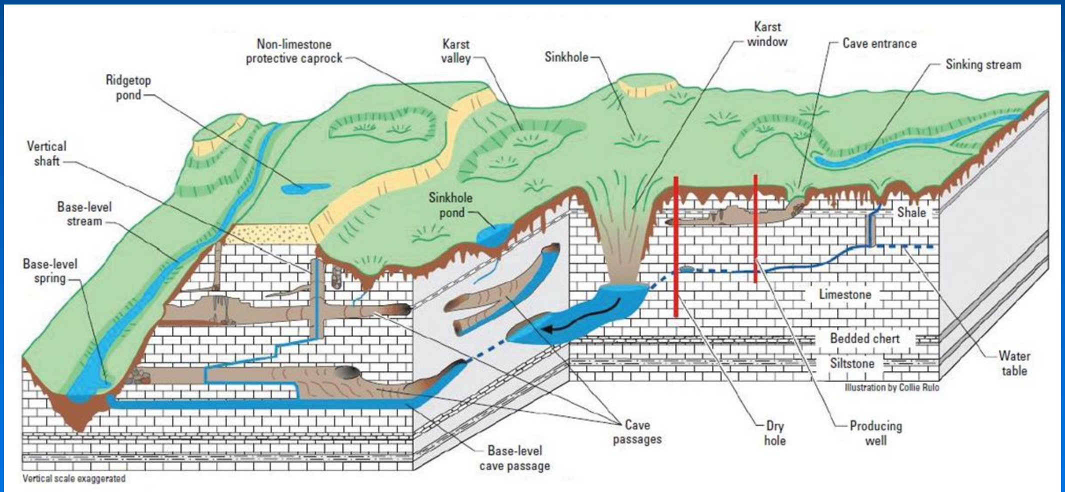
Aquifer Characterization – Groundwater Behavior in the Subsurface Environment

Kentucky Section - American Institute of Professional Geologists

Lexington, KY, May 29, 2014

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



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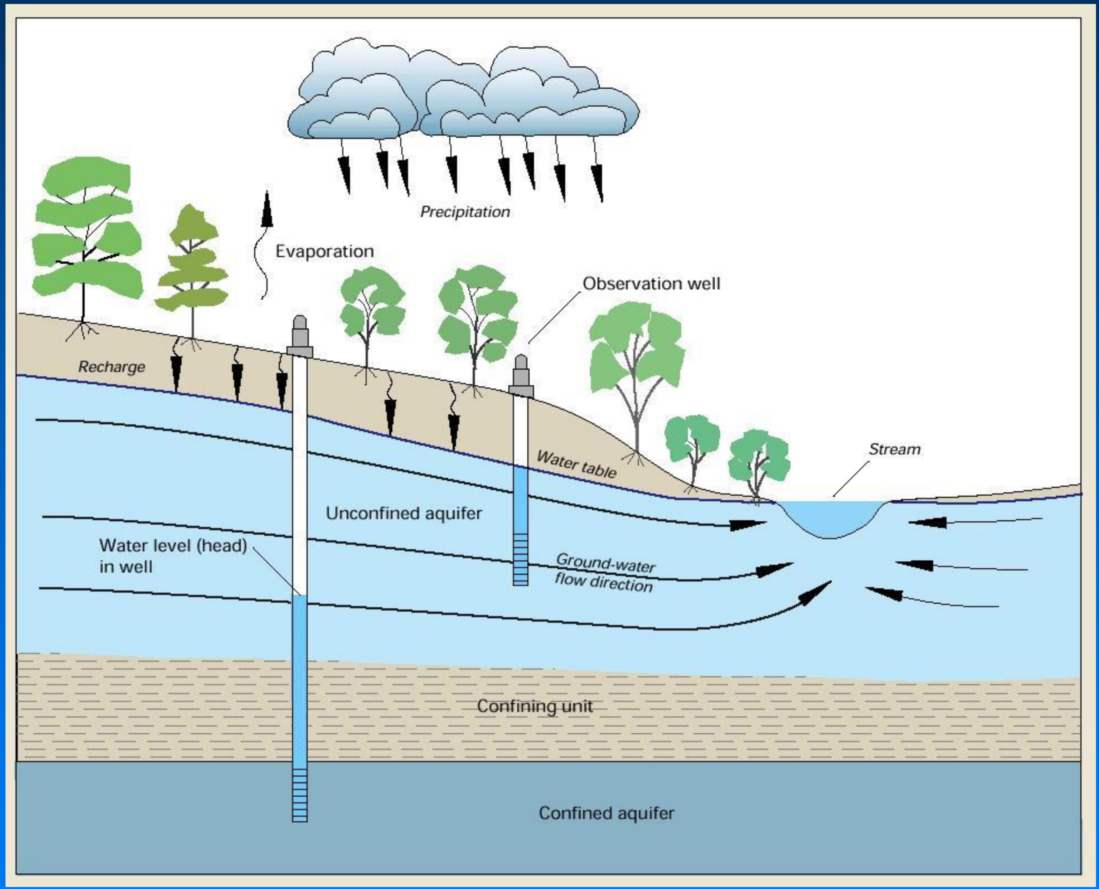
Goals for this Talk

- 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)



USGS Circular 1139

Contrast with Karst Aquifer Properties:

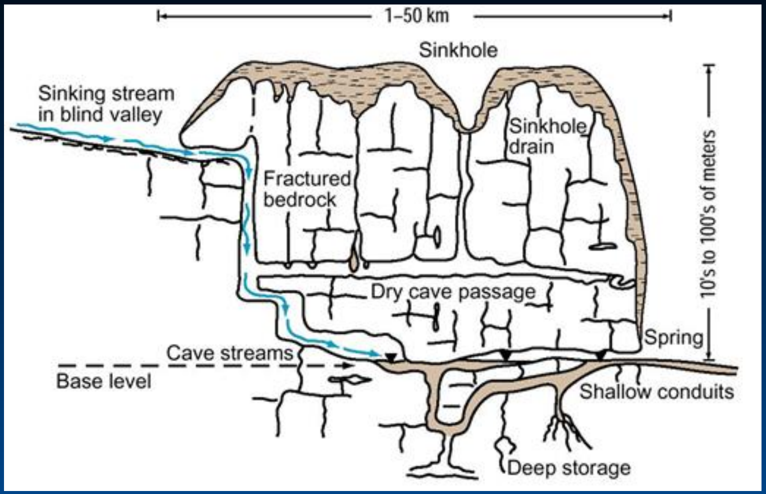
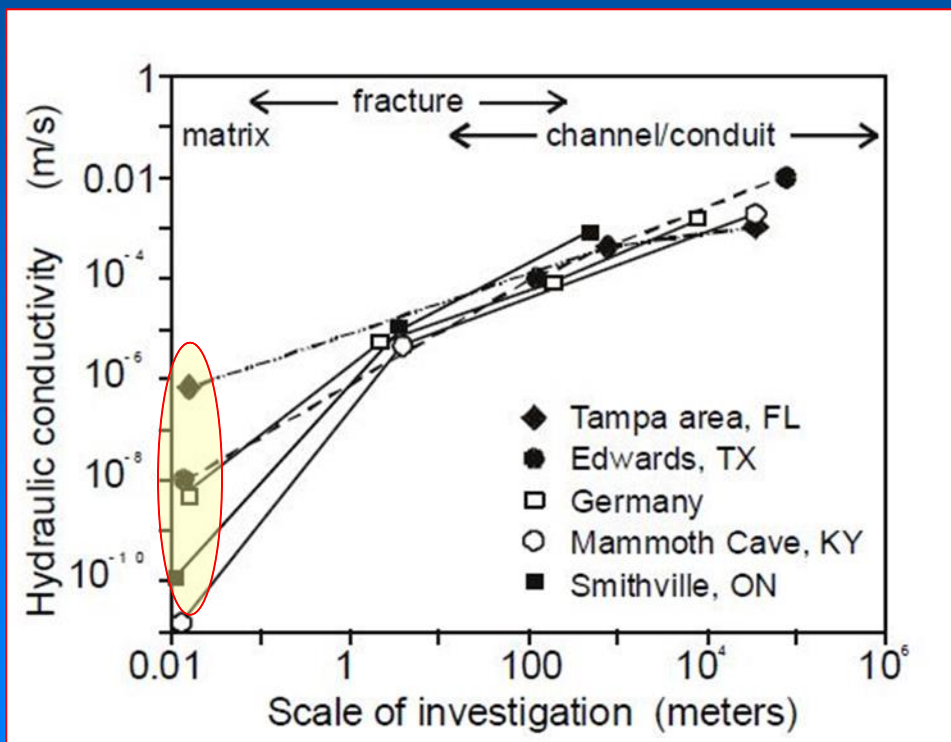


Table 1. Comparison of various hydrogeologic properties for granular, fractured rock, and karst aquifers (ASTM, 2002).

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

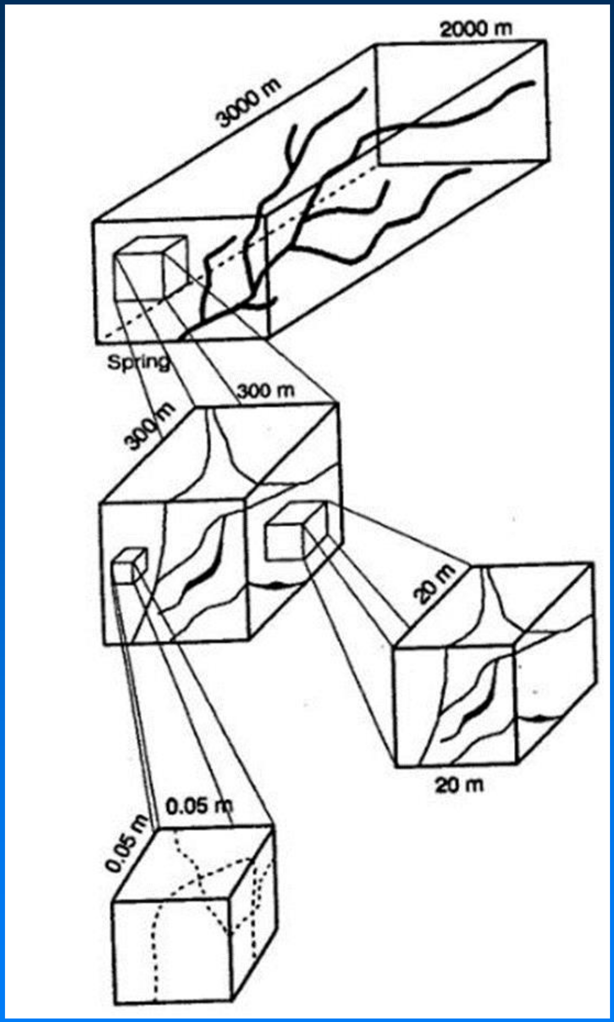
Karst Hydraulic Conductivity and Scale Effects

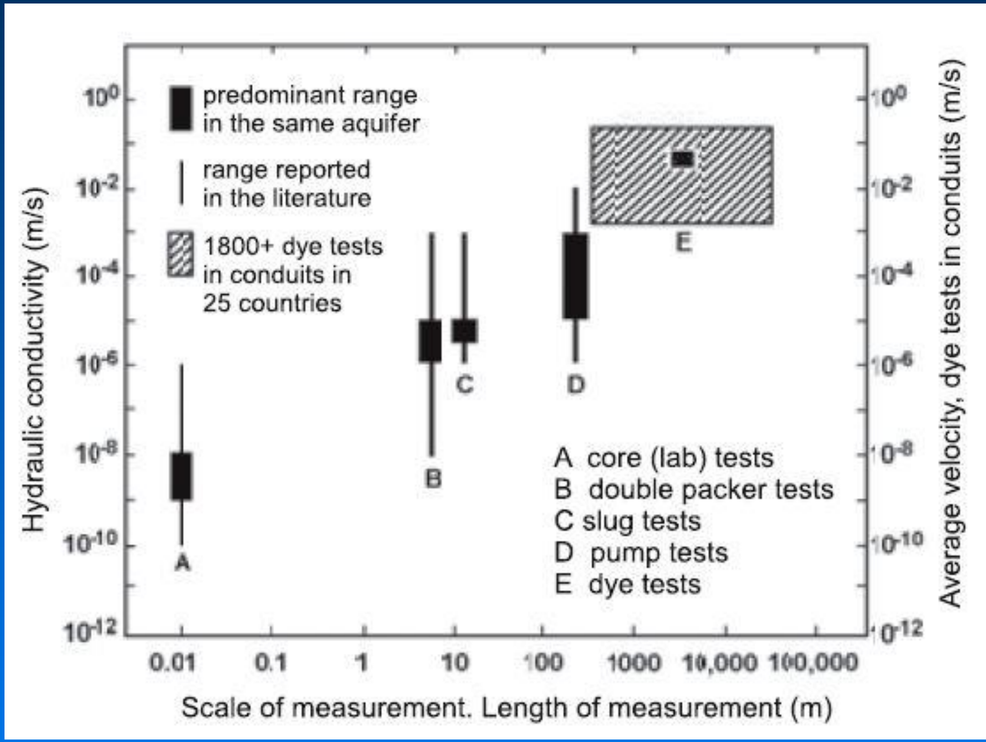
- Heterogeneities at local (matrix-fracture) scale contribute to greater range in measured hydraulic conductivities.
- The heterogeneities are "averaged out" at basin (conduit) scale.



