GROUNDWATER IN KARST: BOREHOLE HYDROLOGY

extract from pages 397-398 of:

Gunn, J., (editor) *Encyclopedia of Caves and Karst Science*, Fitzroy Dearborn, NY.

Boreholes are shafts of a few centimetres diameter drilled into the ground, typically for the extraction or observation of ground-water. In the former case, the borehole is pumped and draws water in from the surrounding aquifer (see Karst Water Resources). In the latter, the borehole remains passive in order to allow determination of undisturbed water levels in the aquifer, although observation boreholes are intermittently pumped to extract water samples or to evaluate aquifer properties. In karst, groundwater monitoring is conventionally located at springs and in caves, and complementary borehole data may prove difficult to reconcile with these observations. Yet many karst aquifers may have no enterable caves, and springs may not be accessible. For example, karst aquifers in weaker or younger limestones may not host caves; many karst aquifers are buried under alluvium and glacial till, or drowned by lakes or oceans; or landowners may deny access. In such cases, boreholes provide the only viable window on the karst aquifer. While boreholes may provide useful information on the aquifer, they need to be monitored using specialized techniques, and care should be exercised in evaluation of the data.

Wells drilled into karst aquifers differ significantly from those placed into porous-medium aquifers, such as sand or sandstone. They are often spectacularly productive, but show significant transient (short-term) degradation in quality, and are especially vulnerable to microbial contamination. It is important to identify and consider such differences, as treating a karst well with protocol devised for porous media may be inappropriate and compromise the user's safety.

A karst aquifer may be conceived as consisting of conduits arranged in a dendritic system placed within the carbonate rock mass. Large conduits are rare; smaller conduits are increasingly common, depending on the rock characteristics and aquifer history. The probability of a borehole intersecting a major, cave-sized conduit is only about 1-2%. Most boreholes in karst therefore only intersect small conduits, at most a few centimetres in diameter. These small conduits and solutionally-enlarged fractures, with apertures in the range 0.1 mm - 1 cm, produce most of the permeability measured in karst boreholes and result in high productivity. Unfortunately, the enlarged fractures and conduits constitute an interconnected network through which not only water but also contaminants and bacteria can move rapidly and without filtration. If the aquifer or ground surface is contaminated, and there is uninterrupted connection to a supply conduit, then a well can become suddenly contaminated.

In conventional hydrogeology, borehole water level and water composition are generally taken to be characteristic of the aquifer at that location. Conduit flow and rapid transmission of water and impulses (e.g. from recharge or pumping) make water level data and water samples from karst boreholes potentially misleading. However, there are a number of useful tests in karst where information may be gathered from a single borehole, from a pair of boreholes, or from a large number of boreholes.

Useful single-borehole tests include drillers' records of bit drops and loss of circulation, flow meter tests, video logs, conductivity profiles, and water level and water chemistry monitoring. Bit drops indicate voids, and these may be isolated vugs or intersections with conduits. Loss of circulation is often associated with conduits. Flow meter tests involve measuring velocities up or down the well bore, and are most useful if done both in ambient flow and under pumping conditions. If the flow metering has sufficient resolution, these tests typically show active inflow and outflow at a small number of horizons. A less expensive method of electrical conductivity profiling supplements this information as well as revealing contrasts in the water chemistry of the different inflows. Downhole video is useful, especially if the camera has a capability of viewing sideways, since it can be seen if inflows are from discrete conduits or from fractures. Rapid changes in borehole water level and water chemistry are diagnostic of karst aquifers, and occur following rainfall or snow-melt events. Karst borehole water level time series often show consistent breaks in slope, which may be related to activation of overflows and underflows in the aquifer. However, since conventional bi-weekly sampling will not reveal such a pattern, continuous monitoring is recommended. Electrical conductivity is straightforward to measure and is proportional to total dissolved solids. Electrical conductivity, water temperature, and water level are often measured together. However, flow pattern in a borehole means the results of point sampling or monitoring may not be representative of the entire water column. Changes in these variables are dependent not only on the properties of the conduit network but also on the connectivity of this network to recharge. For instance, in glaciated areas there may be thick glacial sediments mantling the karst, resulting in the attenuation of the signal from recharging water.

