Hydrogeologic Characterization Methods Used in Karst: A Contrast to the Darcian Aquifer Model

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Goals for this Talk

• Describe some ways that karst aquifers differ significantly from the aquifer type much of groundwater science is based on.

• Highlight a few special techniques useful in studies of karst.

• Give you some ideas that may help you decide what methods to employ for your groundwater site investigations in karst.

• Not a comprehensive treatment.
Darcian (Granular) Aquifers: The Textbook Ideal

- Conceptually simple input, storage, throughput, and output.

- Intergranular porosity and permeability dominates hydraulic properties.

- Homogeneous, isotropic, laminar flow obeys Darcy’s Law.
  - Hydraulic properties ($K_H$, T, S) easily determined by well withdrawal or injection tests.

- Saturated, unsaturated zones clearly demarked.

- Topographically-determined recharge and discharge zones (shallow, unconfined)
## Contrast with Karst Aquifer Properties:

### Table 1. Comparison of various hydrogeologic properties for granular, fractured rock, and karst aquifers (ASTM, 2002).

<table>
<thead>
<tr>
<th>Aquifer characteristics</th>
<th>Granular</th>
<th>Fractured rock</th>
<th>Karst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective porosity</td>
<td>Mostly primary, through intergranular pores</td>
<td>Mostly secondary, through joints, fractures, and bedding plane partings</td>
<td>Mostly tertiary (secondary porosity modified by dissolution); through pores, bedding planes, fractures, conduits, and caves</td>
</tr>
<tr>
<td>Isotropy</td>
<td>More isotropic</td>
<td>Probably anisotropic</td>
<td>Highly anisotropic</td>
</tr>
<tr>
<td>Homogeneity</td>
<td>More homogeneous</td>
<td>Less homogeneous</td>
<td>Non-homogeneous</td>
</tr>
<tr>
<td>Flow</td>
<td>Slow, laminar</td>
<td>Possibly rapid and possibly turbulent</td>
<td>Likely rapid and likely turbulent</td>
</tr>
<tr>
<td>Flow predictions</td>
<td>Darcy’s law usually applies</td>
<td>Darcy’s law may not apply</td>
<td>Darcy’s law rarely applies</td>
</tr>
<tr>
<td>Storage</td>
<td>Within saturated zone</td>
<td>Within saturated zone</td>
<td>Within both saturated zone and epikarst</td>
</tr>
<tr>
<td>Recharge</td>
<td>Dispersed</td>
<td>Primarily dispersed, with some point recharge</td>
<td>Ranges from almost completely dispersed-to almost completely point-recharge</td>
</tr>
<tr>
<td>Temporal head variation</td>
<td>Minimal variation</td>
<td>Moderate variation</td>
<td>Moderate to extreme variation</td>
</tr>
<tr>
<td>Temporal water chemistry variation</td>
<td>Minimal variation</td>
<td>Minimal to moderate variation</td>
<td>Moderate to extreme variation</td>
</tr>
</tbody>
</table>

Karst Hydraulic Conductivity and Scale Effects

- Heterogeneities at local (matrix-fracture) scale contribute to greater range in measured hydraulic conductivities.
- The heterogeneities are “averaged out” at basin (conduit) scale.

(Worthington et al., 2002)
In Karst, Aquifer Test Methods Reflect Effects of Scale

Range of hydraulic conductivities and computed velocities as a function of scale and test method (Sauter, 1992).
Pumping and Slug Tests in Karst

- Darcian-based type curves and solutions may not match observed data and should be applied with caution.

- Use may give erroneous results:
  - A well that intersects one or more conduits may produce large quantities of water with minimal drawdown → large calculated T values.
  - A well that intercepts mostly local matrix-fracture components may have negligibly small yields.

- Long-duration, multi-well pump (withdrawal) tests have the best chance of evaluating conduit-dominated aquifer properties.

- Early time data is most influenced by higher permeability (fractures and small conduits); late time by storage in matrix and fractures.
A well bore is a small object on the scale of the heterogeneities of a karst aquifer:

- Conduit porosity estimated at 2% volume in most aquifers (Worthington et al., 2002).

- Single well tests evaluate very limited volume of aquifer—usually influenced by local-scale (matrix-fracture) aquifer properties only.

- Core permeameter, borehole geophysical, flowmeter logging, and straddle-packer tests can help evaluate local-scale heterogeneities.