(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).

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Pumping and Slug Tests in Karst

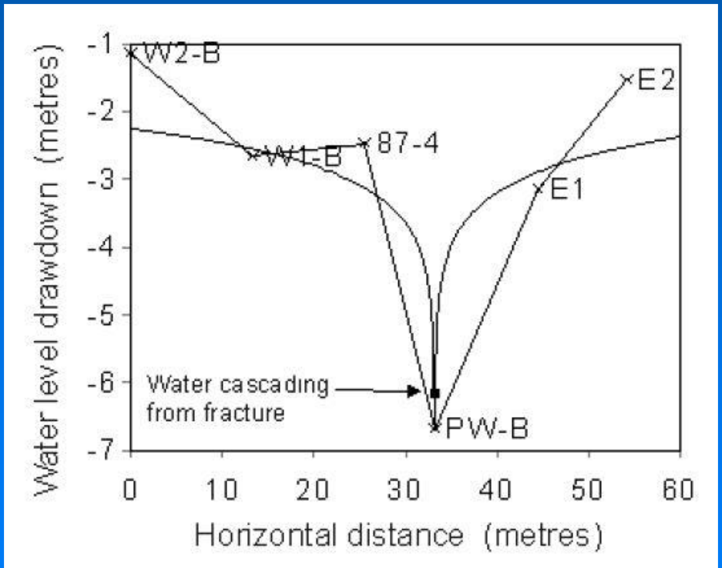
- Darcian-based type curves and solutions may not match observed data and should be applied with caution.

- 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.



Worthington and Ford, 1997

(continued) Use of Wells

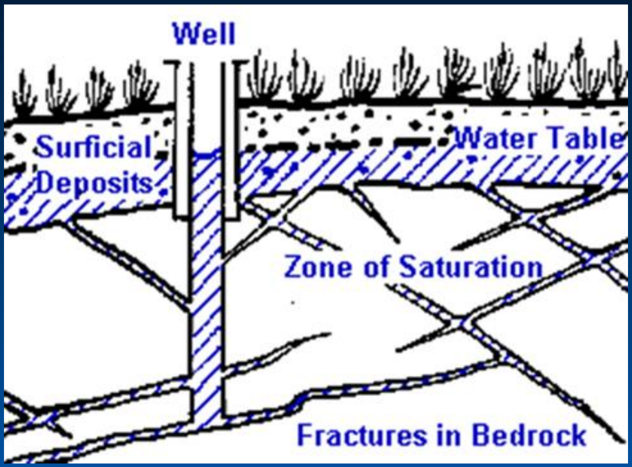
A well bore is a small object on the scale of the heterogeneities of a karst aquifer:

- 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.



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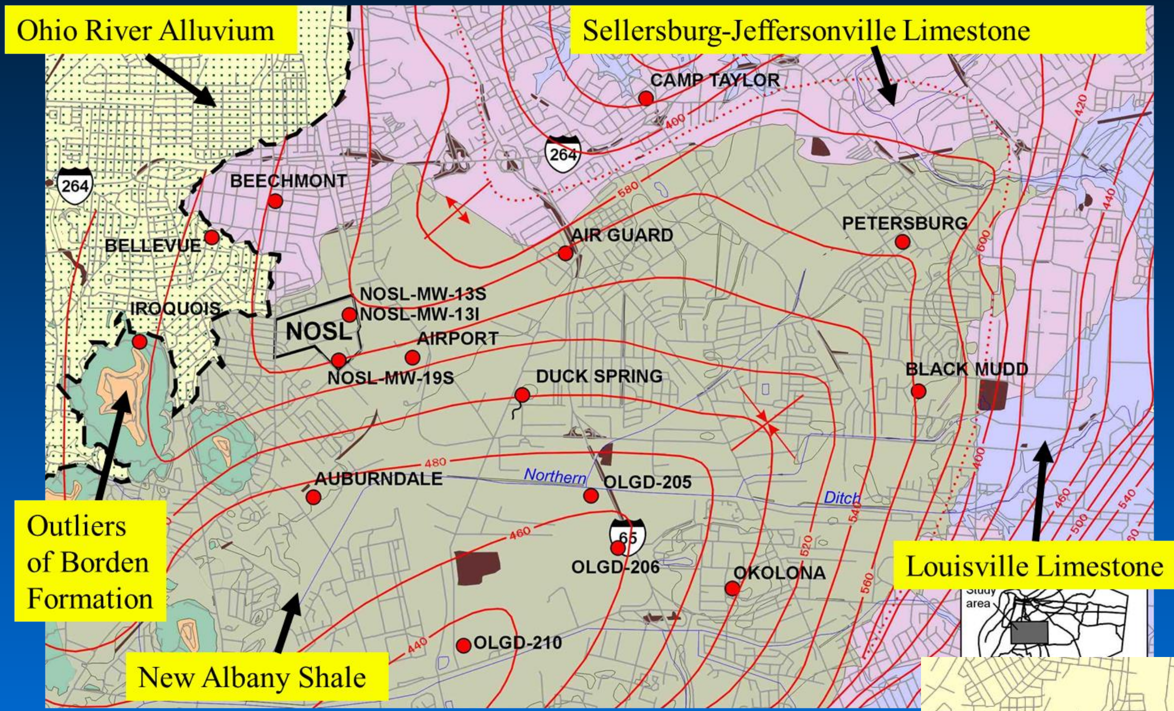
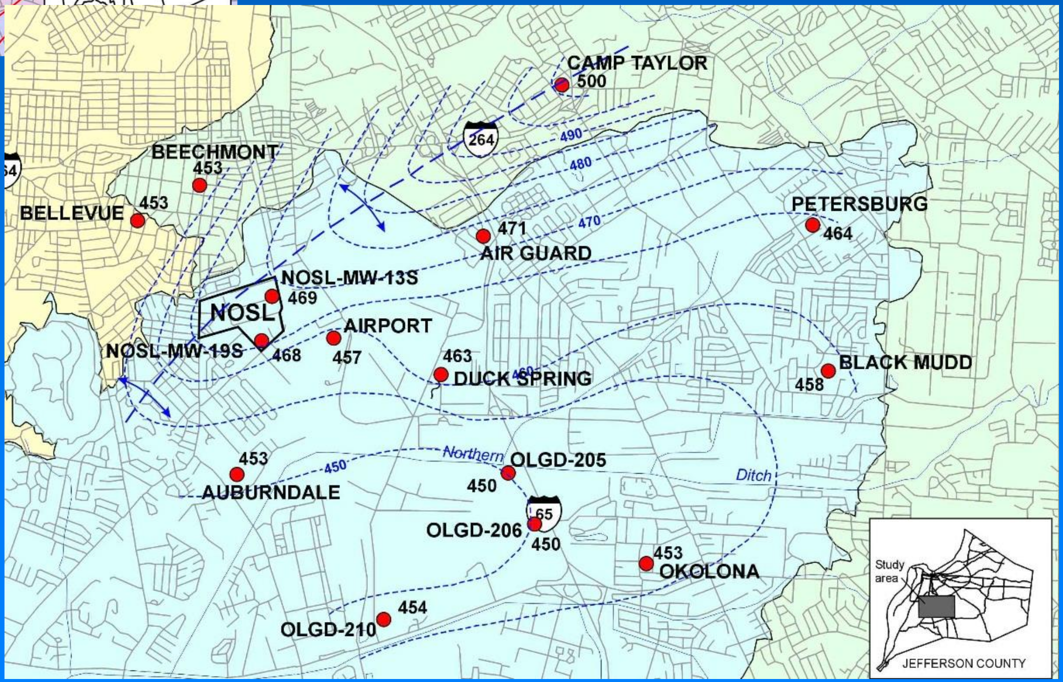
Case Study: NOSL Site, Jefferson County, KY



(Taylor and Hostettler, 2002)

Confined part of regional Silurian-Devonian Limestone Aquifer system

Karst development outside of confined aquifer recharge boundary



Borehole logs, Flowmeter and Straddle-Packer Tests

(NOSL site Louisville-Jefferson County, KY)

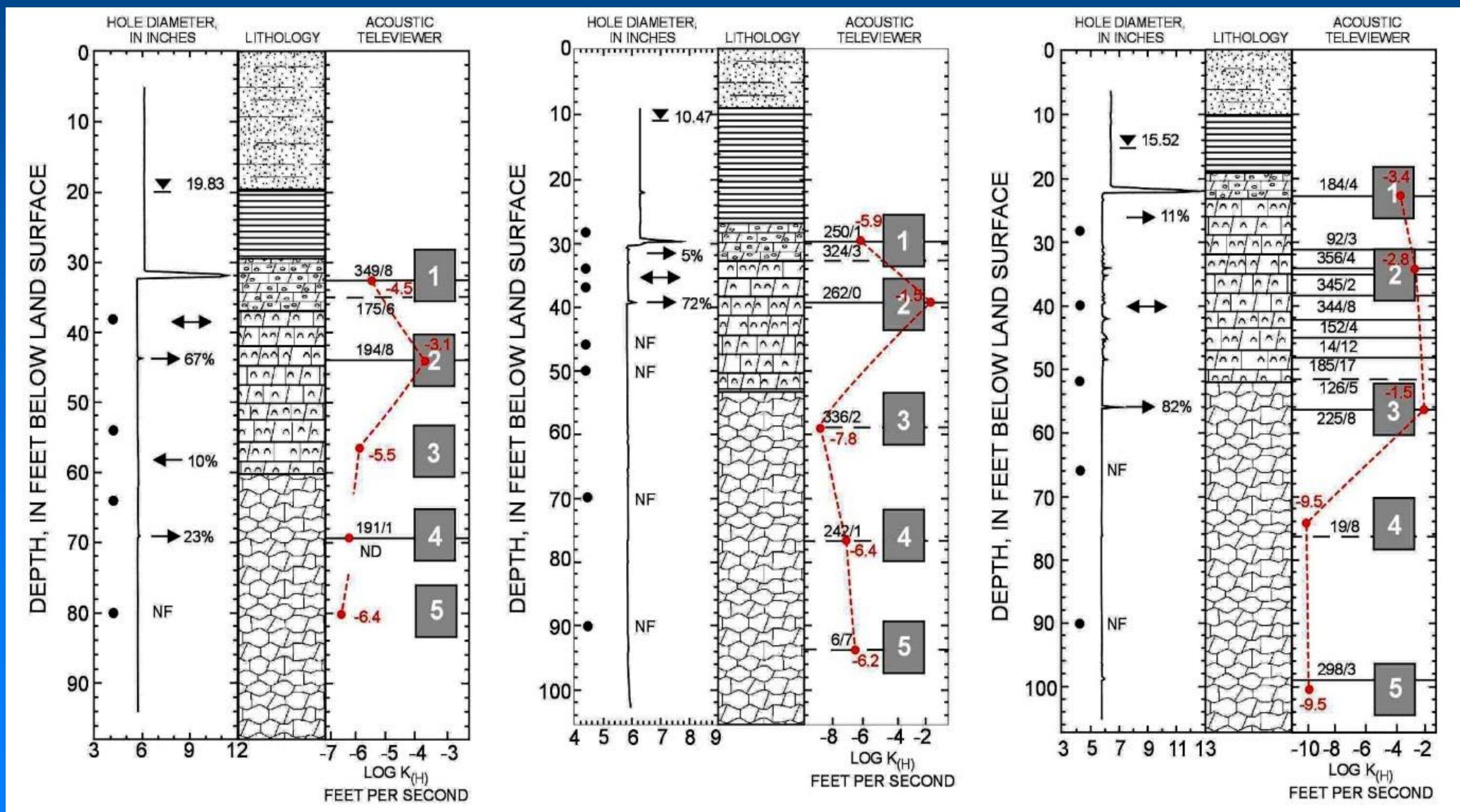
Well	Sample Depth (ft BLS)	Porosity (%)	Hydraulic Conductivity K(max) (ft/s)	K(90) (ft/s)	K(v) (ft/s)	Stratigraphic Unit (ft/s)
Air Guard	29	18.5	3.3×10^{-6}	2.0×10^{-7}	1.5×10^{-8}	Sellersburg Ls.
Auburndale	42	13.2	3.3×10^{-8}	3.0×10^{-8}	3.4×10^{-9}	Sellersburg Ls.
Beechmont	30	6.9	7.8×10^{-9}	2.3×10^{-9}	1.0×10^{-9}	Sellersburg Ls.
Iroquois	138	9.3	1.1×10^{-7}	6.7×10^{-8}	1.7×10^{-9}	Sellersburg Ls.
Okolona	103	8.6	1.3×10^{-7}	1.3×10^{-7}	2.6×10^{-8}	Jeffersonville Ls.
Okolona	117	16.2	4.2×10^{-7}	2.5×10^{-7}	3.7×10^{-9}	Jeffersonville Ls.
Petersburg	37	14.3	6.2×10^{-6}	2.0×10^{-6}	1.6×10^{-6}	Jeffersonville Ls.
Petersburg	67	17.6	7.9×10^{-6}	5.9×10^{-6}	2.1×10^{-7}	Jeffersonville Ls.
Petersburg	51	10.7	8.2×10^{-7}	6.1×10^{-7}	4.2×10^{-7}	Jeffersonville Ls.

