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Conceptual models for karstic aquifers

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Abstract

Karstic carbonate aquifers are extremely heterogeneous with a distribution of permeability that spans many orders of magnitude. They often contain open conduit flow paths with hydraulic characteristics more like surface streams than ground water. Karstic carbonate aquifers have highly efficient interfaces with surface water through swallets and springs. Characterizing parameters include: area of ground-water basin, area of allogenic recharge basins, conduit carrying capacity, matrix hydraulic conductivity, fracture hydraulic conductivity, conduit system response time, and conduit/fracture coupling coefficients. The geologic setting provides boundary conditions that allow the generalized conceptual model to be applied to specific aquifers.

Keywords: karst aquifers, karst modelling

Introduction

In order to model karst aquifers, it is necessary to know what one is attempting to model. That is, one must have a conceptual model before building geochemical, mathematical, or computer models. The conceptual model is usually physical — an interconnected sequence of recharge areas, permeability distributions, and geologic substrates that collectively provide a visualization of the way in which water is added to the system, stored in the system, transmitted through the system, and discharged from the system. However, a well-structured conceptual model should be translatable into mathematics - the physical picture replaced by a set of coupled differential equations that describe the transport processes along with the boundary conditions imposed by the geologic setting. In practice, of course, this translation is at the core of the problem of karst aquifer modeling.

Modeling of karst aquifers in the contemporary meaning of the term "modeling" has not been easy. Anderson and Woessner (1992) in their treatise on ground water modeling list "karst" as one of the advanced topics, and summarize a few of the attempted models up to the time of writing, none of which work very well.

Investigators, in their efforts to sort out the essential features of karst aquifers have often taken one of two essentially different viewpoints. One might be called a view through space. The aquifer with all its parts is taken as a given condition. The discussion then focuses on recharge and groundwater movement without consideration for modifications in the aquifer itself. Many of the groundwater flow models take this viewpoint. The other might be called a view through time. The discussion begins with a mass of fractured carbonate rock and then focuses on the evolution from a fracture aquifer to a fully developed conduit aquifer. Many of the geochemical models take this viewpoint.

It is the objective of this paper to revisit the physical framework within which all mathematical or computer models must be constructed. Of necessity, this will be a view through space — a description of the varieties of aquifer that actually exist.

One early attempt at conceptualizing karst aquifers (White, 1969) focused attention on the variety of geologic settings and their controlling influence on groundwater flow patterns. This scheme was later expanded (White, 1977) to take into account the overall area of the groundwater system. Based only on the type of permeability, Shuster and White (1971) divided aquifers into "conduit flow" aquifers, which contain well-developed conduit systems, and "diffuse flow" aquifers which do not. This binary classification was soon recognized as inadequate, and further attempts to organize a classification scheme were made. Smart and Hobbs (1986) added recharge source and aquifer storage as two additional "coordinates" to construct a three-parameter aquifer classification. Ray et al. (1994) carried this concept a step further to arrive at a combined risk factor for plotting a groundwater sensitivity map for the State of Kentucky.

As more details concerning the variety and properties of karst aquifers have been filled in over the past decade or two, it was inevitable that the same concepts would be formulated by different researchers more or less independently and more or less at the same time. As a result there exists in the literature a certain jockeying for position, for setting the language of the concepts, that is not easy to untangle. The matter is not made easier when many important conceptual insights are hidden in abstracts of unpublished papers, in theses, and in government reports.

Plumbing

The essential components of the karst aquifer flow system are sketched in Fig. 1. Not all of these components are present in all aquifers, and their presence and relative importance are an important part of distinguishing one aquifer from another.

Recharge

At least four sources of recharge for karst aquifers can be recognized:

1. Allogenic recharge: Surface water injected into the aquifer at the swallets of sinking streams.

2. Internal runoff: Overland storm flow into closed depressions where it enters the aquifer through sinkhole drains.

3. Diffuse infiltration: Precipitation onto the land surface, where it infiltrates through the soil and may be held for days or weeks in the epikarst before it migrates downward through the rock matrix or along fractures to reach the water table.