- Trends in water levels and groundwater chemistry can be helpful in assessing hydraulic conductivity/transmissivity distribution in the karst aquifer.
Case Study: NOSL Site, Jefferson County, KY

Confined part of regional Silurian-Devonian Limestone Aquifer system

Karst development outside of confined aquifer recharge boundary

(Taylor and Hostettler, 2002)
Borehole logs, Flowmeter and Straddle-Packer Tests
(NOSL site Louisville-Jefferson County, KY)

Three wells, W-E section, near assumed recharge boundary:

<table>
<thead>
<tr>
<th>Well</th>
<th>Depth (ft BLS)</th>
<th>Porosity (%)</th>
<th>$K_{(\text{max})}$ (ft/s)</th>
<th>$K_{(90)}$ (ft/s)</th>
<th>$K_{(v)}$ (ft/s)</th>
<th>Stratigraphic Unit (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Guard</td>
<td>29</td>
<td>18.5</td>
<td>$3.3 \times 10^{-6}$</td>
<td>$2.0 \times 10^{-7}$</td>
<td>$1.5 \times 10^{-3}$</td>
<td>Sellersburg Ls.</td>
</tr>
<tr>
<td>Auburndale</td>
<td>42</td>
<td>13.2</td>
<td>$3.3 \times 10^{-8}$</td>
<td>$3.0 \times 10^{-8}$</td>
<td>$3.4 \times 10^{-9}$</td>
<td>Sellersburg Ls.</td>
</tr>
<tr>
<td>Beechmont</td>
<td>30</td>
<td>6.9</td>
<td>$7.8 \times 10^{-9}$</td>
<td>$2.3 \times 10^{-9}$</td>
<td>$1.0 \times 10^{-9}$</td>
<td>Sellersburg Ls.</td>
</tr>
<tr>
<td>Iroquois</td>
<td>138</td>
<td>9.3</td>
<td>$1.1 \times 10^{-7}$</td>
<td>$6.7 \times 10^{-8}$</td>
<td>$1.7 \times 10^{-9}$</td>
<td>Sellersburg Ls.</td>
</tr>
<tr>
<td>Okolona</td>
<td>103</td>
<td>8.6</td>
<td>$1.3 \times 10^{-7}$</td>
<td>$1.3 \times 10^{-7}$</td>
<td>$2.6 \times 10^{-8}$</td>
<td>Jeffersonville Ls.</td>
</tr>
<tr>
<td>Okolona</td>
<td>117</td>
<td>16.2</td>
<td>$4.2 \times 10^{-7}$</td>
<td>$2.5 \times 10^{-7}$</td>
<td>$3.7 \times 10^{-9}$</td>
<td>Jeffersonville Ls.</td>
</tr>
<tr>
<td>Petersburg</td>
<td>37</td>
<td>14.3</td>
<td>$6.2 \times 10^{-6}$</td>
<td>$2.0 \times 10^{-6}$</td>
<td>$1.6 \times 10^{-6}$</td>
<td>Jeffersonville Ls.</td>
</tr>
<tr>
<td>Petersburg</td>
<td>67</td>
<td>17.6</td>
<td>$7.9 \times 10^{-6}$</td>
<td>$5.9 \times 10^{-6}$</td>
<td>$2.1 \times 10^{-7}$</td>
<td>Jeffersonville Ls.</td>
</tr>
<tr>
<td>Petersburg</td>
<td>51</td>
<td>10.7</td>
<td>$8.2 \times 10^{-7}$</td>
<td>$6.1 \times 10^{-7}$</td>
<td>$4.2 \times 10^{-7}$</td>
<td>Jeffersonville Ls.</td>
</tr>
</tbody>
</table>
Variability in Groundwater Chemistry

- Spatial pattern in groundwater chemistry is related to variability in infiltration and mixing of recharge in the aquifer.

- Local-scale variability in aquifer transmissivity is probably the controlling factor.
Hydrogeologic Interpretation

The hydrogeologic and geochemical framework reflect the fractured-rock and “transitional” karstic nature of the aquifer system:

- Recharge from the unconfined, more karstified aquifer zone is freshening the water in the confined, less karstified aquifer zone.

- Younger, bicarbonate-dominated water occurs where infiltration and circulation of fresh meteoric water are enhanced because of greater transmissivity (residual brine is completely flushed or diluted).

- Older, chloride-dominated (saline) water occurs where infiltration and circulation of fresh meteoric recharge are restricted because of poor transmissivity (residual brine is not completely flushed or diluted).

(Taylor and Hostettler, 2002)
Conduits: Major Control Over the Transport of Water, Sediment, and Contaminants

• Conduits typically form hierarchal drainage networks similar to surface streams.

• Size, organization, and hydraulic drainage capacity of conduits generally increase in downgradient direction.