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

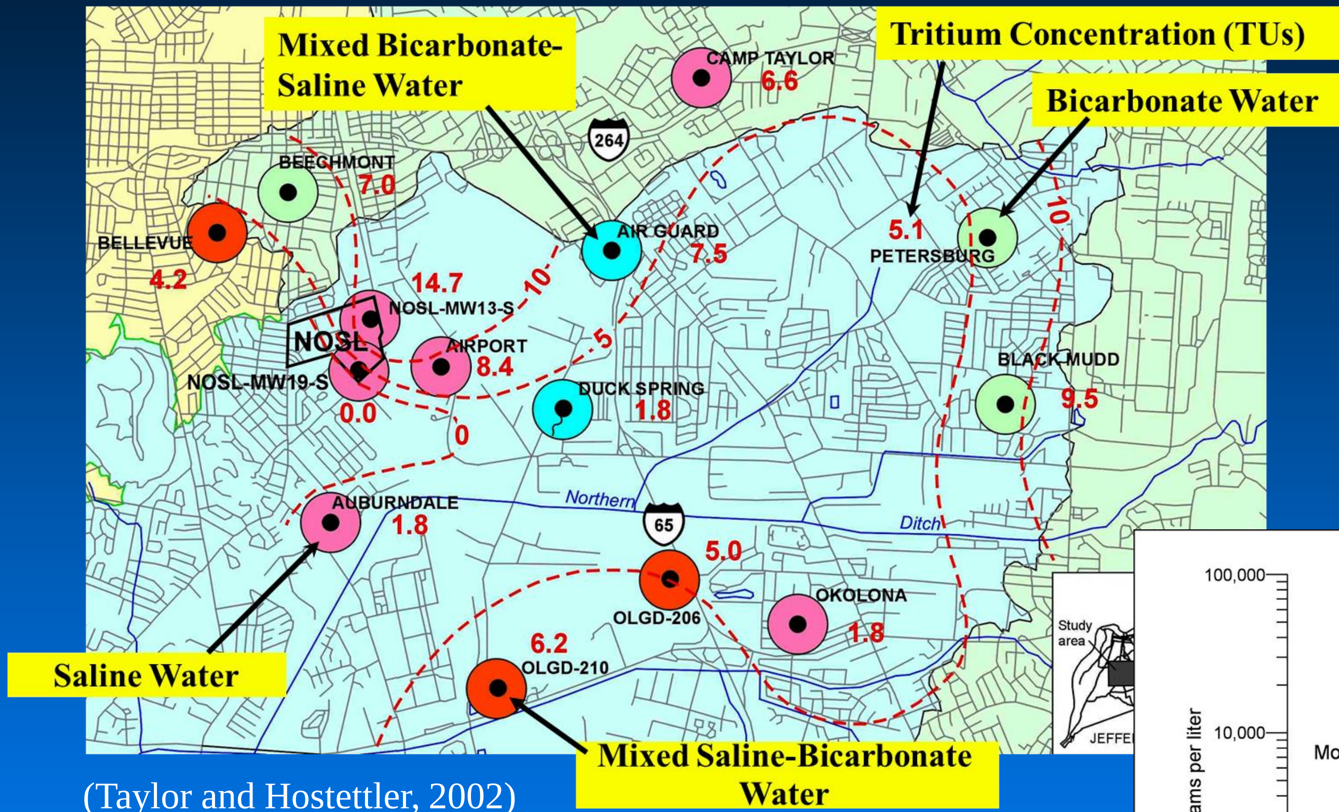
Beechmont

Air Guard

Petersburg

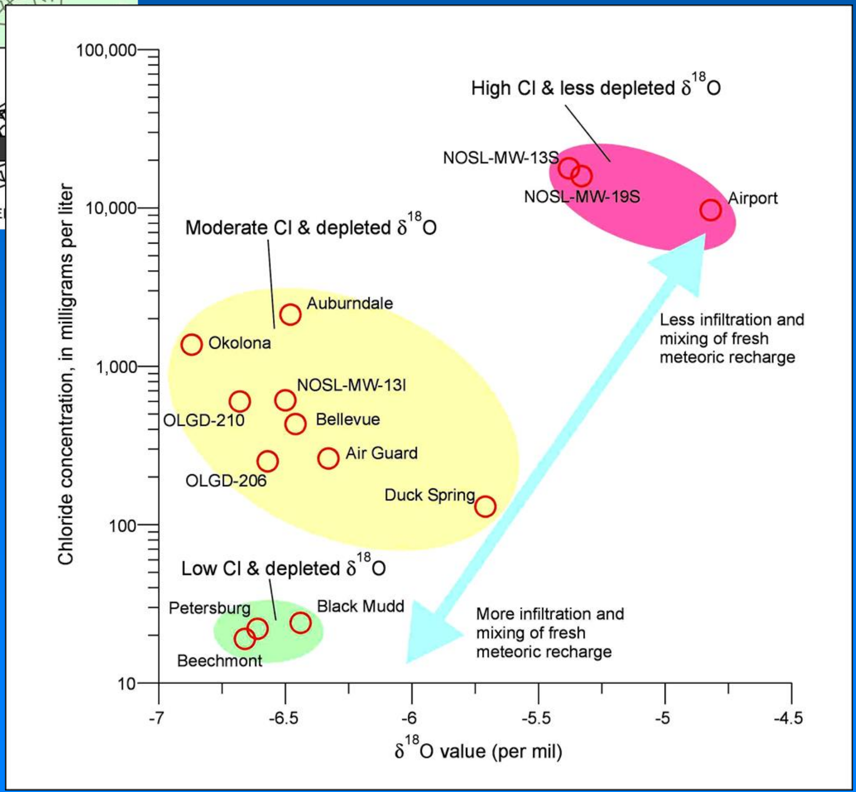


Variability in Groundwater Chemistry



(Taylor and Hostettler, 2002)

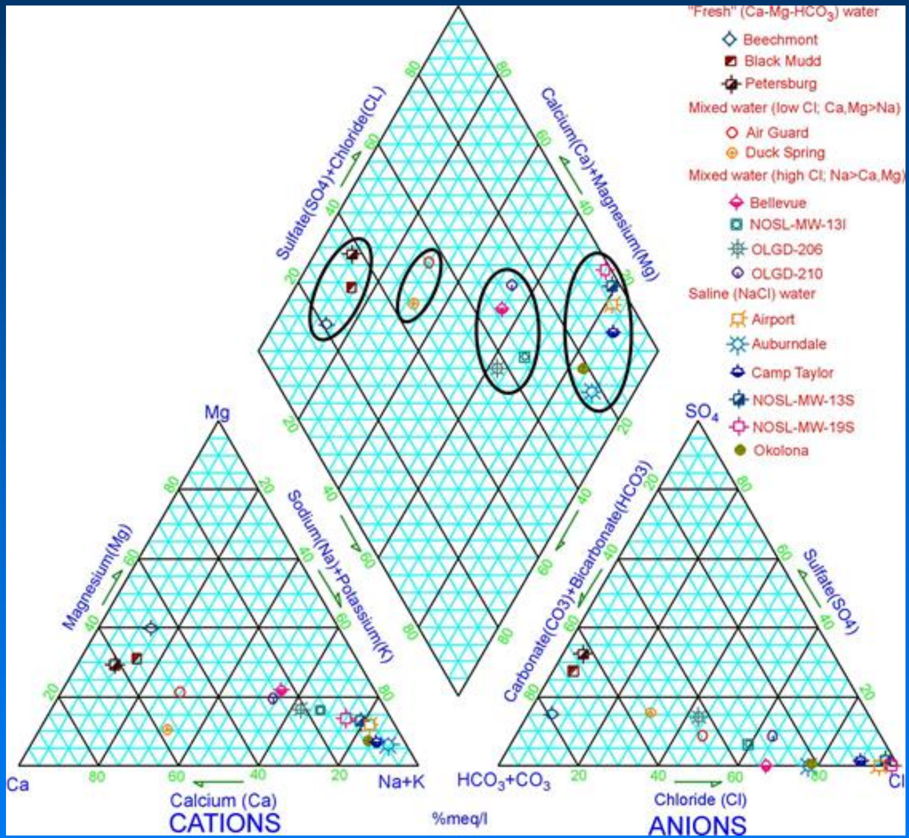
- Spatial pattern in groundwater chemistry is related to variability in infiltration and mixing of recharge in the aquifer.



- 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).



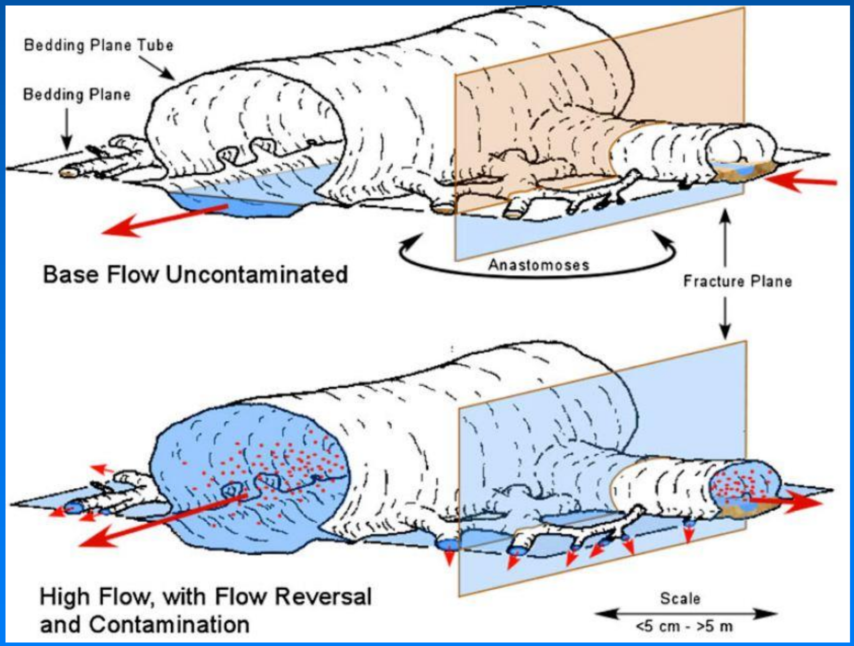
(Taylor and Hostettler, 2002)

Conduits: Major Control Over the Transport of Water, Sediment, and Contaminants

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

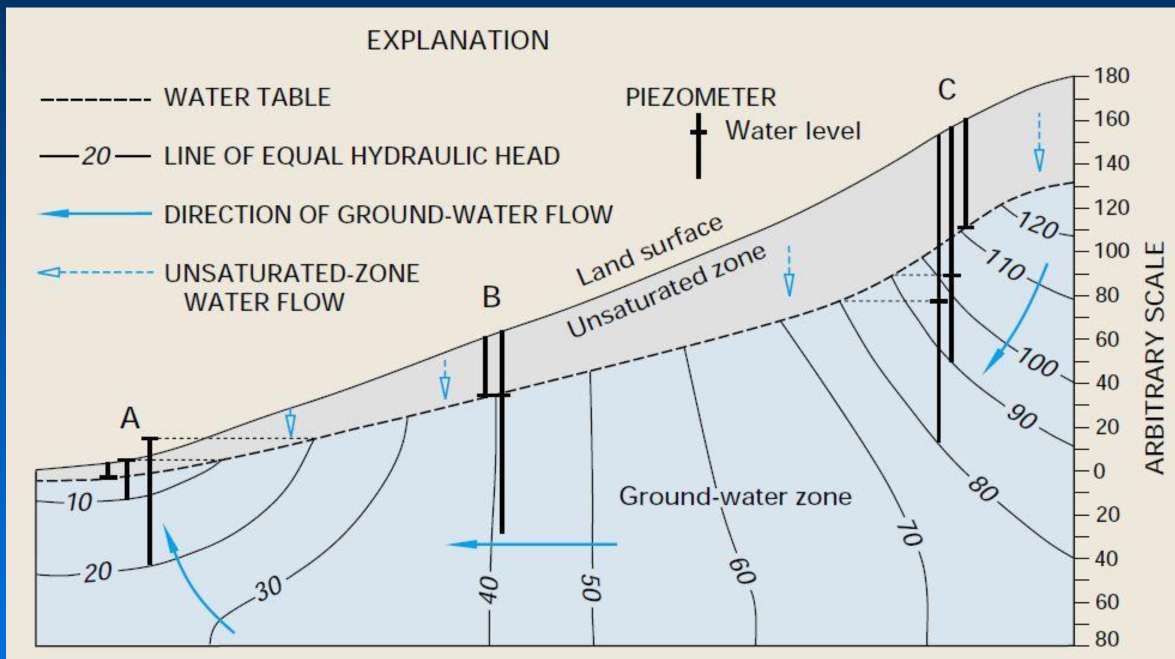
- Size, organization, and hydraulic drainage capacity of conduits generally increase in downgradient direction.

