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ESSAY

Contrasting definitions for the term ‘karst aquifer’

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Abstract It is generally considered that karst aquifers have distinctly different properties from other bedrock aquifers. A search of the literature found five definitions that have been proposed to differentiate karst aquifers from non-karstic aquifers. The five definitions are based upon the presence of solution channel networks, hydraulic conductivities $>10^{-6}$ m/s, karst landscapes, channels with turbulent flow, and caves. The percentage of unconfined carbonate aquifers that would classify as ‘karst’ ranges from <1 to >50%.

Keywords Karst · Conceptual models · Dual porosity · Carbonate rocks · Silicate rocks

Introduction

Karst aquifers have distinctive characteristics that contrast strongly with aquifers with intergranular flow such as sand aquifers. This is because fracturing and dissolution both enhance permeability, resulting in tributary networks of channels that discharge at springs (Ford and Williams 2007). Most of the flow is in the fractures and channels but most of the storage is in the matrix, resulting in dual- or triple-porosity aquifers (Quinlan et al. 1996; Worthington and Ford 2009). These aquifers have rapid flow through the fractures and channels but long residence times in the matrix. Karst aquifers are often accompanied by a karst landscape on the surface (Ford and Williams 2007). There are a range of opinions in the literature for the defining characteristics of karst aquifers, and this essay discusses the different definitions that have been proposed.

Contrasting definitions

Five contrasting definitions for the term ‘karst aquifer’ can be distinguished:

1. *Network definition*. Karst aquifers have been defined in terms of interconnectivity, with the threshold being where enlargement by weathering (principally dissolution) has produced a network of enlarged pathways that enhance aquifer permeability (Huntoon 1995; Klimchouk 2015; Chen et al. 2017). Simulations of flow in fractured-rock aquifers often utilize fracture apertures in the range 0.01–0.1 mm (Long et al. 1982; Hyman et al. 2015), but solution channel networks are characterized by substantially larger apertures. For instance, the solutional openings visible in televiewer or downhole video logs are commonly

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millimeters to centimeters in aperture (Price et al. 1982; Schürch and Buckley 2002; Maurice et al. 2012).

2. *Hydraulic conductivity definition*. In a table of hydraulic conductivity values, Freeze and Cherry (1979 p. 29) differentiated between *limestone and dolomite* and *karst limestone*, with the hydraulic conductivity of karst limestone being $>10^{-6}$ m/s.
3. *Geomorphic definition*. The geomorphic definition associates the presence of a karst aquifer with surface karst landforms. These landforms are most commonly found where rocks that dissolve congruently are exposed at the Earth's surface. These include limestone, dolostone, quartzite, gypsum, and halite (Wray 1997; Gunn 2004; Weary and Doctor 2015). Solutionally sculpted rock (karren) and enclosed depressions formed by dissolution such as dolines (sinkholes) are common landforms, and sinking streams and springs are the major hydrologic features of karst landscapes (Ford and Williams 2007).
4. *Hydraulic definition*. Atkinson and Smart (1981) suggested that karstic conduits should be defined by the presence of turbulent flow. The onset of turbulent flow occurs at apertures of about 1 cm under common hydraulic gradients (Ford and Williams 2007), so this would define the minimum channel diameter for karstic flow.
5. *Speleological definition*. The presence of caves formed by dissolution are a diagnostic feature of karst aquifers, and the presence of extensive caves with underground streams are generally considered to exemplify a well-developed karst aquifer (Ford and Williams 2007; Kresic 2013). In this case, the minimum channel aperture for a karst aquifer would be the size of passages that people can enter, which is about 0.5 m.

Pros and cons of the five definitions

The advantage of the solution-channel-network definition is that tracer tests can be used to identify whether a network of interconnected large-aperture pathways is present in an aquifer. Flow along such pathways results in groundwater velocities that are often >100 m/day, even with hydraulic apertures as small as 1 mm. These velocities are substantially greater than groundwater flow through the matrix of a rock or through networks of narrower fractures produced by tectonic processes. Consequently, this provides a useful diagnostic test for identifying preferential flow along enlarged pathways (Worthington 2015b). The definition is most often applied to rocks that dissolve congruently, including carbonates, evaporites, and quartzite (Weary and Doctor 2015; Chen et al. 2017); however, weathering can also enlarge apertures in rocks dominated by incongruent weathering such as many igneous and metamorphic rocks, shale, and arkosic sandstone. Nevertheless, these aquifers are not usually regarded as karstic because the clay minerals that are formed as a by-product of weathering usually inhibit the development of enclosed depressions and of caves (Lachassagne et al. 2011; Worthington et al., 2016).

