GROUNDWATER IN KARST: CONCEPTUAL MODELS

extract from pages 399-401 of:
Gunn, J., (editor) *Encyclopedia of Caves and Karst Science*, Fitzroy Dearborn, NY.

Groundwater is present in virtually all rocks but the defining characteristic of karst aquifers is the presence of water in an interconnected network of solutionally enlarged fractures. These enlarged fractures are sometimes called channels, especially where apertures are less than 1 cm. The vast majority of enlarged fractures are of this size. Where apertures exceed one centimetre then turbulent flow is likely, and the enlarged fractures are called conduits. Where people can enter the conduits they are called caves. Small channels tend to have elliptical shapes, being elongated along fractures. As aperture increases there is a progression towards a circular shape, as long as the conduit is below the water table. Conduits above the water table tend to be eroded downwards and hence are usually much taller than they are wide.

The three fundamental requirements for a karst aquifer to develop are a soluble rock, flow through the rock of a fluid capable of dissolving the rock, and sufficient time. This discussion considers only carbonate rocks (limestones, dolostones, and metacarbonates), and water acidified by dissolved carbon dioxide from the atmosphere or soil, since these are the principal constituents in about 95% of carbonate aquifers. Dissolution occurs where meteoric water is able to infiltrate and flow through the rock. This situation includes all unconfined carbonate aquifers and some confined aquifers. High concentrations of dissolved solids (>10 000 mg L^{-1}) in an aquifer are an indication that flow through the rock is sluggish and karstification is likely to be slow. Conversely, potable water in a carbonate aquifer is an indication of active flow and such an aquifer is almost certainly karstified. The third requirement for karstification is time. The evidence from field studies and from numerical modelling indicates that conduit networks can be created in as short a period as a few thousand years where there is a combination of steep hydraulic gradients, large initial apertures, and short flow pathways. However, periods of up to a million years are required in most aquifers. Most carbonate rocks were formed tens to hundreds of millions of years ago and many have been exposed at the surface for at least some millions of years, so there is almost always ample time for karstification to have taken place in any carbonate rock exposed at the surface.

Definition and evaluation of flow in carbonate karst aquifers has been subject to much speculation in the past. Only in the last 30 years has a coherent understanding emerged of how karst aquifers develop, as a result of progress in three main areas. First, experiments in the 1970s and 1980s showed that dissolution rates of calcite and dolomite drop precipitously as chemical saturation approaches. The implication is that fractures *throughout* a limestone aquifer can become enlarged, rather than just in the upper few metres, as earlier experiments had implied. A second development since the 1990s has been the use of computer modelling to integrate this new knowledge of dissolution kinetics with hydraulic equations to show the rate and distribution of conduit development in carbonate aquifers. Third, detailed measurements have shown that in most carbonates flow into boreholes occurs at just a few locations, and that these locations are fractures that have been greatly enlarged by dissolution. Thus it is the dissolution of the bedrock (i.e. karstification) that results in carbonate rocks becoming productive aquifers. It is now possible to combine these three developments to understand the processes and products of karstification.

Carbonate rocks of all ages evolve into karst aquifers. For instance, at one extreme there are caves in Archean marbles more than 2 billion years old near Lake Baikal in Russia, and at the other extreme there are caves in limestones less than 100 000 years old in the Bahamas. Young carbonates are unlikely to have been deeply buried below the surface, and so retain a high porosity. On the other hand, compaction has usually resulted in the loss of most of the intergranular porosity of pre-Cenozoic carbonates, although fracture openings develop and persist. Karstification in the older, more compacted carbonates has been better studied than in younger rocks. The conceptual model presented for flow in these aquifers is based on the relationship between porosity components (the fraction of void space) and permeability (the ease of flow through the rock). This standard model is followed by an exploration of the differences in young aquifers.

Most pre-Cenozoic carbonate aquifers have well-developed bedding planes and joints, and these intersecting fractures result in fracture porosity and permeability in these aquifers. The matrix blocks between the fractures yield a second type of porosity and permeability, and the linear, interconnecting conduits form a third order of porosity and permeability. Together, these three types of permeability result in a triple porosity (or triple permeability) aquifer. Tables 1 and 2 give examples of these three permeability types in four contrasting carbonate aquifers. The rock matrix accounts for almost all the porosity (usually >95%) in carbonate aquifers, but the pores are usually small and often poorly connected, and so matrix permeability is low. The fractures typically have apertures of 0.01–0.1 mm, and collectively have a much lower porosity than the matrix. However, because the fractures are connected together they result in moderate permeability. The third porosity element consists of the interconnected network of channels and conduits arising from solution. The network of solution channels varies from hierarchic, convergent tributary systems to braided maze patterns. In both cases there are large numbers of small channels (<1 mm in aperture) feeding larger channels and conduits, with the largest conduits being in the down gradient parts of the aquifers close to the springs. The conduit network dominates the transport of water through the aquifer although it makes up only a small fraction of the porosity of carbonate aquifers (Table 2).

Young carbonate aquifers are somewhat different from older aquifers. Porosity is much higher than in older aquifers because of the limited compaction, and matrix permeability can be high in these aquifers, in part due to the presence of unconnected voids, known as vugs. The effect of fracturing is more variable than in older aquifers. Conduits form both along fractures and also as vug-linking channels, which have apertures in the millimetre to centimetre range. In some young limestones there are zones where the vug-linking channels are so ubiquitous that the rock appears like a sponge. However, the lateral extent of these zones is uncertain, and the processes responsible for their development have yet to be fully understood.