4. Recharge from perched catchments: Many geologic environments support locally perched groundwater systems above carbonate aquifers. This water reaches the main aquifer by means of vadose shafts and open fracture systems along the margins of the perched aquifers.

Permeability

The "karstification" of an aquifer is in large part measured by its permeability distribution. For many years, this has been discussed in terms of the "triple permeability" model. Karst aquifer permeability consists of

1. The matrix (or granular) permeability of the bedrock itself.

2. Fracture permeability

3. Conduit permeability

The flow fields through each of these permeability types operate on different scales

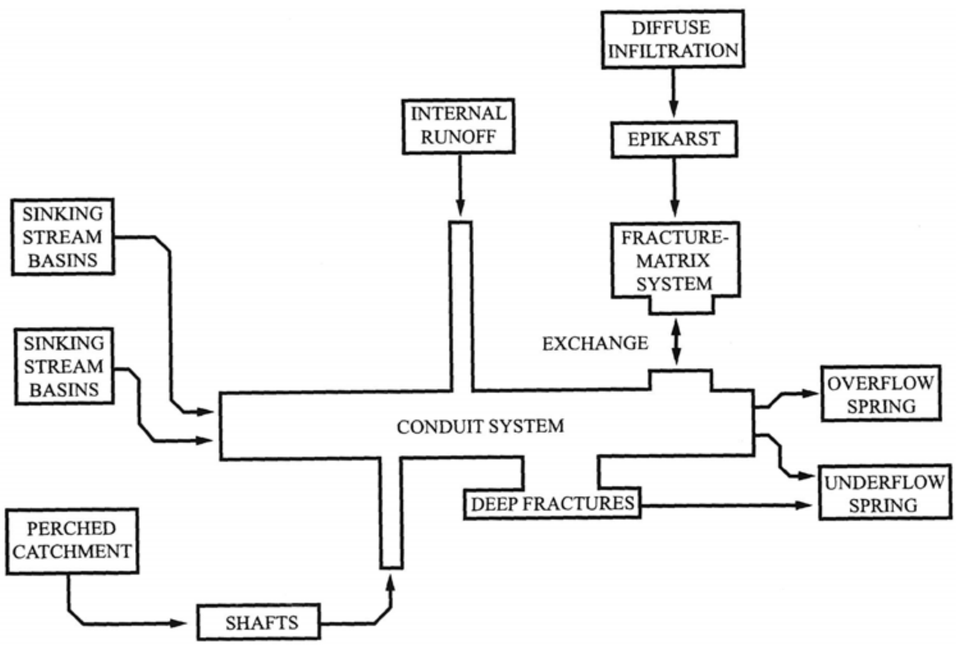

Fig. 1. Conceptual model for a carbonate aquifer.

(Teutsch and Sauter, 1991). The hydraulic conductivity of the rock matrix can be measured on test blocks at the laboratory scale. The hydraulic conductivity produced by the fracture permeability must be averaged over a large volume of rock at a scale of hundreds of meters. Values calculated from pump and packer tests on appropriately sited wells can probe the aquifer at the fracture scale. The conduit system operates on the scale of the entire groundwater basin - a scale of kilometers to tens of kilometers. Travel times in the conduit system can be very short and although both have units of velocity, it is not appropriate to speak of a hydraulic conductivity of the conduit system.

The matrix permeability of many Paleozoic limestones and dolomites is very low and can often be ignored. Young limestones such as those of Florida and the Caribbean islands may have very high matrix permeabilities. There is indeed a continuum, and actual measurements are needed to determine the importance of matrix permeability.

