Borehole tests for megascale channeling in carbonate aquifers

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Abstract

Dissolution processes in carbonate aquifers commonly result in an interconnected network of enlarged fractures, or channels, which make up only a very small fraction of the rock volume. This means that averages from hydraulic testing represent the relatively slow flow through the matrix and tectonic fractures, and give little information on channeling.

We have analyzed hydraulic conductivity, water level and water quality data from dolomite terranes in Ontario (Canada) and limestone terranes in Kentucky (USA) with known networks of channels. Seven test methods in particular have been found useful in indicating the presence of extensive channels. The combination of several of the above seven methods is an excellent way of detecting whether an aquifer has an extensive network of interconnected channels with rapid solute transport.

1. Introduction

Two conceptual models of flow in carbonate aquifers have been developed over the last hundred years. One model considers that solution is not normally of major importance in enhancing the permeability of carbonates, so that carbonate aquifers may be studied in the same way as other bedrock aquifers. Thus the fracture networks are tectonic in nature, cavities encountered in drilling are "vugs" rather than laterally persistent channels, and flow may be studied by equivalent porous medium (EPM) models. This view is implicitly followed in general hydrogeology texts such as Freeze and Cherry (1979).

The second conceptual model of flow in carbonate aquifers stresses that solution is commonly of considerable importance in enhancing the permeability of carbonate rocks. The landscapes over such aquifers are often so distinctive that they are termed karst landscapes. This model is followed in specialist texts on carbonate hydrogeology such as White (1988) and Ford and Williams (1989).

The differences between the two models are fundamental, and of considerable significance to the movement of contaminants. The two models represent end members of a spectrum. There has been some discussion in the literature of this spectrum (e.g. White, 1969), but there are no practical tests using borehole data that are currently in widespread use to differentiate where on the spectrum a given field site lies. Given the considerable differences between the end members of the spectrum, there is a need for explicit borehole tests. Seven possible tests are outlined below.

2. Terminology: channels, conduits, macrofissures and karst

Confusing and contradictory terminology is a major barrier to communication of ideas on flow in carbonate aquifers. Meteoric water circulating through an unconfined carbonate aquifer will tend to produce an integrated network of solutionally-enlarged fractures. These enlarged fractures have been called channels (Choquette and Pray, 1970), macrofissures (Reeves, 1979), or secondary fissures (Price et al., 1993), and larger examples are known as conduits (>1cm diameter) or caves (~>1m, enterable by people) (White, 1988; Ford and Williams, 1989). The interconnectivity of the enlarged fractures is of prime importance, and this is emphasised in the term megascale channeling (Winograd and Pearson, 1976). This latter term will be used in the following account to describe interconnected solutionally-enlarged fractures, which may range in aperture from less than 1mm to more than 10m, and in lateral extent up to tens of kilometres (Winograd and Pearson, 1976; Quinlan and Ewers, 1989).

The term karst is generally understood to describe a landscape which is distinctive because it is underlain by soluble rocks. Aquifers in the soluble rocks underlying karst topography are often called karst aquifers or karstic aquifers. To many hydrogeologists caves are an essential component of a karst aquifer. Thus a karst aquifer can be thought of as an extreme example of an aquifer with megascale channeling.

3. Seven test methods that may indicate interconnected channels

An important characteristic of carbonate aquifers with networks of solutionally-enlarged fractures is that these networks can function effectively at transporting solutes rapidly yet only occupy a very small fraction of aquifer volume. For instance, for the limestone aquifer in the Mendip Hills (England) Atkinson (1977) calculated that the interconnected conduit network accounted for only 0.03% of the aquifer volume. Consequently, boreholes are unlikely to intersect the major arteries of the network. Instead, tests should be designed to sample for the existence of the network of interconnected channels. One proven method and six potentially useful methods are described below.

i) Well-to-well or well-to-spring tracer tests

Tracer testing is a well-proven method of measuring flow direction and velocity in carbonate aquifers (Ford and Williams, 1989, pp. 219-241). The technique is more than 100 years old, and more than 10,000 successful tests have been conducted. Most tests have been under natural gradient conditions from sinking streams to springs, with boreholes used in a smaller number of tests. Fluorescent dyes are the most popular tracers, combining low cost and low toxicity with high detectability.

An example of a well to spring test in Ontario is shown in Figure 1. The orange dye Rhodamine WT was used, with 19mg of dye being injected at a well. The dye was recovered at a spring 120m away, demonstrating a solute velocity of 6.2×10^{-3} m/s. This measured velocity is some thousand times faster than velocities calculated using hydraulic conductivity measurements and EPM assumptions.