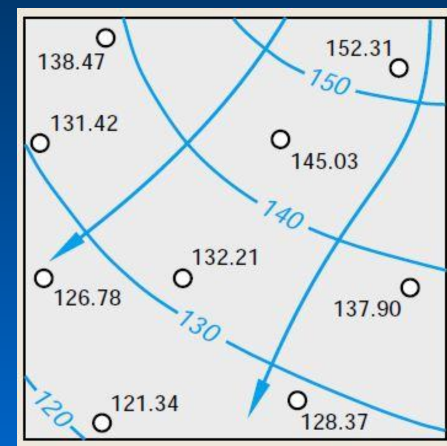
- Exhibit hydrologically-mediated flow dynamics:
  - Driven by hydraulic head differentials.
  - Matrix, fractures, tributary conduits “feed” trunk conduits under base flow.
  - Conduits inject water into matrix-fractures during flood flows.
  - “Overflow” routes and outlets may be activated during high-flow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



Ewers, 2010

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





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- 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.

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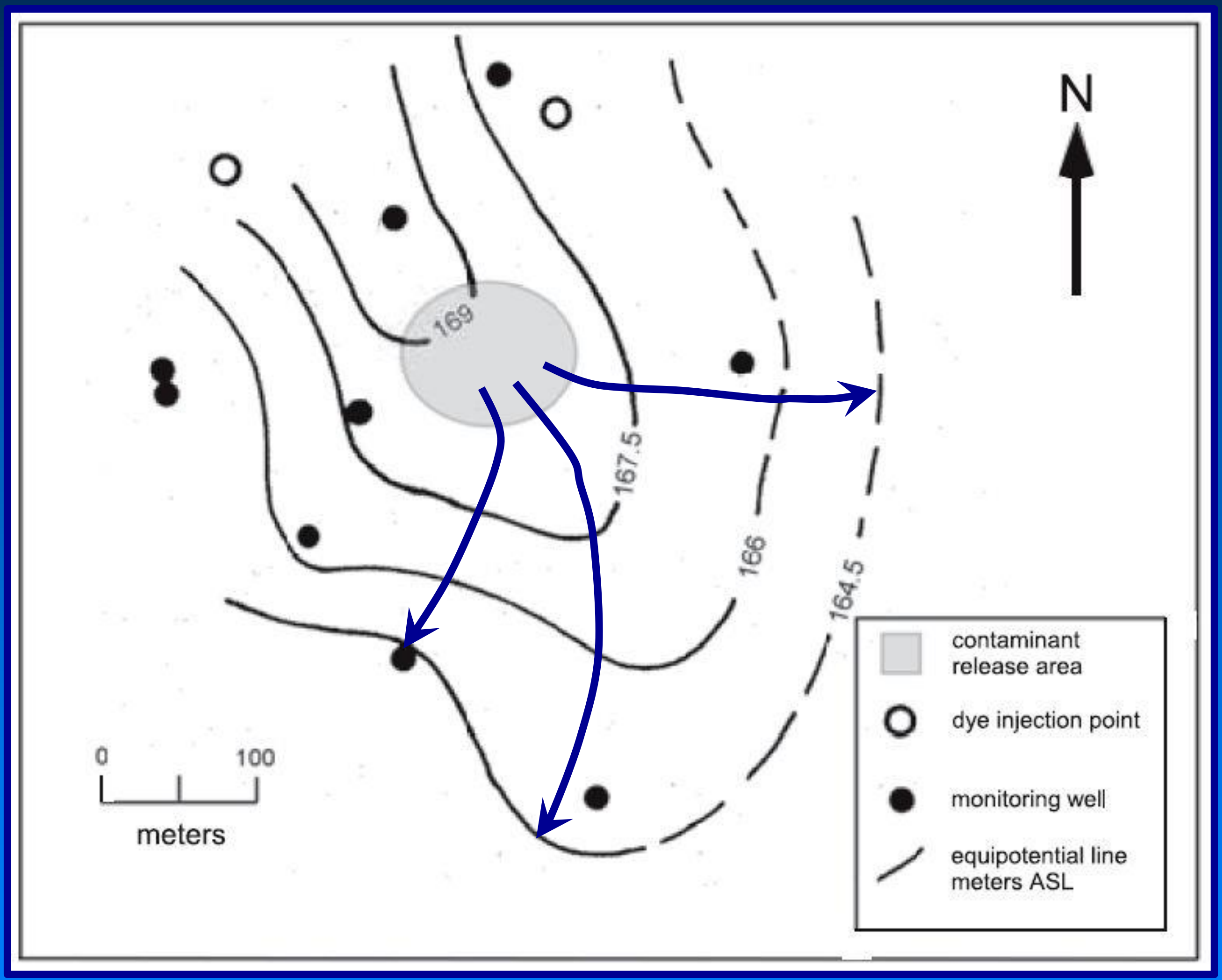
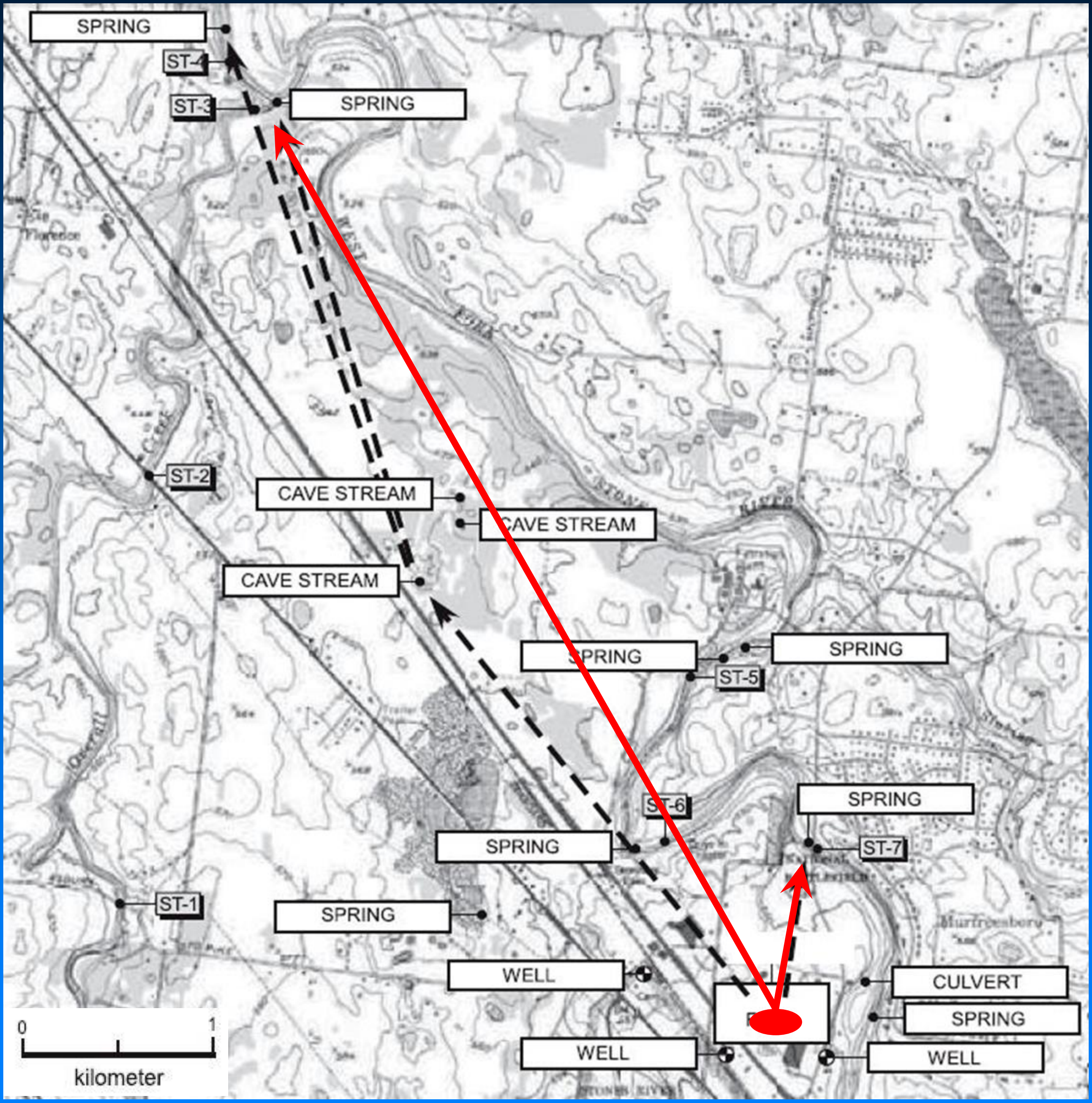
Not Always Reliable In Conduit-Dominated Karst



Example from Ewers (2010)

Site investigation in Ordovician karst terrane, Tennessee

Actual (Traced) Groundwater Flow Directions

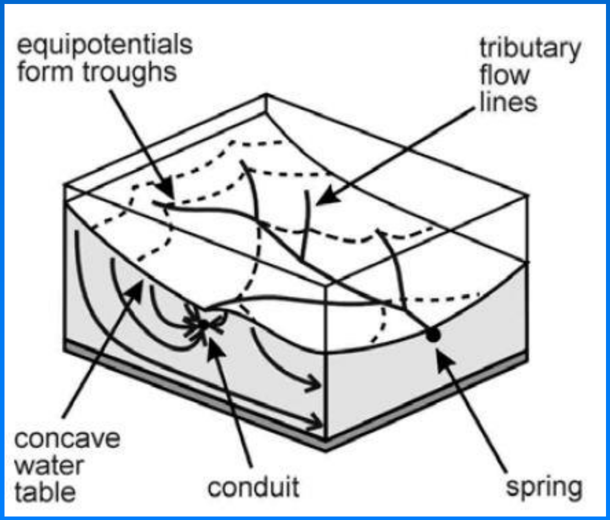


In conduit-dominated karst, tracer tests are the only truly reliable way to identify groundwater flow directions and basin boundaries.