Fracture permeability requires two parameters, the fracture aperture and the fracture spacing. Both are statistical and have a range of values within the same aquifer. Fracture permeability is modified by solution so that fracture apertures range from tens or hundreds of micrometers in unmodified limestone up to 10 millimeters. The latter is the aperture at which non-linear effects begin to appear in the flow field and marks a useful boundary between large fractures and very small conduits.

Conduits can range in size from 10 mm to tens (sometimes hundreds) of meters. Hydrologically, they behave much like storm drains. In map view, conduits take on many different patterns depending on local geology and various characteristics of the flow field itself.

To understand the dynamics of a karst aquifer, then, it is necessary to understand the rate of recharge into the various components of the permeability and the exchange of water between these components.

Discharge

A distinguishing feature of karst aquifers is that most of the groundwater is discharged through a small number of large springs. In some aquifers, the entire discharge is through a single spring. In other aquifers there is a distributary system to a small number of springs. One or a few of these carry the base-flow discharge and are called "underflow springs" while other springs flow only during periods of high discharge and are called "overflow springs" (Worthington, 1991).

The discharge from karst springs is a composite of all water moving through the aquifer. The spring (or springs) therefore is an optimum location for measuring hydrographs, chemographs, and also for monitoring the aquifer for contaminants.

Groundwater basins

Although aquifer thickness is an important parameter in granular aquifer modeling, the lateral extent of the aquifer is often only loosely defined. Karst aquifers, in contrast, borrow a concept from surface water, that of the "ground-water basin." Much like surface-water basins, but without the definitive boundary provided by topographic highs, groundwater basins can be delineated, although basin boundaries may shift with water levels and piracy and flood-overflow routes across basin divides are common. Within the confines of a karst groundwater basin, all recharge water makes its way to a single spring or related group of springs. The spring outlets define the downstream end of the basin.

Mostly, groundwater basins have been established by systematic tracer tests (Jones, 1973; Quinlan and Ray, 1981; Quinlan and Ewers, 1989) but other evidence is provided by the patterns of explored caves, water-table gradients, geological constraints, and area/discharge relationships.

Parameters for karst aquifers

Instead of trying to pigeonhole aquifers into specific categories along the lines of "conduit-diffuse" or the three-dimensional scheme of Smart and Hobbs (1986) and its embellishments, an alternative approach might be to set down the important parameters that characterize karst aquifers. These parameters should lend themselves to numerical measurement. Then, if it were really necessary to classify a particular karst aquifer, it would be represented by a point in an n-dimensional parameter space where n is the number of characterizing parameters.

Area of the groundwater basin

The total area of the groundwater basin, including surface catchments of allogenic streams, is easily determined once the underground divides of the groundwater basin have been established.

Allogenic recharge

Two parameters arise:

1. The total area of the allogenic basins, which is simply the sum of the areas of individual sinking-stream basins.

2. The total allogenic recharge, Q_a .

Allogenic recharge can be measured by direct gauging of allogenic surface streams at their swallets, taking account that many sinking streams lose their water at a series of swallow points upstream from the main swallet. The total allogenic recharge is then obtained by summing the contributions of the individual allogenic basins. Allogenic recharge will have a rapid response to storms.

Conduit carrying capacity

Karst groundwater basins often have a surface component. In some karst basins the drainage is completely underground with no remnant of a surface stream or, indeed, of a surface stream channel. Other basins retain a dry stream bed that carries water only during flood flows. Still others retain a perennial surface stream that loses only part of its flow to the subsurface.

The conduit system has a certain carrying capacity, Q_c, which can be compared with Q_a :

1. $Q_c > Q_a$ (max): All allogenic recharge including storm peak can be accommodated by the conduit system.

2. Q_a (max) > Q_c > Q_a (base): The conduit system can accommodate base flow, but flood flows that exceed Q_c spill over into the surface channel.

3. $Q_c > Q_a$ (base): The conduit system cannot accommodate all of the base flow, so the excess allogenic runoff must travel through the karst basin as surface flow.

