterogeneity that cannot be ignored in the modeling process. Thus, a distributed parameter model approach is used to incorporate known heterogeneities determined from field data. The three major distributed parameter approaches to describing flow include; 1) equivalent porous media, 2) discrete fracture, and 3) double porosity or double continuum approach. Examples are shown and each type of model is discussed.

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