The advantage of the hydraulic conductivity definition is that it enables carbonate aquifers to be classified as karstic or non-karstic because hydraulic conductivity is commonly determined using well tests, but a drawback is that the choice of a value to differentiate the two aquifer types is arbitrary. There is also the problem that scaling effects are usually substantial in carbonate aquifers, and so well tests are likely to underestimate aquifer permeability (Kiraly 1975).

The advantage of the geomorphic definition is that it is simple to apply and does not involve any hydrogeological testing. The presence of surface karstic features such as sinking streams, dolines, and springs are common indicators of the presence of an underlying karst aquifer with extensive solution channels. However, the lack of surficial karst features does not necessarily imply the lack of an underlying karst aquifer—for instance, Mammoth Cave, Kentucky (USA), the world's most extensive mapped cave, is formed in Mississippian limestone, but the surficial rock over most of the cave is younger sandstone and conglomerate, with an absence of karst features (Granger et al. 2001); thus an aquifer that is clearly karstic underlies a non-karstic landscape. Consequently, the geomorphic definition does not give a reliable indication of whether there is an underlying karst aquifer.

The advantage of the hydraulic definition is that there is a clear hydraulic difference between laminar flow (where discharge is proportional to hydraulic gradient) and turbulent flow (where discharge is proportional to the square root of hydraulic gradient). However, it can be difficult to determine even from tracer testing whether flow is laminar or turbulent, which limits the usefulness of this definition (Worthington and Ford 2009).

The speleological definition is problematic because only a fraction of all caves are known—for instance, the number of caves in the world with at least 3 km of mapped passages increased from eight in 1900 to 46 in 1950, and to 1488 in 2001 (Worthington 2015a). Discovery and exploration of caves continues, and the total number and length of known caves continues to increase by several percent each year. Consequently, it is almost certain that only a small fraction of all caves is known, thus limiting the use of the speleological definition. Furthermore, wells do not provide a reliable method for revealing the presence of caves in an aquifer because the probability of a randomly drilled well intersecting a cave is usually <0.05, even in areas with extensive caves (Worthington 2015a).

Discussion and conclusions

Springs are widely monitored and characterized in karst aquifers (e.g. Bonacci 1993), but there are also some large springs

Table 1 Permeability of the major bedrock lithologies and indicators of dissolution

Hydrolithology	Hydraulic conductivity[a] (m/s)	Solution rate[b] (mol/m²/s)	TDS[b] from weathering (mg/l)	Frequency of karst landforms	Frequency of interception by wells[c]	
					Solution channels	Solution caves
Carbonate, e.g. limestone	1×10^{-5}	$10^{-6.8}$	277	High	High	Low
Coarse-grained sedimentary siliciclastic, e.g. sandstone	2×10^{-6}	$10^{-11.6}$	260	Low	?	Very low
Volcanic, e.g. basalt	2×10^{-6}	$10^{-10.9}$	135	Negligible	?	Negligible
Crystalline igneous and metamorphic, e.g. granite	7×10^{-8}	$10^{-12.0}$	47	Negligible	?	Negligible
Fine-grained sedimentary siliciclastic, e.g. shale	3×10^{-10}	$10^{-13.2}$	26	Negligible	?	Negligible

[a] Geometric mean permeability from regional numerical models from Gleeson et al. (2011), converted from permeability values assuming a temperature of 10 °C

[b] *TDS* is total dissolved solids; mean values from Worthington et al. (2016)

[c] The frequency of interception by wells are first approximations. It is unclear how often wells in silicate rocks intercept solution channels

in basalt and sandstone; however, there is no test in the literature that uses spring characteristics to differentiate karst aquifers from non-karstic aquifers.