It seems that the critical flow when $Q_a = Q_c$ would be a useful parameter for characterizing the conduit permeability. It would require gauging the surface channels above and below the swallet and recording the discharge at which the swallet is exactly overtopped.

Matrix hydraulic conductivity

K_m is best measured on bedrock cores using a permeability cell. The rock cores must be selected carefully to avoid fractures. For most Paleozoic carbonates, K_m will be too small to be significant.

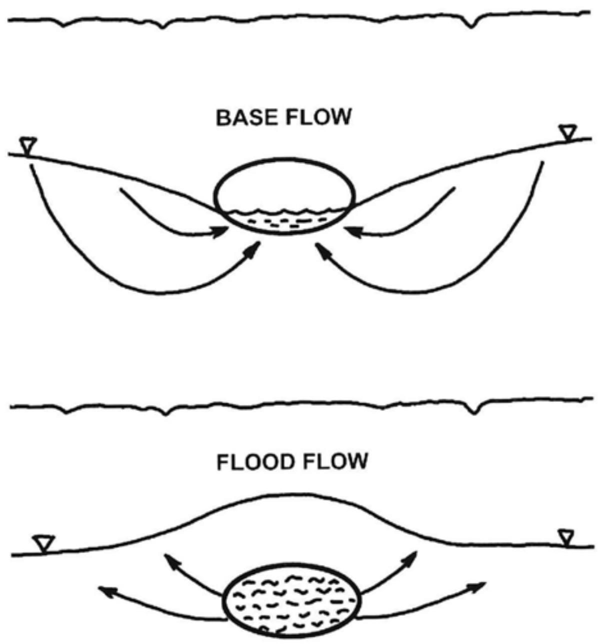

Fig. 2. Sketch showing exchange of groundwater between conduit system and matrix and fracture system during base flow and flood flow.

Fracture system hydraulic conductivity

K_f must be determined by pumping tests or packer tests. The difficulty is in siting wells that will intersect a representative sampling of the fractures. Fracture trace mapping on aerial photographs can often be used to identify fracture swarms and intersections of fracture swarms. These represent the high-permeability pathways within the fracture permeability. Assignment of a hydraulic conductivity to random joints and bedding-plane partings is very difficult without drilling an unrealistic number of wells.

Conduit-system response time

Because conduit flows are often turbulent, it is not appropriate to speak of a conduit hydraulic conductivity. Two measurements can provide a surrogate. One is travel time determined by quantitative tracer breakthrough curves from swallets to spring. The other is response time(s) computed from the recession limbs of storm hydrographs measured at the springs. Travel time and response time are not equivalent measurements, but each will tell something of the rate of movement of water through the conduit system and thus indirectly how well the conduit system is developed.

What no quantitative measurement will provide, however, is the geometry of the conduit system itself. Direct exploration and survey of active conduits, including water-filled portions mapped by divers, gives very precise information, albeit in descriptive form. In very few karst aquifers, however, is a sufficient sampling of the conduit system possible.

Conduit/fracture coupling coefficients

Conduit systems act as low-hydraulic-resistance drains, so that the flow field in the surrounding matrix and fracture system is directed toward the conduit rather than toward groundwater discharge zones on the surface. During base flow conditions, groundwater recharged from diffuse infiltration and stored in the fracture and matrix porosity will drain toward the conduit system (Fig. 2). However during storm flows, the conduit system may flood to the roof and indeed establish a substantial piezometric head above the roof of the conduit. During intervals of storm flow, the flow field will reverse and water will move from the conduit into the surrounding fracture and matrix porosity. The effectiveness with which these two (or three) systems are coupled, combined with the intrinsic hydraulic conductivity of the matrix and fracture systems, will determine the rate of movement of groundwater into and out of storage and also the base-flow discharge of the springs.

