

Steps Toward Better Models of Transport in Karstic Aquifers

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Abstract

One of the most difficult challenges of geophysical sciences is the accurate modeling of contaminant transport in karstic aquifers. This task requires expertise, knowledge and resources which transcend any single agency, company or university; a cooperative approach to this problem is needed. The Hydrogeology Consortium is a new scientific organization seeking to catalyze the development and use of better models of flow and transport in karstic aquifers; see hydrogeologyconsortium.org. A new conceptual model of karstic aquifers has been developed and will provide the basis for the development of a new mathematical and computational model.

INTRODUCTION

It is well known that models of contaminant transport which employ the advection-diffusion equation perform very poorly in karstic settings. There is a strong need for better models of flow and transport, which simulate realistically the conduit system of a karstic aquifer, and its effect on flow and transport. In the following section the nature of the problem is described, then an important and necessary administrative step in addressing the problem is described in the subsequent section. A new conceptual model of karstic aquifers is described in the following section, then the process of sequestration and the importance of springs are briefly discussed.

NATURE OF THE PROBLEM

Karstic aquifers, as well as other highly heterogeneous aquifers, are characterized by the presence of preferred pathways (e.g., conduits) in which flow speeds are very much larger than average. Contaminants within these pathways travel much faster, and consequently have much shorter travel times, than predicted by standard models based on Darcy's law and the advection-dispersion equation. This is a dangerous situation; for example, conventional modeling may predict a water supply to be safe from contamination, when in fact it is not. The result of an inaccurate prediction of contaminant behavior can be a costly clean-up.

The problem of accurately predicting contaminant transport is made more difficult by the fact that the preferred pathways are difficult to observe. The most common and reliable (but tedious and costly) method of locating large karstic conduits is by scuba diving. In virtually all field situations, the available site-characterization data will be of unsatisfactory density and quality.

This problem has not been vigorously addressed by the scientific community for several reasons: it is large in scope, difficult to analyze and lacking in adequate data. However, contaminant transport is an important problem that is likely to get worse, as population pressures increase. It needs to be addressed.

THE HYDROGEOLOGY CONSORTIUM

About three years ago a group of individuals concerned about aquifer quality and protection formed the *Hydrogeology Consortium*, in order to provide a forum in which to address these concerns. The HC is an independent, not-for-profit organization which is affiliated with the Geophysical Fluid Dynamics Institute at Florida State University.

The vision of the Consortium is to have an abundant supply of clean water for human use while maintaining a healthy natural environment. To help achieve that vision, the Consortium has chosen as its mission *to cooperatively provide scientific knowledge applicable to ground water resource management and protection*. The primary goal is improved effectiveness and efficiency of management and protection of water resources, particularly ground water, through better understanding and application of scientific knowledge. The activities of the Consortium include, but are not be limited to :

- endeavoring to develop the necessary scientific knowledge and collect field data, when and where they are found to be lacking, in order to continuously improve our conceptual understanding of hydrogeological environments and associated models.
- fostering the cooperative development of valid scientifically based models of ground water: including its flow and the behavior of waterborne contaminants, as critical factors in determining the health of complex three-dimensional ecosystems.

- coordinating the development and implementation of specific pilot studies and laboratory simulations designed to calibrate and test these models.

Although the activities of the Consortium will be focused primarily on issues of direct concern to the State of Florida, the scientific problems of ground water it will address are endemic to many other areas.

A NEW CONCEPTUAL MODEL

The distinguishing feature of karstic aquifers is the set of connected conduits which form preferred pathways for flow and transport. This feature forms the basis for a new model, consisting of a classic porous matrix, permeated by a tree-like network of conduits. A conduit is defined as any interconnected pathway of sufficient size to have turbulent flow. With a typical head gradient of 10^{-4} , turbulent flow occurs in conduits having cross-sectional area greater than 10 cm^2 .

In the simplest form of the model, water is assumed to enter the smallest conduits, then proceed through a series of increasingly larger conduits, finally emanating at a spring. Conservation of water yields a unique relation among conduit length, conduit area and map area. The distance between adjacent conduits depends on their size (i.e., cross-sectional area) and the recharge rate. In Florida, the spacing between smallest conduits is typically 50 – 100 m.

Resistance to flow in conduits is much less than that in the adjacent matrix. Consequently nearly all regional flow is carried by conduits. By the same token, matrix flow is local, directed toward the nearest conduit. The local gradient associated with this conduit recharge may be quite different than the gradient associated with regional flow.

Dispersion of contaminants occurs by a variety of mechanisms in this model. First is dispersion in the matrix, associated with the local recharge. It is likely that this can be adequately quantified by the advection-dispersion equation. Second is dispersion within a single conduit due to turbulent flow. Rather surprisingly, turbulent dispersion is much weaker than Taylor dispersion, so that this mechanism may be ignored as a first approximation. Third is travel-time dispersion caused by the existence of multiple conduit pathways having a spectrum of lengths, areas and flow speeds. This latter mechanism is likely to be dominant in field and regional settings, is certain to be site-specific and is likely to be difficult to quantify.

SEQUESTRATION

The new aquifer model, consisting of a conduit network imbedded in a porous matrix, has the ability to simulate an important physical process: *sequestration*. In the parlance of continuum mechanics, the conduits and matrix form a set of two interpenetrating continua, each of which can have its own distinct pressure. If the conduit system has a larger pressure than the matrix (caused for example by a rainstorm flooding a sinkhole), water will be actively forced from the conduits into the matrix. Any contaminant carried by that water will be sequestered in the matrix, to be released at some later time when the pressure differential is reversed (as in a time of drought). The process of sequestration can have a profound effect on the break-through curve of the aquifer, greatly extending the residence time of contaminants. It is important to understand and quantify sequestration, but virtually nothing is known of this process at present.

THE IMPORTANCE OF SPRINGS

Springs are singular points of an aquifer system. Typically an aquifer is recharged primarily by rainfall distributed over the catchment area (though sinking streams provide a few point sources), and is discharged at a few singular locations, called springs. The properties of the discharge at a spring (head, flow rate, water temperature, water chemistry) are governed by, or strongly modified by, the physical nature of the aquifer through which the water has moved. It follows that there is a wealth of information about the aquifer and the catchment area contained in these properties.

In order to extract information of aquifer properties from spring-discharge data, several things are needed. First is a realistic model of the aquifer, incorporating the salient physical processes in a minimal set of parameters, which can be run as a forward model to simulate the properties of the spring discharge. Second is an inverse model, based on then forward model, which is capable of determining the aquifer parameters from a perfect set of discharge data (which does not exist). Third is adequate data obtained at certain springs. “Adequate” data should be of the proper type (e.g., head, flow rate, temperature, etc.), of sufficient duration (e.g., several years), of sufficient temporal density (e.g., daily) and of sufficient accuracy.

Springs are the integrators of change occurring in their catchment basin, and the consequence of change can be deduced from a lengthy and detailed data record. Given the need for a relatively long data record, it would be prudent to begin now to collect the data necessary to characterize an aquifer basin associated with any springs of interest or concern.