Natural gradient well to well tests are not assured of success since the main channel network may not be intersected by the well. Therefore moderate pumping is recommended to draw the tracer to the monitoring well.

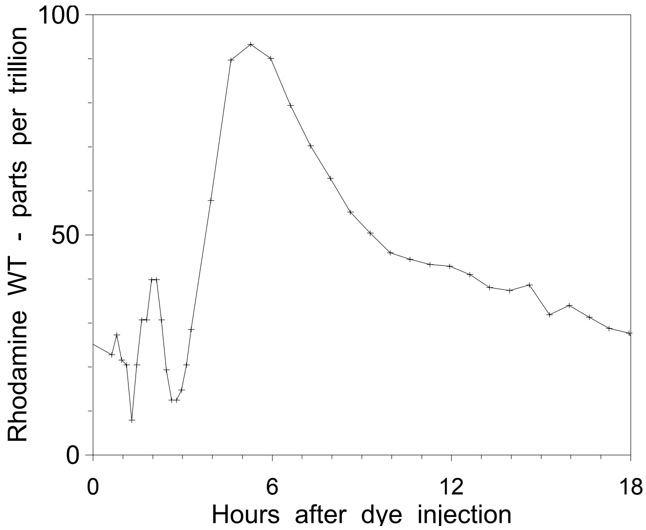

Figure 1. Breakthrough curve of a Rhodamine WT tracer test in dolomite from a borehole to a spring. Typical features shown are the rapid rise and exponential recession, and high sensitivity of the technique.

ii) Combination of core, packer, slug and pump tests

In an ideal porous medium, permeability is independent of the test scale. Thus the permeability calculated from core and pumping tests should be similar. This will not be true in many fractured media, and is especially untrue where there is extensive solution. In such cases, core tests and packer tests across unfractured intervals only measure matrix permeability. Packer tests across fractured intervals and slug tests will give higher values as they include both the matrix and some fracture permeability. Pump tests will give yet higher values as they will also sample the channel network. Thus the permeability increases with the scale of a test (Quinlan et al., 1992).

Some examples of permeability tests in Paleozoic carbonates are shown in Figure 2. All five sites are broadly similar in packer or slug permeability, but other hydraulic tests give considerably different results.

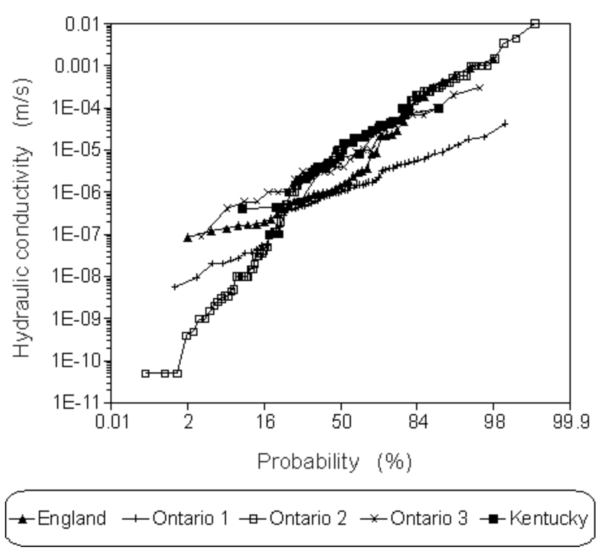

Figure 2. Log-normal hydraulic conductivity tests in Paleozoic carbonates using packers (Ontario) and slug tests (England, Kentucky).

In the central Kentucky limestones core tests have given hydraulic conductivity values of 10^{-11} m/s (Brown and Lambert, 1963), but slug tests give values a million times higher (Figure 2). A similar range of values is found in the Ordovician dolomites in Ontario, from consultants reports at sites along the Niagara Escarpment. Packer tests across unfractured intervals give values of 10^{-11} to 10^{-8} m/s, while pump tests and packer tests across open fractures commonly give values of 10^{-5} to 10^{-3} m/s.

The site in Kentucky is in the Mississippian limestones of the Turnhole Spring catchment. Turnhole Spring lies within Mammoth Cave National Park, and Mammoth Cave is the most extensive cave in the world. Most of the borehole tests shown in Figure 2 were made within 50m of a megascale channel, which has been shown by tracer testing and flow measurement to be at least 18km long and to have an aperture of at least several metres (Quinlan and Ewers, 1989). Primary porosity of the limestone is 3.3% (Brown and Lambert, 1963).