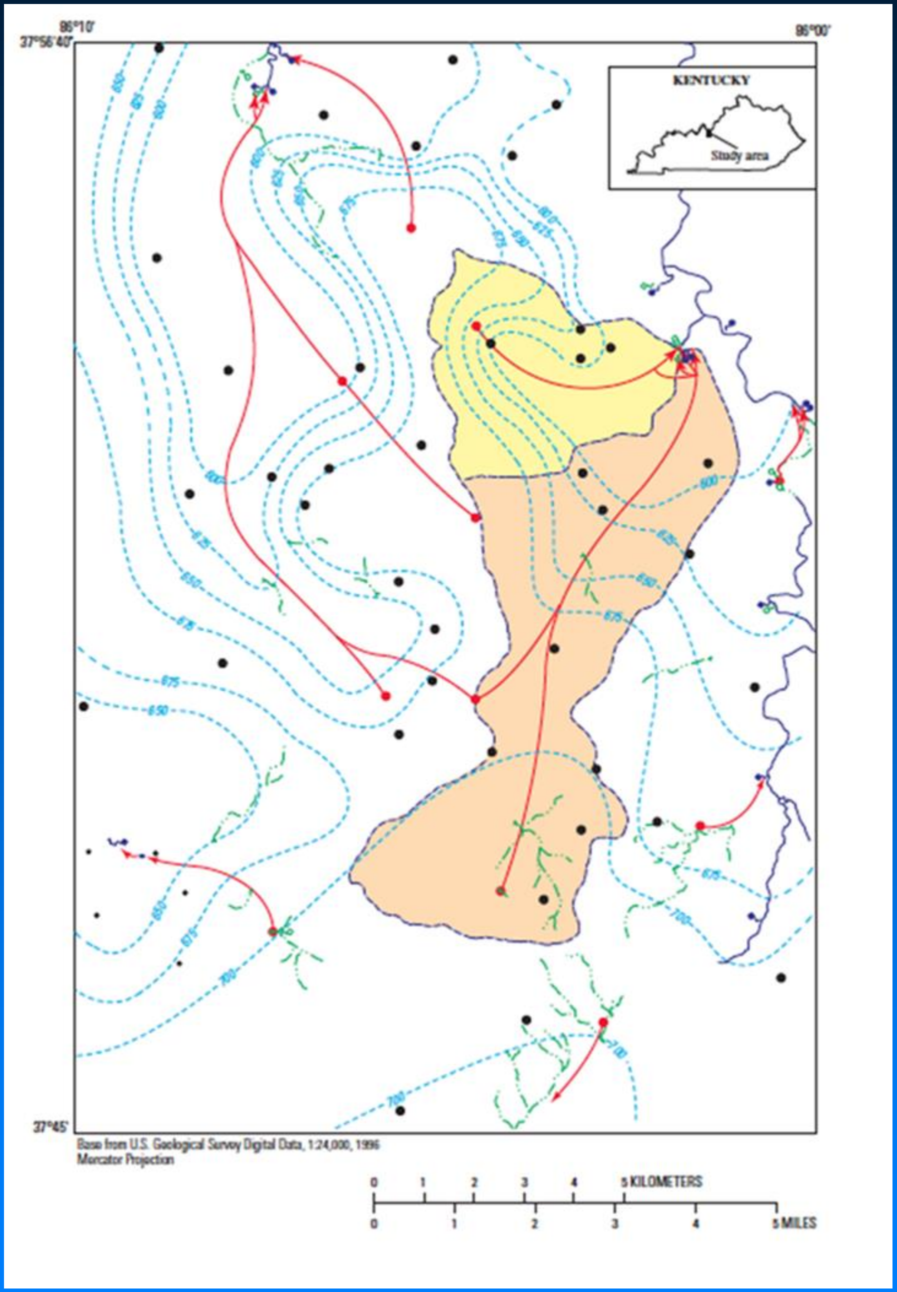
Method: Tracer Tests Combined with Water-Level Mapping

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



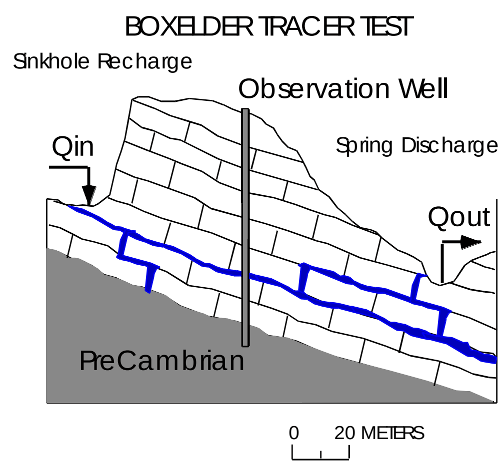
Taylor and McCombs, 1998

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

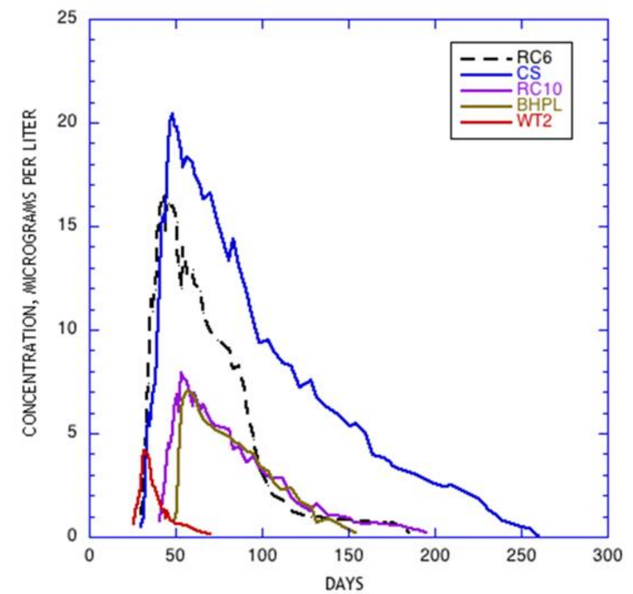
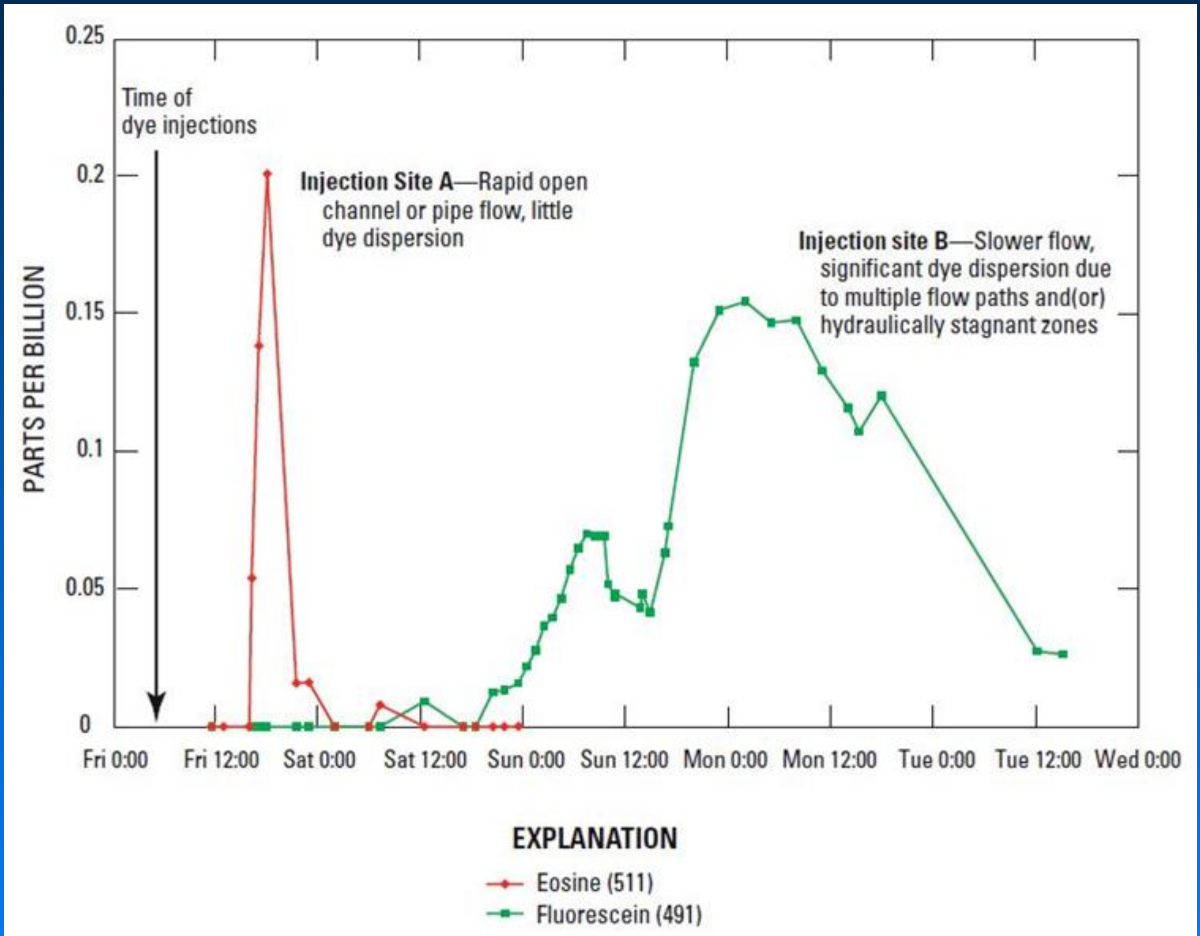


Figure 5. Breakthrough curves of Rhodamine WT sampled from wells and springs during the Boxelder Tracer Test (Greene, 1999)

Table 2. Transport Parameters for the Boxelder Tracer Test

Breakthrough Well	Curve Initial Days (days)	Data Peak Days (days)	End Days (days)	Mass Recovered (grams)	Percent Recovered	Mean Mass (days)
WT2	26	32	73	112.5	0.8	40
CS	30	48	261	1604.9	11.5	90
RC6	30	45	186	1442.1	10.3	74
RC10	41	53	198	1882.3	13.4	79
BHPL	49	57	159	41.7	0.3	90
Total Mass Recovered				5083.46		
Percent Recovered					36.3	

Shape of Tracer Breakthrough Curves Can Indicate Aquifer Characteristics Along Flowpaths



From Taylor and Greene, 2008

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

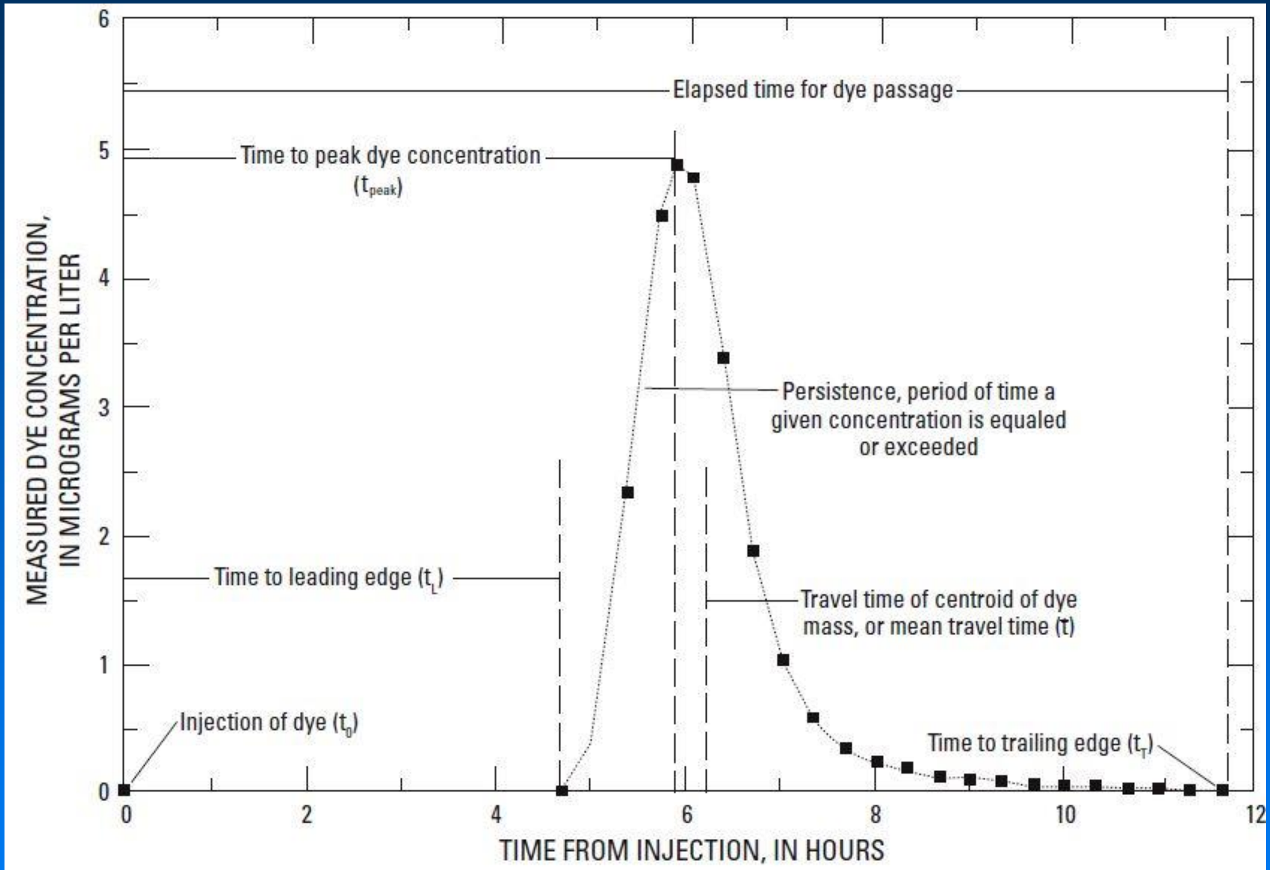
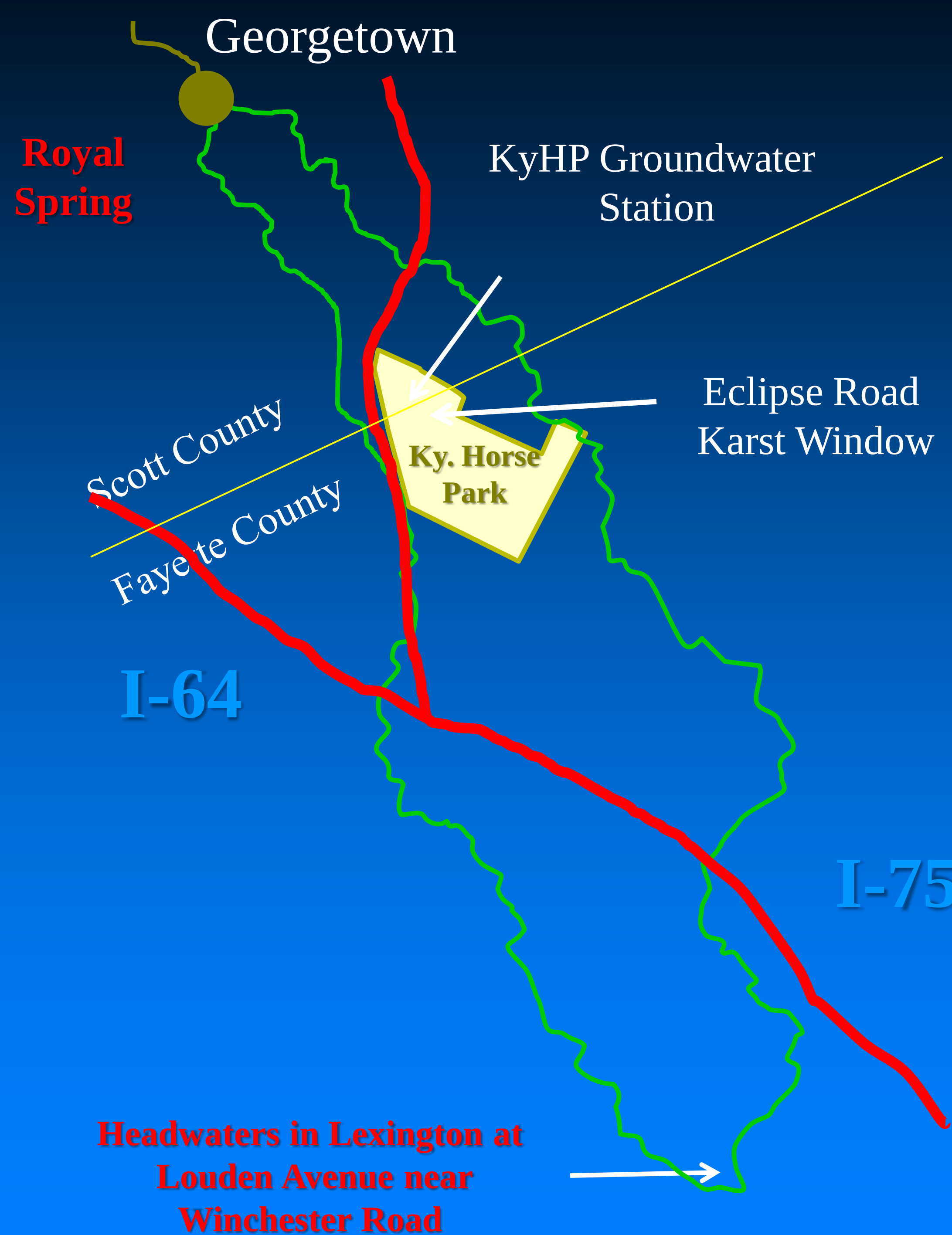