Strong correlations have been found between hydraulic conductivity of the five major lithologies and both solute concentrations and dissolution rates of the constituent minerals (Table 1). This table also gives estimates of how frequently channels and caves in the different lithologies are intercepted by wells. Not surprisingly, the lithologies with higher mean solute concentrations and higher dissolution rates have more channels and caves. Solution channels have a fractal size distribution, with there being many small channels and few large channels (Curl 1986; Jeannin 1992; Worthington 2015a). Consequently, a randomly drilled well will have a very low probability of intersecting a cave passage (a very large channel), a higher probability of intersecting a conduit (a channel > ~ 1 cm with turbulent flow), and an even higher probability of intersecting a 1 mm channel enlarged by dissolution but that only has laminar flow (Table 1; Fig. 1).

A first approximation of the frequency of karst aquifers can be estimated for the different definitions (Fig. 1). These estimates are for near-surface carbonate aquifers, within tens to hundreds of meters of the surface; at greater depths there is generally less dissolution and a decrease in hydraulic conductivity. Figure 1 shows that the fraction of carbonate aquifers that are defined as karstic varies from hardly any to most, depending on the definition adopted. The wide range of values suggests that caution needs to be used where referring to the term 'karst aquifer' because of the wide range of definitions.

Quartzites, like carbonate and evaporite rocks, have congruent dissolution, and caves are sometimes found in them (Piccini and Mecchia 2009). Most minerals in other silicate rocks dissolve incongruently, and caves are only rarely found in these rocks (Chabert and Courbon 1997; Willems et al. 2002); nevertheless, there may still be channels with turbulent flow, especially near large springs. Smaller channels with apertures of a few millimeters or less are probably common in most bedrock aquifers, and provide an explanation for the positive correlation in the five major lithologies between hydraulic conductivity and both solute concentrations and dissolution rates (Table 1; Worthington et al. 2016).

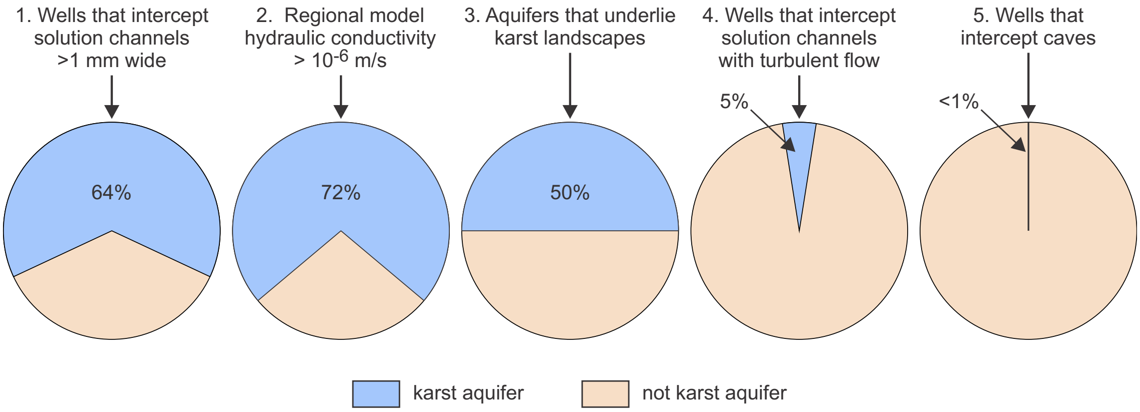

Fig. 1 Estimated percentage of near-surface carbonate aquifers that can be classified as karstic, based on five different criteria. Details of the methodology used are explained in the electronic supplementary material (ESM).

There are several practical reasons for determining which aquifers are karstic, and the definition used may vary with the goal of the study. Definition 1 would be most useful for characterizing contaminant transport in aquifers, and in particular the rapid transport that occurs where solution channel networks are present. On the other hand, definitions 3, 4, and 5 are the most useful for assessing karst hazards that may result in the collapse of infrastructure into sinkholes or subsurface voids (Waltham et al. 2005).

The wide range in dissolution rates and solute concentrations in the major lithologies (Table 1) means that there is no simple division of bedrock aquifers into karstic aquifers and aquifers that can be treated as inert. Rather, there is a progression from low-solubility rocks such as shale that may have enhanced permeability from solution channel networks to more soluble rocks such as limestone that may have not only solution channel networks but also caves and karst landscapes on the surface (Worthington et al. 2016). This range in properties has resulted in several valid definitions with contrasting meanings for the term 'karst aquifer', and means that there is no single ideal definition.

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