The site in England is the Mendip Hills, a Mississippian limestone aquifer with 0.8% effective porosity, but with extensive surface karst features and caves (Atkinson, 1977). The slug tests were undertaken in a quarry to which several tracer tests were made. The tests showed velocities of 0.001-0.003 m/s, indicating megascale channeling (Edwards et al., 1992).

The three sites in Ontario in Figure 2 are in low porosity (<5%) Ordovician dolomites. Glaciation as recently as 13,000 years ago has removed or infilled most surficial karst features. However, megascale channelling in the dolomite aquifer has been demonstrated by tracer tests (Figure 1).

iii) Variable rate pumping test

Hickey (1984) showed that the pumping rate should be proportional to the drawdown in observation wells if Darcy's Law is valid within the cone of depression. In the carbonate aquifer in Florida this was found to be true for one series of tests. It has yet to be shown whether how sensitive this technique is for detecting departures from Darcy's Law in the vicinity of channel networks with turbulent flow.

iv) Matrix and fracture packer test to calculate fracture extent

Price (1994) described a method for estimating the extent of interconnected fractures intersected by wells by using steady-state packer testing. The contrast between the permeability of the matrix and of a fracture isolated by packers can be used to estimate fissure extent. The method uses some simplifying assumptions (e.g. homogeneous, isotropic matrix, parallel plate constant aperture fissures), but is useful for differentiating whether an open fracture intersected by drilling is an isolated vug or is connected to an extensive interconnected channel network.

v) Symmetry of cones of depression at pumping wells

The cone of depression at a pumping well is symmetrical in a homogeneous porous medium. However, the cone of depression is likely to be irregular if there is extensive channeling nearby. Figure 3 shows an example from a pumping test in Ordovician dolomite in Ontario. Most of the observation well water levels do not closely correspond to the idealised cone of depression, and between two of these wells (87-4B and W1-B) the hydraulic gradient is away from the pumping well. However, the most interesting feature is the cascading of water into the well from a single fracture. Most of the pumped water came from this single fracture, indicating an extensive interconnected channel network.

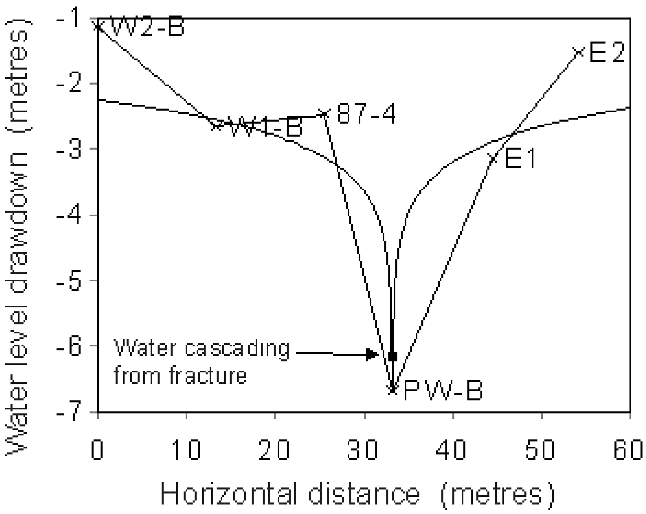

Figure 3. Water level profiles during a pumping test in dolomite in Ontario. The curved lines represent the best-fit cone of depression from all nine observation wells.

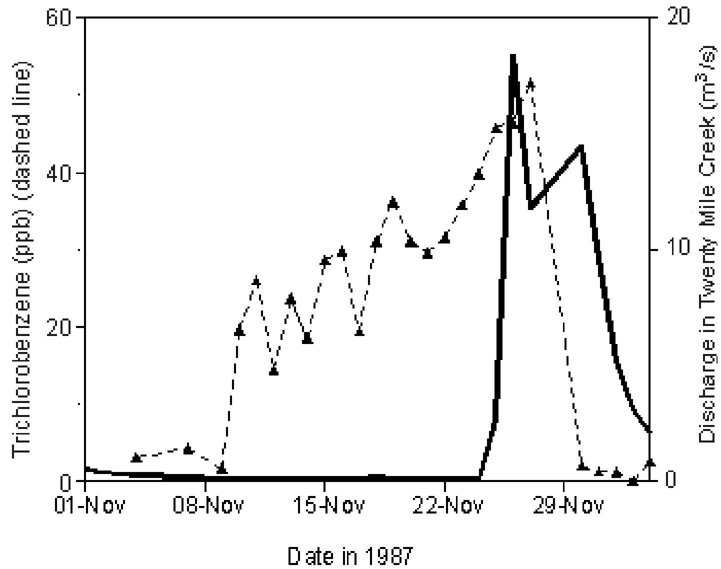

Figure 4. Rapid changes in trichlorobenzene concentrations in a dolomite aquifer in Ontario, showing lagged inverse correlation to runoff.