Figure 18. Some important physical characteristics of a dye-breakthrough curve (from Mull and others, 1988).

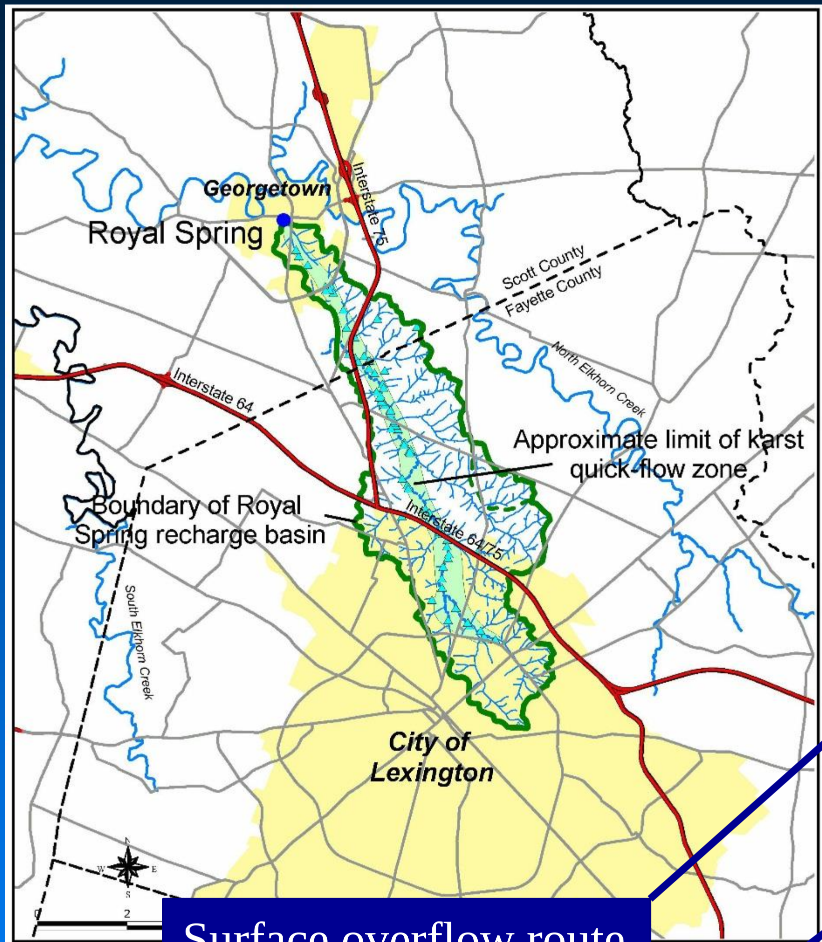


Case Study: Cane Run/Royal Spring Basin Study (for Nutrient Mass Flux)

Distance from headwaters to the spring is approximately 15 miles.

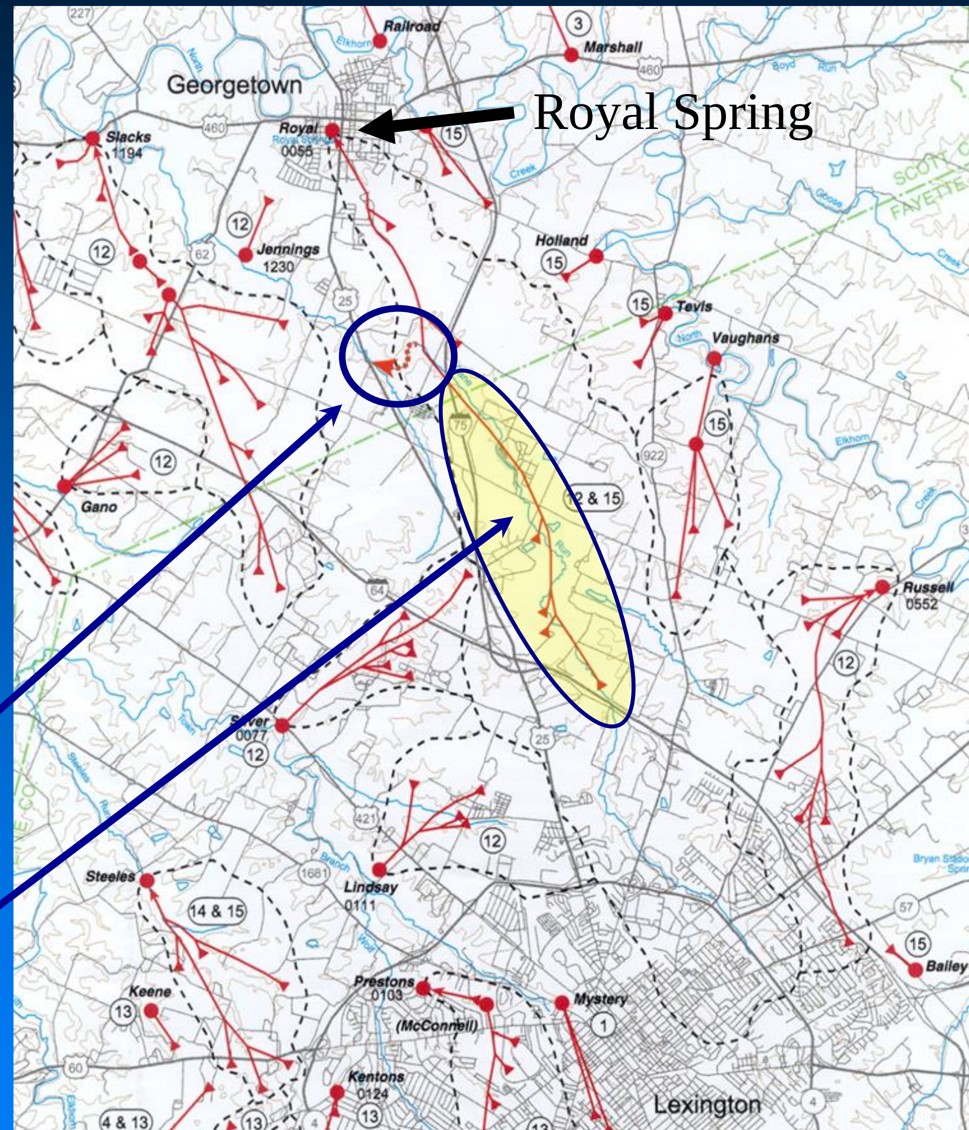
Unpublished data courtesy of Jim Currens, KGS