• Exhibit hydrologically-mediated flow dynamics:
  • Driven by hydraulic head differentials.
  • Matrix, fractures, tributary conduits “feed” trunk conduits under base flow.
  • Conduits inject water into matrix-fractures during flood flows.
  • “Overflow” routes and outlets may be activated during high-flow conditions.

Ewers, 2010
In Darcian aquifers, water-level measurements can be reliably used to determine groundwater flow.

- Darcian Aquifer Model relies on use of hydraulic head data from monitoring wells to determine groundwater flow direction and velocity.

- Groundwater flow paths follow hydraulic gradient determined by distribution of head and equipotentials.

USGS Circular 1139
Not Always Reliable In Conduit-Dominated Karst

Example from Ewers (2010)

Site investigation in Ordovician karst terrane, Tennessee
In conduit-dominated karst, tracer tests are the only truly reliable way to identify groundwater flow directions and basin boundaries.
Method: Tracer Tests Combined with Water-Level Mapping

Particularly useful for delineating conduit flow paths and groundwater basin boundaries in karst aquifers.

- Tracer test results help guide interpretation of water level contours.
- Equipotentials depict troughs (around conduits and high-permeability zones).

Worthington, 2003

Taylor and McCombs, 1998
**Other Uses for Water-Tracer Tests:**

Quantitative traces can be used to characterize karst aquifer properties based on tracer transport and breakthrough curve characteristics.

Relies on mass balance of tracer and tracer recovery.

Can be applied to wells using natural gradient or (better) forced gradient methods.

*from: Taylor and Greene, 2008*
Shape of Tracer Breakthrough Curves Can Indicate Aquifer Characteristics Along Flowpaths

**Figure 19.** Example of dye-breakthrough curves for two dye-tracing tests conducted in the Edwards aquifer, Texas, showing a quick-flow response with little or no dispersion (Injection site A, left), and a slow-flow response showing the effects of dye dispersion (Injection site B, right) (courtesy of Geary Schindel, Edwards Aquifer Authority).
Tracer Breakthrough Curves Can Be Used to Simulate Contaminant Transport Behavior:

Caveat:

Tracer used must have physiochemical or hydrodynamic properties similar to contaminant of interest:

- Solute vs. Particle
- Reactive vs. Conservative

Figure 18. Some important physical characteristics of a dye-breakthrough curve (from Mull and others, 1988).
Case Study: Cane Run/Royal Spring Basin Study (for Nutrient Mass Flux)

Distance from headwaters to the spring is approximately 15 miles.

Unpublished data courtesy of Jim Currens, KGS
Cane Run Creek Loses Flow to Royal Spring Conduit

Part of the Lexington 30X60 minute Karst Groundwater Basin Map
Water-Tracing Tests in Cane Run/Royal Spring Basin Used to Determine TOT Characteristics
Monitoring Well Drilling Locations Selected Using Geophysical Survey:

Unpublished data courtesy of Jim Currens, KGS
Cartoon Showing Intercepted Conduits:

Northeast

Wells 20, 23, and 25

Southwest

0.85 meters +/-

5 meters +/-
Well 1 drilled in 2007

Stage Recorder

Well 25: Velocity sonde
Well 24: Stage Recorder
Well 20: Pump
Well 23: Water Quality Logger

Wells 21 and 22 are off the plot to the southwest

CAVE: height is 0.9 meters, width is 4+ meters

Flow

Well 18 is unusable

Stage Recorder

Barton Well

Monitoring Wells at the KyHP Monitoring Site
Monitoring Wells at KyHP Groundwater Station

20, 23, and 25 are into the cave
Hydraulic Communication and Water Levels in KyHP Monitoring Wells:

Unpublished data courtesy of Jim Currens, KGS
Quantitative groundwater traces can be used to measure groundwater discharge.

\[
\frac{(C_i \times Q_i)}{C_r} = Q_r
\]

- \(C_i\) is the concentration of tracer at the injection site
- \(Q_i\) is the rate of inflow of tracer
- \(C_r\) is the concentration at the recovery site
- \(Q_r\) is the discharge at the recovery site

If the velocity at the recovery site is also known, the cross-sectional area can then be calculated.
Provisional Results of Quantitative Dye Tracing

Rhodamine WT injected at a constant rate, at Eclipse karst window to calculate discharge.

A spike of fluorescein is introduced midway through Rhodamine WT injection for calculating velocity.

Table 2. Summary of quantitative traces made from the Eclipse Karst Window to the groundwater station in the Royal Spring conduit at the Kentucky Horse Park between July 7, 2011 and April 12, 2013. Results for four omitted experiments were incomplete or had flaws. COM is center of mass, QT is quantitative trace, TV is tank volume, PR is pumping rate.