Tests between boreholes form a second category. The probability of two boreholes encountering a common conduit is very low indeed, which means that natural gradient tracer tests seldom work in karst. Quinlan and Ewers (1989) exemplify the natural gradient problem with heavy-metal laden effluent from a sewage treatment plant in Kentucky, United States. Contamination was not picked up at any of 23 domestic wells in the down-gradient direction. Instead, the signature was picked up beyond the wells at a major spring. The effluent had flowed through a major conduit not intersected by any of the wells. The conduit formed an efficient, low-head pathway, resulting in convergent flow towards it. However, well contamination might have been induced by sustained pumping of the wells, or through flooding of the conduit.

Tracer tests between boreholes in karst are much more likely to be successful if a convergent flow test is carried out, with sampling at a pumping borehole. Such "induced gradient" tests are often successful over distances of tens or hundreds of metres. However, there is often considerable tracer loss, and the resulting velocities are not necessarily indicative of the peak velocities possible in a conduit.

A third category of borehole analysis is to use water-level data from a number of boreholes. An array of boreholes allows discrimination of general patterns of behaviour from idiosyncratic effects, unique to particular wells. The former may be taken as an "aquifer" signal, the latter as arising from the particular connectivity of the well. More controlled effects of this kind may be obtained using observation wells to define the pattern of drawdown around a pumping well. Karst aquifers frequently show marked departure from the radial symmetry predicted for the cone of depression in a porous medium. Elongation of the cone may be indicative of a conduit.

The classical multiple borehole study is of the Mammoth Cave area in Kentucky, where a water table map was compiled from water level in 1500 boreholes, supplemented by results from 500 tracer tests to springs and by maps of cave and surface streams. Care had to be taken to eliminate anomalous borehole water-level data arising from local pumping, poor connection, or storm runoff. The map showed that flow is convergent to distinctive troughs in the water table, and the troughs terminate at springs. The troughs are associated with major conduits and decrease in hydraulic gradient towards the spring. A decrease in gradient towards springs is a diagnostic feature of karst aquifers and is the opposite of the pattern in porous-medium aquifers.

The majority of work in karst hydrogeology has been undertaken from a speleological perspective. While this approach has been rewarding, it has not focused attention on the important unexplorable parts of karst aquifers, and has led to an implicit association of karst aquifers with a karst landscape. Where carbonates do not develop explorable caves, or they have been planed off and buried by glaciation, karst aquifers may still exist, and boreholes provide the primary window on these aquifers. Karst aquifers unfortunately compromise the interpretation of conventional pumping tests on boreholes, and karst hydrogeologists have been slow to develop alternative diagnostic techniques. Fortunately, these specialized methods are evolving and may provide important insight into water supply and aquifer management.

CHRIS SMART AND STEPHEN R.H. WORTHINGTON

Works Cited

Quinlan, J.F. & Ewers, R.O. 1989. Subsurface drainage in the Mammoth Cave area. In *Karst Hydrology: Concepts from the Mammoth Cave Area*, edited by W.B. White & E.L. White, New York: Van Nostrand Reinhold

Further Reading

Milanovic, P.T. 1981. *Karst Hydrogeology*, Littleton, Colorado: Water Resources Publications

Quinlan, J.F. & Ray, J.A. 1981. Groundwater basins in the Mammoth Cave Region, Kentucky. Mammoth Cave, Kentucky: Friends of the karst (Occasional Publication 1)

Smart, C.C. 1999. Subsidiary conduit systems: A critical hiatus in aquifer monitoring and modelling. In *Karst Modelling*, edited by A.N. Palmer, M.V. Palmer & I.D. Sasowsky, Charles Town, West Virginia: Karst Waters Institute

Worthington, S.R.H. 1999. A comprehensive strategy for understanding flow in carbonate aquifers. In *Karst Modelling*, edited by A.N. Palmer, M.V. Palmer & I.D. Sasowsky, Charles Town, West Virginia: Karst Waters Institute