Possible routes to the calculation of conduit/fracture coupling coefficients include:

1. Deconvolution of spring hydrographs, particularly the relationships of peak flow to base flow.

2. Analysis of the normalized base flow for various families of drainage basins. Base flow is proportional to basin area, but the proportionality constant varies with different hydrogeologic settings.

3. (Speculative.) Comparison of storm response in a well drilled on a fracture swarm near a conduit, vs. the storm response of a second well placed in the conduit to act as a piezometer.

Geologic boundary conditions

The aquifer system described above is the naked plumbing. It must be clothed in the geologic framework before the concept is complete. If we knew the mathematics, the previous description would give us the differential equations and identify the coefficients within the equations. The geology provides the boundary conditions that allow us to select the correct solution. The geology is also what links the generalized model for karst aquifer behavior to the specific aquifer of interest.

Karst aquifer/surface basin architecture

In regions of fluviokarst such as eastern United States, karst aquifers and karst drainage basins are embedded in larger basins that include areas of non-carbonate rock. The placement of the carbonate sequence within the larger basins is the primary constraint that determines areas of allogenic recharge, location of springs, and general limitations on possible flow paths.

Basin relief

The head difference between recharge area and springs is the primary driving force for the movement of water through the aquifer.

Lithologic and stratigraphic factors

Factors having to do with the carbonate bedrock are:

1. Thickness of the carbonate rock sequence.

2. Lithologic character of the carbonate rock. Limestones tend to develop more elaborate conduit systems than dolomites. Sandy limestones can be as karstic as nearly pure limestones, but shaly limestones tend to have limited conduit- and surface-karst development. Variation of lithology in the stratigraphic section focuses groundwater flow and conduit development into favorable rock units.

3. Confining layers. Shales, primarily, but also sandstones and igneous dikes, interbedded within the carbonate section can block groundwater flow, limit vertical circulation, confine flow in artesian conditions below the confining layer, and perch the groundwater flow above the confining layer.

4. Clastic rock units below the carbonate sequence can perch groundwater flow and prevent deep circulation. Clastic rock units above the carbonate sequence act as capping beds and limit or rearrange recharge.

Structural influence and control

Structural influences combine with stratigraphic and lithologic factors to place boundaries on possible routes of groundwater flow. Structural controls operate on many size scales from regional features down to individual joint orientations. These are outlined only in very general terms:

1. Degree of folding. In regions of strongly folded rock, conduits tend to be oriented along the structural strike, both because of the larger aperture of strike joints and because of the orientation of favorable lithologies for conduit development. In regions with little folding, the nearly flat-lying rocks provide two-dimensional flow paths along bedding-plane partings with the development of more highly integrated drainage patterns.

2. Regional dip. Aquifers where the bedrock dip is (more or less) in the downgradient direction tend to develop shallower flow paths than in aquifers where groundwater must move across the structure. Deeper circulation and completely flooded conduits are more common.

3. Faults. Faults play several roles. Active faults can act as paths of high permeability and concentrate groundwater flow. Old, stable faults tend to be sealed by secondary mineral deposition and have little influence on flow paths. Faults that have moved poorly soluble or non-soluble rocks into potential paths of groundwater flow create groundwater dams which can divert flow.

From conceptual models to mathematical and computer models

Comparison of the aquifer components in Fig. 1 with the large number and diverse character of aquifers that have been examined in detail, suggests that the conceptual model is reasonably complete or can at least be easily modified to new situations. The processes of groundwater flow are individually amenable to theoretical analysis and mathematical description. Most of the hydraulic conductivities, recharge terms, and exchange terms have been identified, and there is at least the beginning of a methodology for obtaining numerical values for these parameters. Most of the geologic boundary conditions are sufficiently well understood to also be reduced to mathematical terms. What remains is our general inability to predict the layout of the conduit system. In the most realistic models that have been constructed so far, the conduits are put in "by hand" and the success of the model depends on how accurately this can be done.

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