vi) Continuous water level monitoring

Interconnected channel networks transmit water quickly, so a prompt water level response in boreholes can be expected following rainfall. Such a response will not be detected by conventional weekly or monthly water level measurement programmes. Continuous water level monitoring is technically straightforward, and the response magnitude and lag following precipitation is valuable for indicating channel connectivity. In Central Kentucky water levels in well often rise by several metres within hours of major rainfall events (Quinlan and Ewers, 1989).

vii) Frequent water quality monitoring

Precipitation which rapidly infiltrates along channel networks commonly has a much lower solute concentration than long-residence matrix water. Thus variation in solute concentration at a well should be an indicator of connectivity to major channel networks. Frequent sampling is necessary to detect the rapid response following rainfall. Quinlan et al. (1982) have shown how a sampling interval of hours rather than days may be necessary for an adequate understanding of solute changes following rainfall.

Figure 4 shows trichlorobenzene concentrations in a bedrock well at a contaminated site on Ontario dolomites. Daily measurements here reveal increasing concentrations during a runoff recession (November 1 - 24) and a hundredfold decrease following precipitation (November 27 - December 4th). The lag here between precipitation and dilution at the well is about three days. Traditional infrequent sampling such as quarterly would completely miss such short-term variability in solute concentrations.

4. Discussion

Tracer testing is the only one of the seven techniques that is likely to give simple, unequivocal evidence that megascale channeling is present. This is because the groundwater velocities measured in carbonates are usually in the range 0.002 - 0.2 m/s. Such velocities are orders of magnitude more rapid than predictions based on Darcy's Law, and can only be explained by megascale channeling.

The remaining six techniques make use of, or are extensions of commonly collected data from boreholes. Each of them can be used to investigate the possibility of megascale channeling; together the evidence from several of these techniques may give strong evidence for megascale channeling.

Major karst hydrological features such as sinking streams, caves containing streams, and large springs definitively show that megascale channeling is present. However, there is no simple test that will show that megascale channeling is not present.

Some authors have suggested that limestones and dolomites have higher permeability and porosity values if they are karstic (e.g. (Freeze and Cherry, 1979, pp. 26, 37). However, the permeability enhancement is likely to be minor, especially if tested by low aquifer volume core, packer or slug tests. Furthermore, porosity enhancement due to megascale channeling is negligible; even for the well-karstified aquifer in the Mendip Hills, England, where extensive caves have been found, the porosity enhancement by channeling is only 0.03% (Atkinson, 1977).

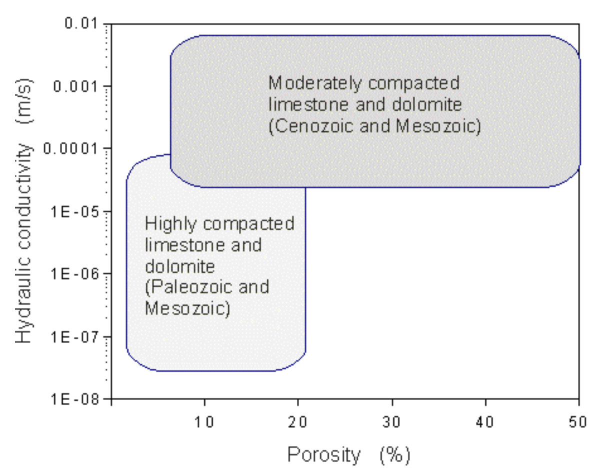

Figure 5. General range of hydraulic conductivity and porosity in unconfined carbonate aquifers, as a function of compaction and age.

Instead, the substantial range in permeability and porosity in carbonate aquifers is explained primarily by compaction (Figure 5). Most Paleozoic carbonates have been subjected to deep burial, resulting in low porosities (often $<2\%$) and low permeabilities. Conversely, most Cenozoic carbonates have been compacted less, and thus have both higher porosity and higher permeability (Figure 5).

As well as compaction, the solubility of calcite and dolomite also plays a substantial role in porosity and permeability development at all stages in the life of a carbonate deposit. From deposition through burial, uplift and erosion carbonate rocks contrast strongly with siliciclastic rocks (Choquette and Pray, 1970). The seven test methods outlined in this paper can help show that solute transport in carbonate rocks, and especially unconfined carbonates, is profoundly influenced by solution, which inexorably leads to megascale channeling.

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