<table>
<thead>
<tr>
<th>Date and time</th>
<th>Velocity from spike injection of Fluorescein Dye, m/sec</th>
<th>Stage in Well 24 at Fluorescein COM, Meters above 800 ft.</th>
<th>Q at KyHP*, m³/sec</th>
<th>(Measured pumping rate and duration used to determine rate of inflow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/6/11 14:50</td>
<td>0.21</td>
<td>6.56</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>3/1/12 14:00</td>
<td>0.10</td>
<td>3.25</td>
<td>1.40</td>
<td></td>
</tr>
<tr>
<td>12/10/12 15:40</td>
<td>0.13</td>
<td>4.21</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>2/7/13 18:00</td>
<td>0.09</td>
<td>2.38</td>
<td>2.90</td>
<td></td>
</tr>
<tr>
<td>3/12/13 13:20</td>
<td>0.12</td>
<td>3.82</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td>3/19/13 11:35</td>
<td>0.18</td>
<td>5.23</td>
<td>3.18</td>
<td></td>
</tr>
<tr>
<td>4/12/13 15:30</td>
<td>0.09</td>
<td>1.12</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>AVERAGE</td>
<td>0.13</td>
<td>3.80</td>
<td>1.60</td>
<td></td>
</tr>
</tbody>
</table>

*Discharge estimated from constant flux of Rhodamine WT at injection site divided by concentration at recovery site.
Use of these data:

Ultimate goal here is to develop stage-discharge relation curve for Well 24 (in hydraulic communication with RS conduit) to enable calculation of mass flux discharge of nutrients through Royal Spring groundwater basin.

Unpublished data courtesy of Jim Currens, KGS
Use of Spring Discharge Analysis:

- Springs integrate flows from the entire karst aquifer system (matrix-fractures-conduits).
- Their discharge is also representative of recharge sources and mechanisms.
- Concentrated vs. Diffuse
- Allogenic vs. Autogenic
- Use to assess aquifer characteristics by spring storm-pulse monitoring, hydrograph analysis, and chemical-hydrograph separation analysis.
Spring Storm-Pulse Discharge Monitoring:

![Graph showing flow in gallons per minute and precipitation over time, with peaks indicating rapid conduit-dominated flow response.](image)

**Figure 7.** Variable response of springs to precipitation. Copperhead Spring hydrograph shows rapid conduit-dominated flow response. Langle Spring hydrograph shows slow diffuse-dominated flow response. These are related to the relative proportion of conduit permeability to nonconduit permeability (courtesy of Van Brahama, University of Arkansas).
Spring Storm-Pulse Water-Quality Monitoring

Discharge hydrograph and chemograph for the July 1998 high-flow event at Pleasant Grove Spring.
Spring Discharge Recession Analysis

Has been used to calculate discharge and storage related to the triple permeability components of karst aquifers.

A huge variety of analytical methods, including statistical lumped-parameter, linear, and non-linear, modeling are described in the scientific literature.

from: Taylor and Greene, 2008
Spring Chemical-Hydrograph Separation

Example from Lee and Krothe (2001):

Four-component mixing models of natural tracers (δD, sulphate, DIC, and δ13C) used to separate spring hydrograph into components identifying discharge contributions from different parts of karst aquifer.

Use of this method depends on ability to identify water-chemistry signal (solute, isotope) distinctive of each recharge source.
Collective Results of Many Karst Aquifer Studies Using Tracer Tests and Various Types of Spring Hydrograph Analysis

Demonstrate that karst aquifers may be best conceptualized within a three-tier continuum of:

- Recharge
- Flow
- Storage

Karst hydrogeologic investigations should incorporate appropriate methods to evaluate all three.

Quinlan and others, 1991
Summary:

• Karst aquifers are extremely heterogeneous, possess triple porosity/permeability, and are often dominated by conduit flow.

• Always consider the implications and limitations when applying conventional groundwater methods based largely on Darcian aquifer concepts.

• Also be aware of scale of measurement considerations, investigate, and adjust accordingly.

• Take advantage of use of special methods such as tracer testing and spring hydrograph analysis when conducting karst investigations—these are reliable ways of collecting good data on karst aquifer properties.
Useful Sources of Information

http://pubs.usgs.gov/tm/04d02/

Chapter 3 “Hydrogeologic characterization and methods used in the investigation of karst hydrology” (Taylor and Greene, 2008)

Not a “cookbook”—Presents a broad, but comprehensive, overview of field and analytical techniques, citing specific references to methods and case studies.
(continued) Useful Sources of Information

http://www.karstportal.org/

http://www.karstwaters.org/

http://water.usgs.gov/ogw/karst/index

http://water.usgs.gov/ogw/techniques.html