Channels and conduits form the principal pathways for water movement through carbonate aquifers, and the average velocity from many tracer tests along large conduits is 1700 m day^{-1}. Where there are sinking streams recharging a karst aquifer and springs draining it, then tracer tests are commonly used to evaluate which sinks are connected to which springs. However, evaluation of conduits is much more difficult where recharge to a karst aquifer is only by percolation and where springs are not visible (e.g. where an aquifer discharges into large rivers, lakes, or along coasts). Boreholes are very useful in evaluating matrix and fracture flow, but are very problematic in evaluating conduit flow because of the low probability (0.01–0.02) of a borehole intersecting a conduit. Therefore, combining results from both boreholes and springs gives a much more comprehensive understanding of how a carbonate aquifer behaves than either alone can do.

The mode of recharge is important to aquifer evolution and a distinction is commonly made between allogenic and autogenic karst aquifers. The former receive some recharge from non-karst rocks, while the latter are fed solely by precipitation falling onto the area of outcrop or the overlying soil / sediments. In practice all "allogenic" aquifers also receive some autogenic recharge, although the proportion can be quite small, and some aquifers that are presently "autogenic" may have received allogenic recharge in the past. Allogenic recharge is usually concentrated and occurs where surface streams sink underground but recharge through a permeable non-carbonate caprock is also possible. In contrast, most autogenic recharge is dispersed and either enters the carbonate bedrock directly at outcrop or after infiltrating through the soil and any superficial deposits. However, concentrated autogenic recharge also occurs where dolines act to focus flow in the epikarst.

Sinking streams provide ideal tracer injection points, and many thousands of successful tracer tests have been conducted between sinking streams and springs that may be as far distant as several tens of kilometres. The springs in allogenic karst aquifers are known as resurgences, and are often characterized by substantial variation in water quality since they reflect the changing water quality of the sinking streams. Furthermore, streams often sink into accessible caves, and cave exploration and cave studies have provided substantial knowledge about allogenic karst aquifers.

Groundwater in Karst: Conceptual Models: Table 1. Matrix, fracture, and channel permeability in four carbonate aquifers (after Worthington, 1999)

	Hydraulic conductivity (ms^{-1})		
Area	**Matrix**	**Fracture**	**Channel**
Silurian dolostone, Smithville, Ontario, Canada	1×10^{-10}	1×10^{-5}	3×10^{-4}
Carboniferous limestone, Mammoth Cave, Kentucky, United States	2×10^{-11}	1×10^{-5}	3×10^{-3}
Cretaceous chalk, England	1×10^{-8}	4×10^{-6}	6×10^{-5}
Cenozoic limestone, Yucatan, Mexico	7×10^{-5}	1×10^{-3}	4×10^{-1}

Groundwater in Karst: Conceptual Models: Table 2. Matrix, fracture, and channel porosity in four carbonate aquifers (after Worthington, 1999)

	Porosity (%)		
Area	**Matrix**	**Fracture**	**Channel**
Silurian dolostone, Smithville, Ontario, Canada	6.6	0.02	0.003
Carboniferous limestone, Mammoth Cave, Kentucky, United States	2.4	0.03	0.06
Cretaceous chalk, England	30	0.01	0.02
Cenozoic limestone, Yucatan, Mexico	17	0.1	0.5

Autogenic karst aquifers feed springs known as exsurgences. Where recharge is dispersed, the relatively slow percolation of water through the soil and epikarst zones into the conduits results in there being relatively little variation in water quality at exsurgences, and discharge variations are often less than at resurgences. However, where recharge is concentrated it is also more rapid and tracer tests from dolines in areas of polygonal karst have recorded velocities similar to those from sinking streams. The focusing of flow starts at the surface in dolines or in the epikarst zone with small conduits, which coalesce to form progressively larger conduits in a down gradient direction. Gaining knowledge about these conduits in the aquifer is difficult, however, as tracer testing is only possible where there is surface water (usually only during periods of high rainfall) or where water is introduced artificially from a tanker. Passable cave entrances in dolines or directly into the epikarst are less common than at sinking streams and most exsurgences are flooded and therefore accessible only by diving. Thus much less is known about the conduits in autogenic aquifers than in allogenic aquifers. Nevertheless, mathematical modelling has shown that autogenic karst aquifers should develop conduit networks, and this is substantiated by, for instance, exploration in areas of polygonal karst and in autogenic alpine karst aquifers. There are over 70 caves that have been explored to a depth of more than 1000 m and most are found high on mountains, lack sinking streams, have narrow entrance passages but have much larger cave passages at depth (often with substantial cave streams), and flow to flooded springs.

Cave streams in both allogenic and autogenic settings typically descend down dip along bedding planes and vertically via joints or, more rarely, faults to the water table. Once this is reached it is common for conduits to be below the water table for most of the distance to springs. This is indicated by studies of major relict conduits, most of which were below the water table for most of the time that water flowed through them, and by the low hydraulic gradients typically found in karst aquifers.

In thick carbonate aquifers conduit flow often extends to a considerable depth below the water table. This has been vividly demonstrated by the efforts of divers and several springs have been explored to depths of over 150 m. Evidence from thermal karst springs and from cavities intercepted in deep wells indicates karstification in some areas to depths exceeding 1000 m, such as in the Edwards aquifer in Texas. It has been found that the depth of conduit flow is proportional to the stratal dip and to the length of the catchment. Thus springs with large flows, which of necessity drain large catchments, often have very deeply descending conduits, as do conduits in steeply dipping Alpine aquifers. Conversely, platform carbonates often have low dips, and conduits in these aquifers often develop just a few metres below the water table.

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See also **Inception of Caves; Patterns of Caves; Speleogenesis (various entries)**

Further Reading

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