Cane Run Creek Loses Flow to Royal Spring Conduit



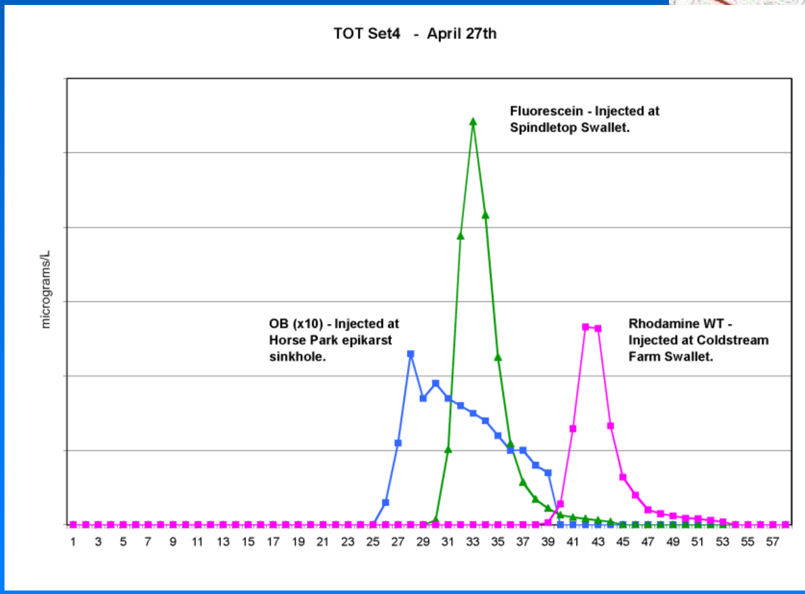
Surface overflow route

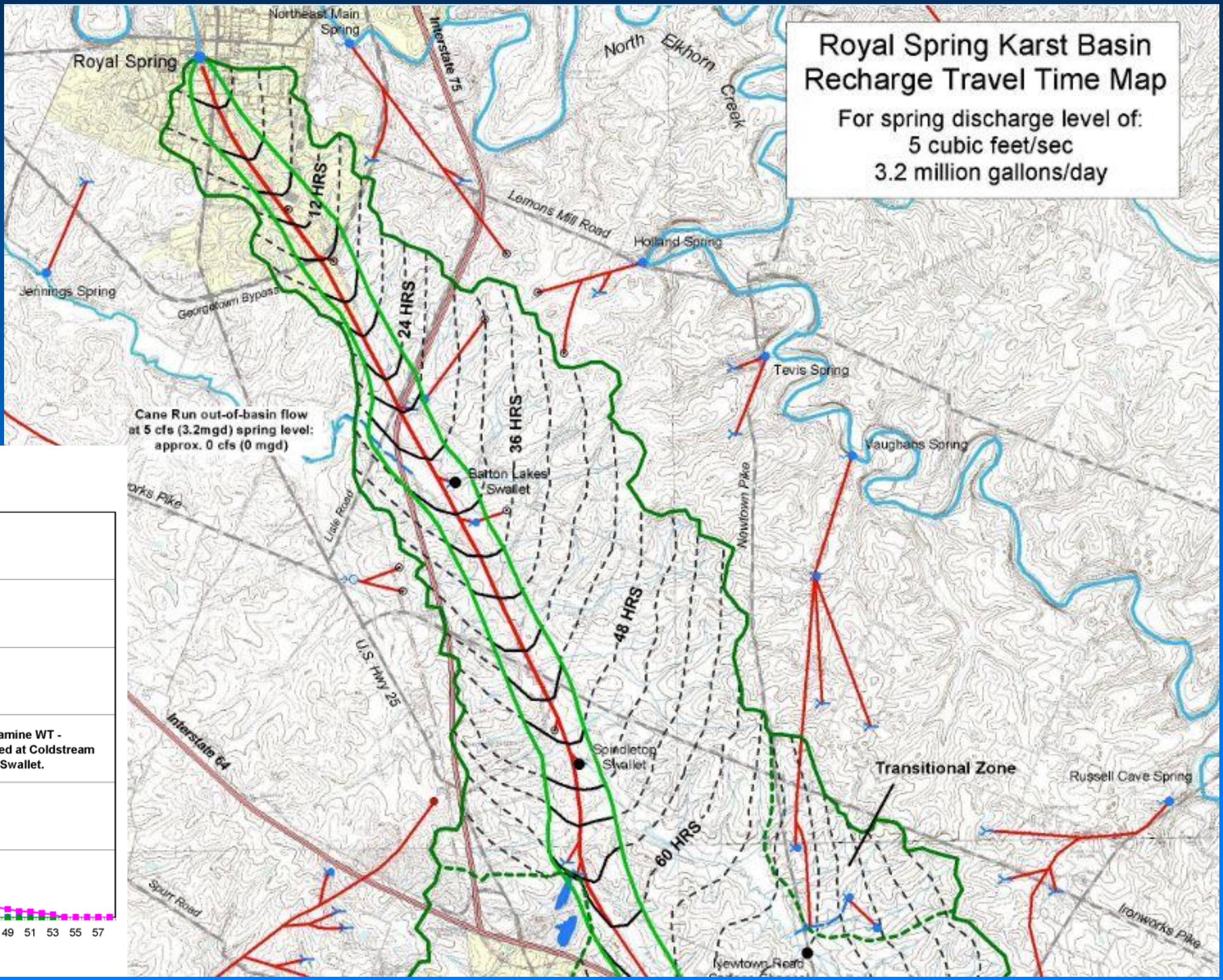
Main sinking reach



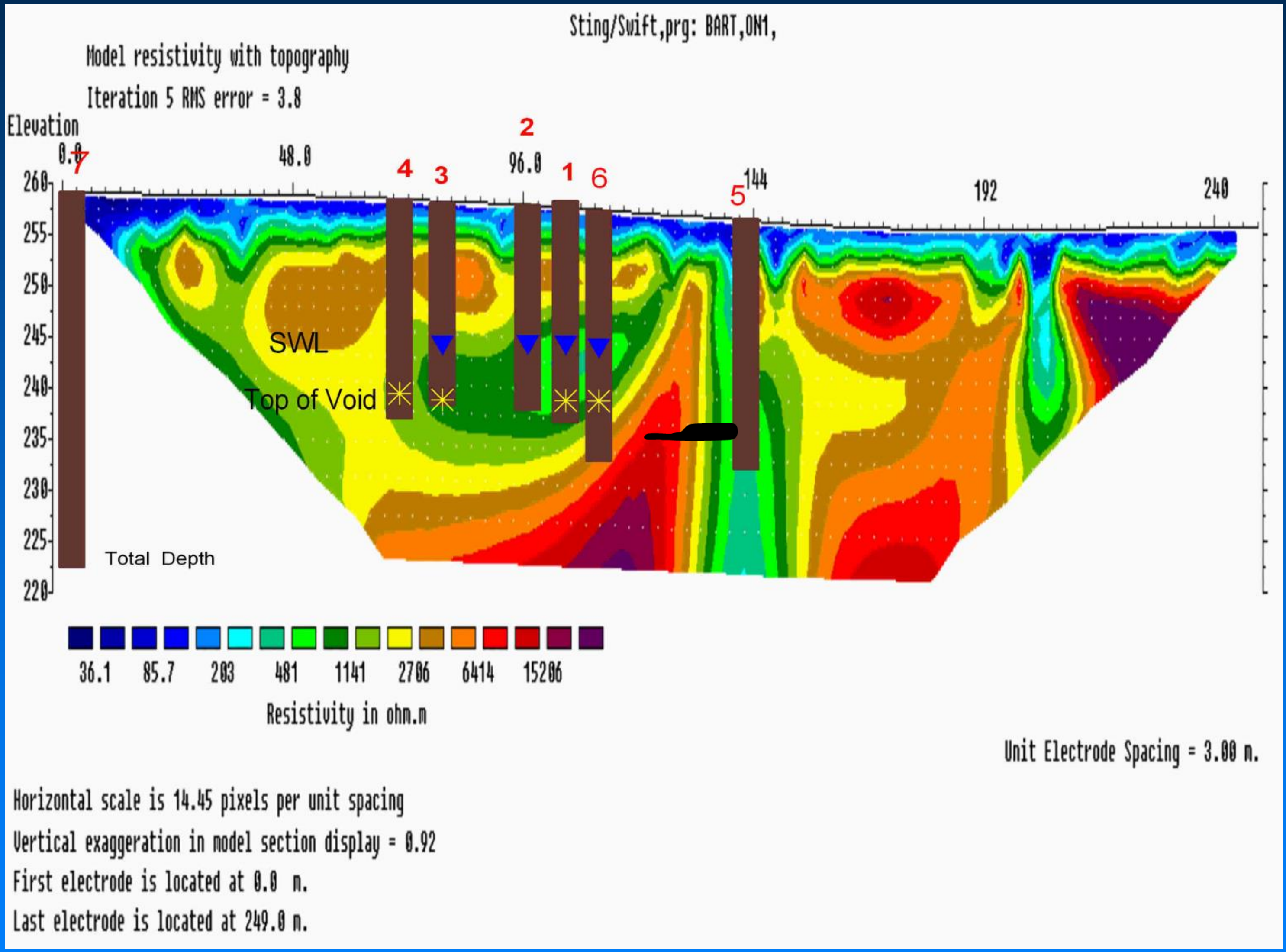
Part of the Lexington 30X60 minute Karst Groundwater Basin Map

Water-Tracing Tests in Cane Run/Royal Spring Basin Used to Determine TOT Characteristics



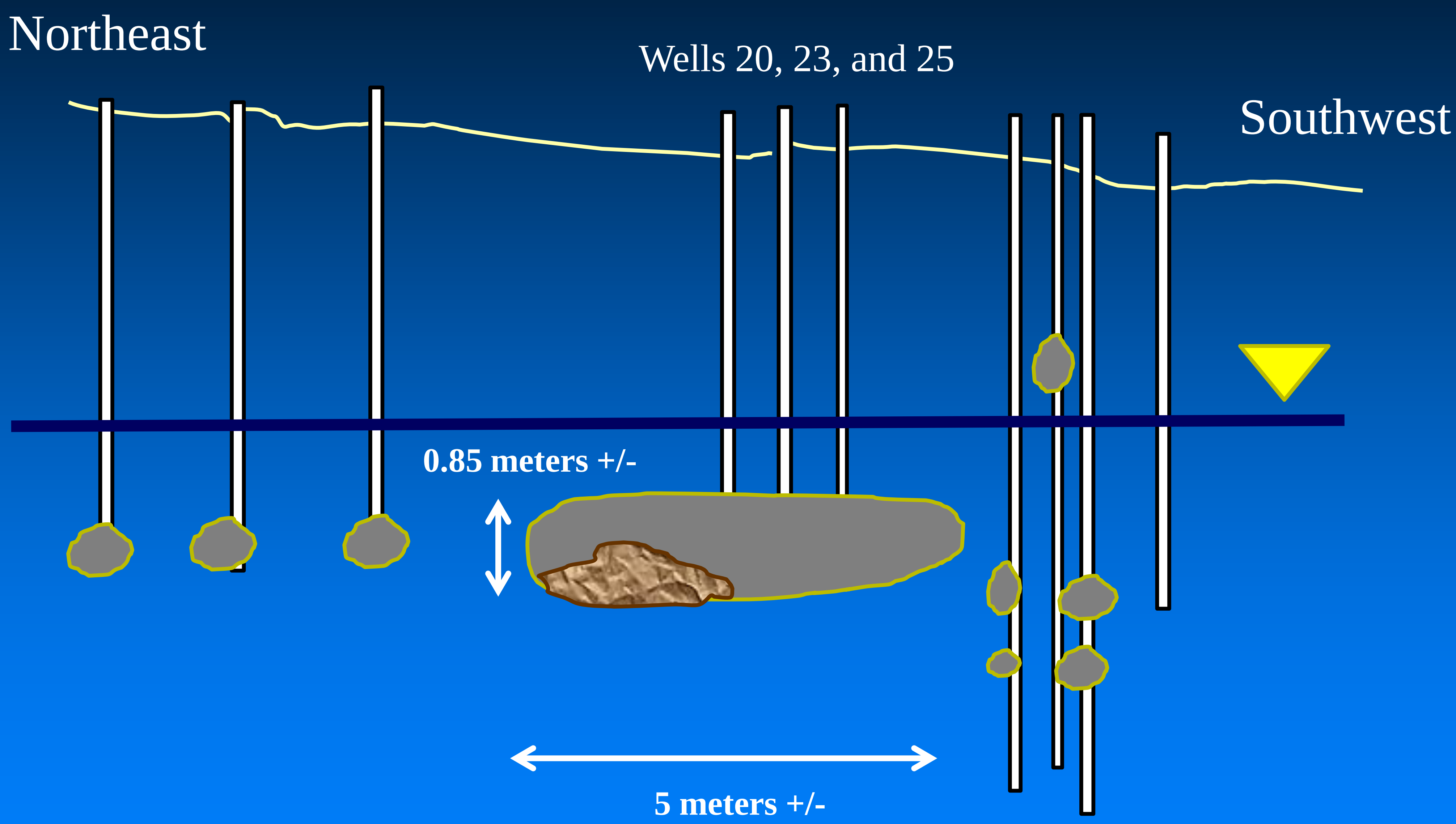


Monitoring Well Drilling Locations Selected Using Geophysical Survey:

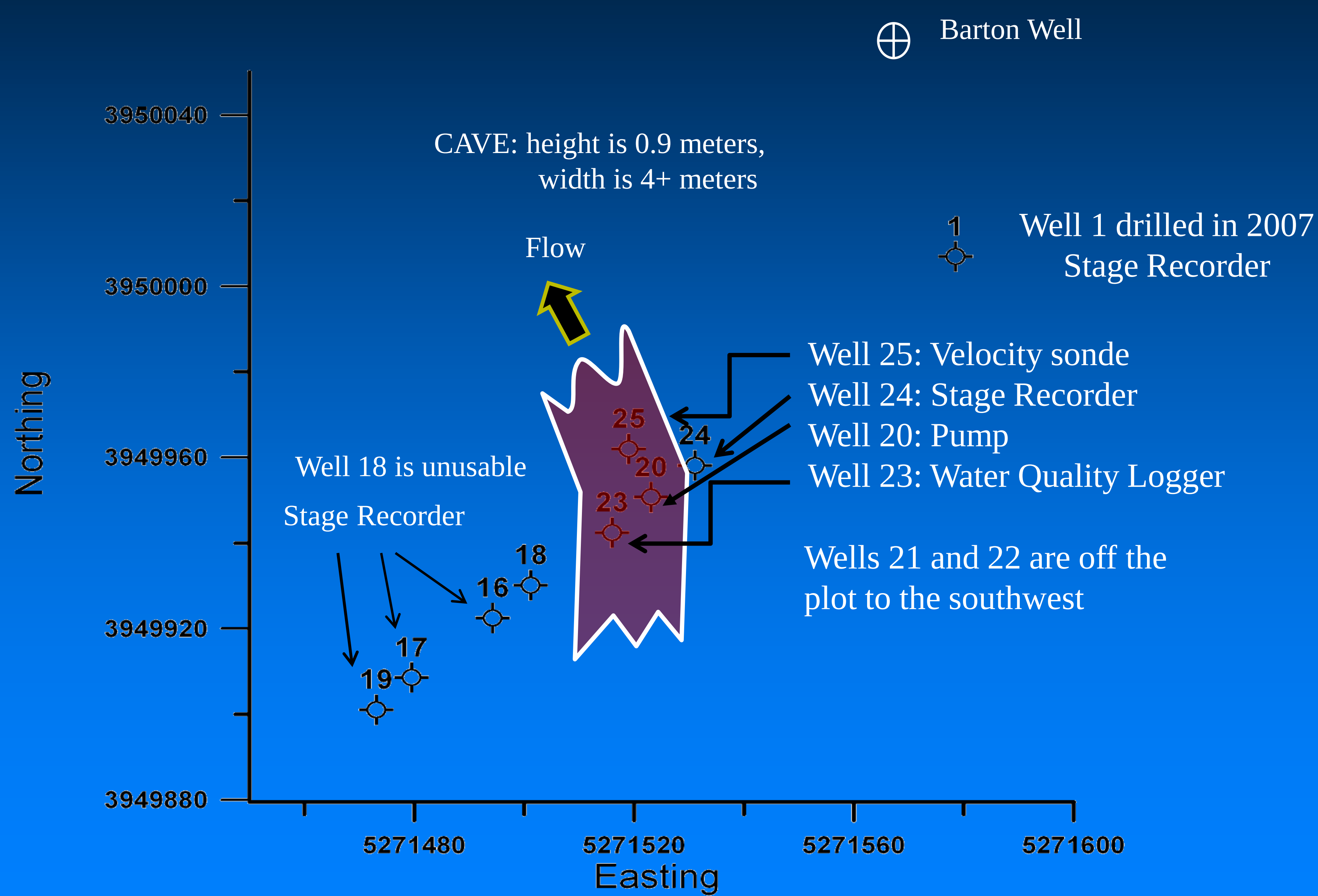


Unpublished data courtesy of Jim Currens, KGS

Cartoon Showing Intercepted Conduits:

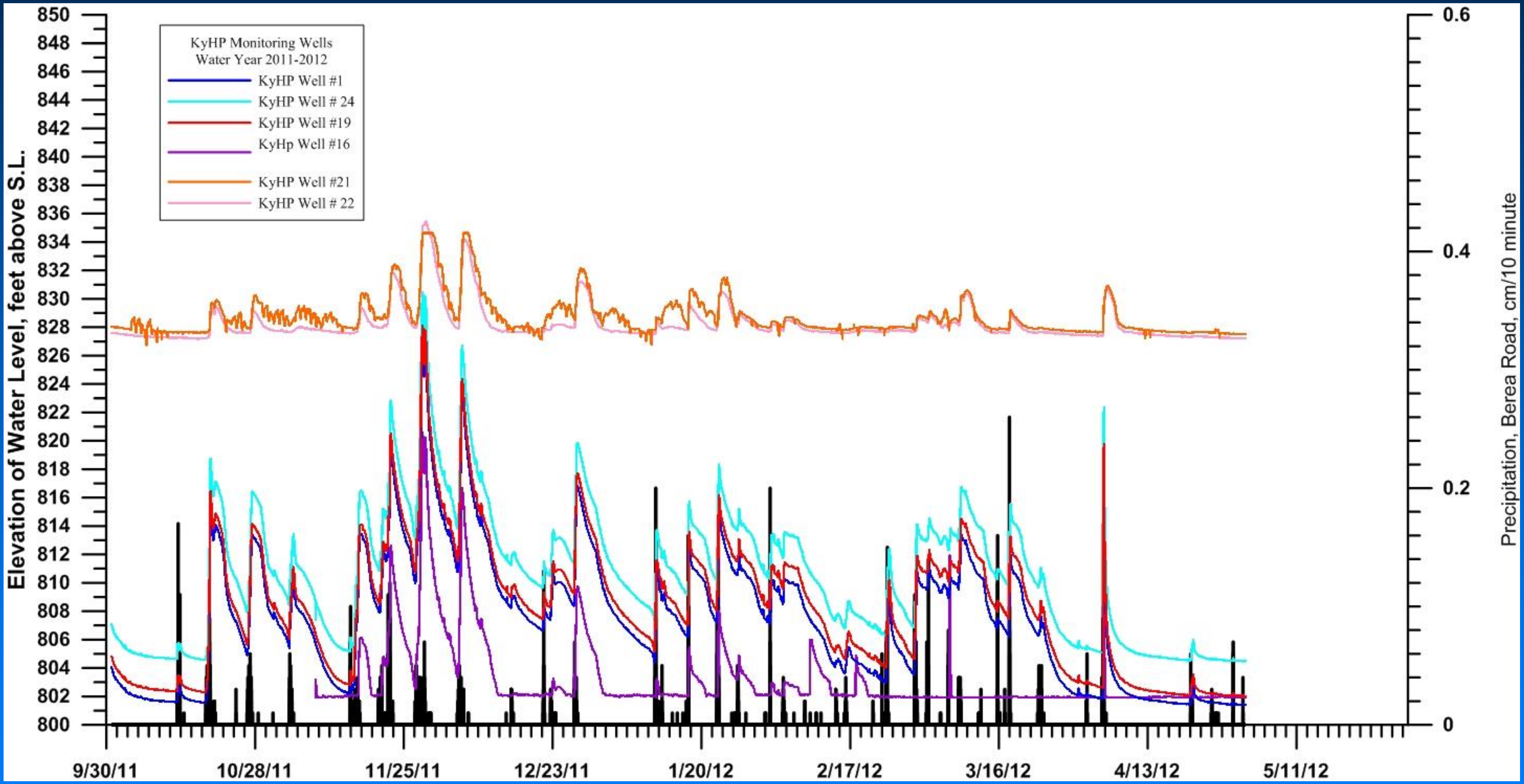


Monitoring Wells at the KyHP Monitoring Site



Monitoring Wells at KyHP Groundwater Station

Hydraulic Communication and Water Levels in KyHP Monitoring Wells:



Unpublished data courtesy of Jim Currens, KGS

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Another Aspect of KYHP Investigation:

Quantitative groundwater traces can be used to measure groundwater discharge.

$$\frac{(C_i * Q_i)}{C_r} = Q_r$$

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.

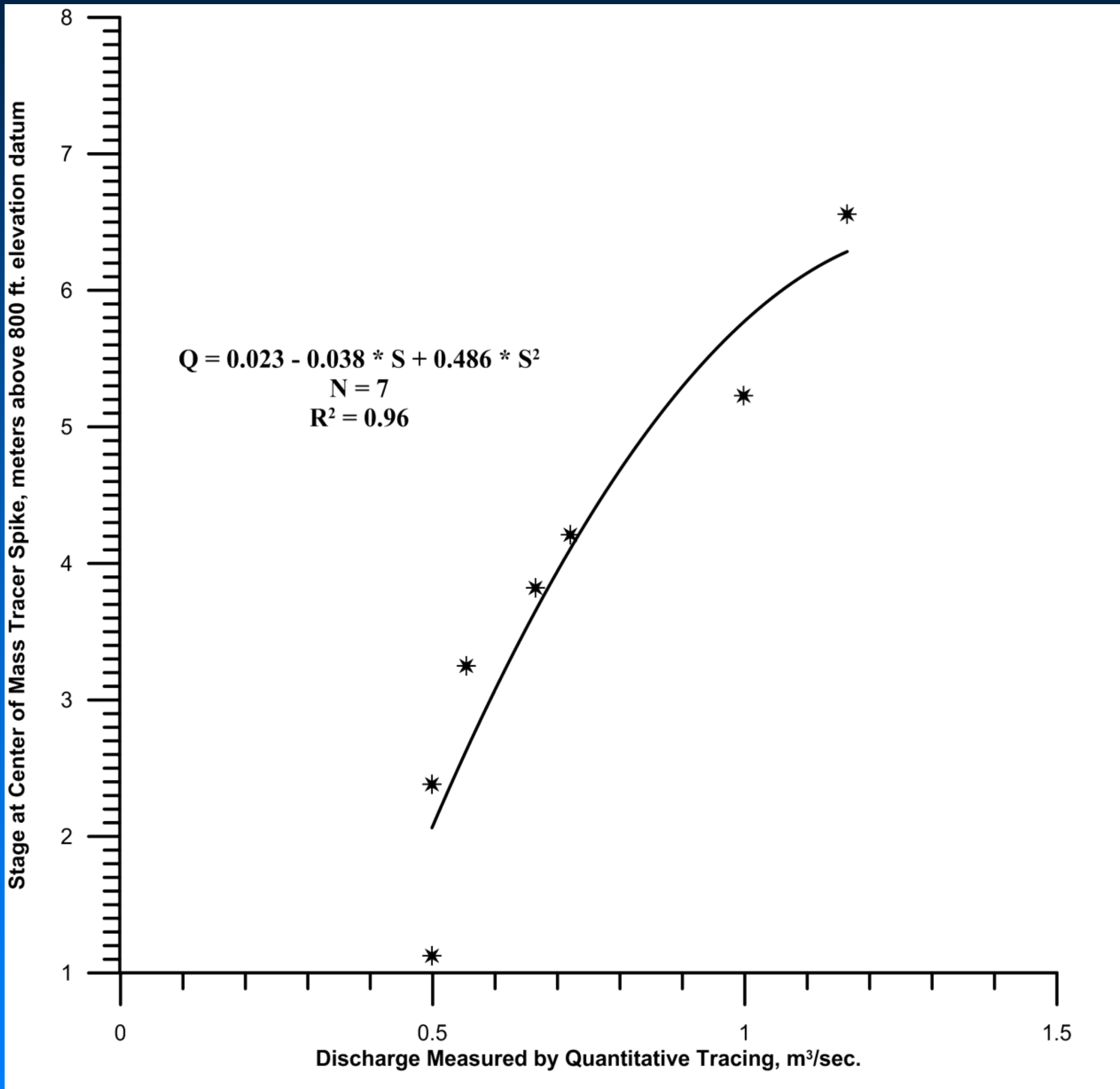
A spike of fluorescein is introduced midway through Rhodamine WT injection for calculating velocity.

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.

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

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

Use of these data:



Unpublished data courtesy of Jim Currens, KGS

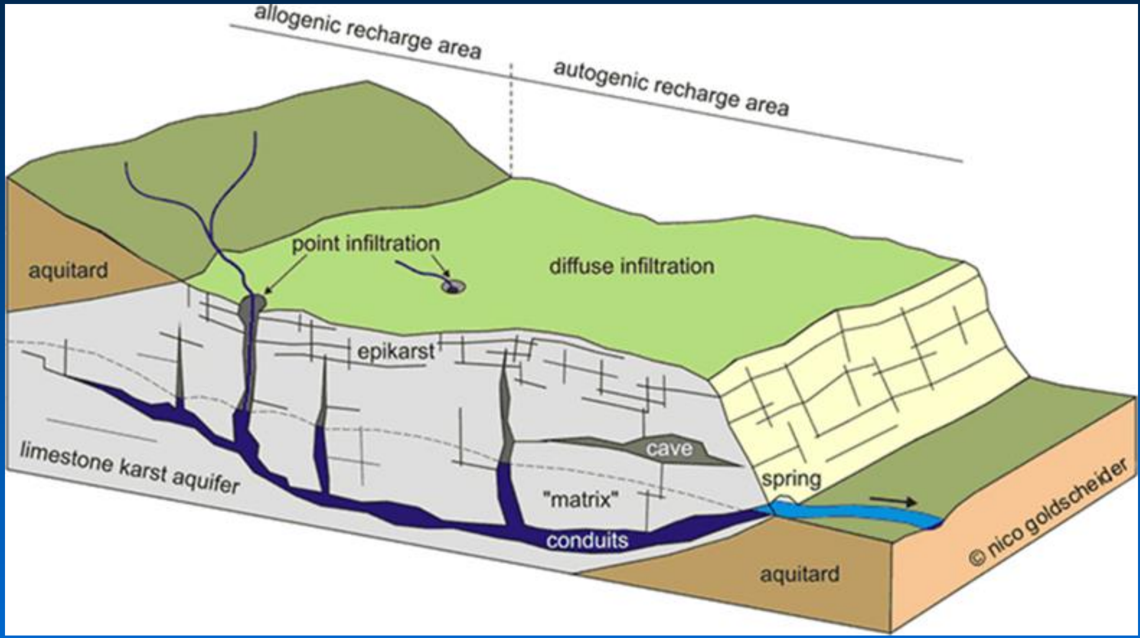
Ultimate goal here is to develop stage-discharge relation curve for Well 24 (in hydraulic communication with RS conduit) to enable calculation of mass flux discharge of nutrients through Royal Spring groundwater basin.

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.



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Spring Storm-Pulse Discharge Monitoring:

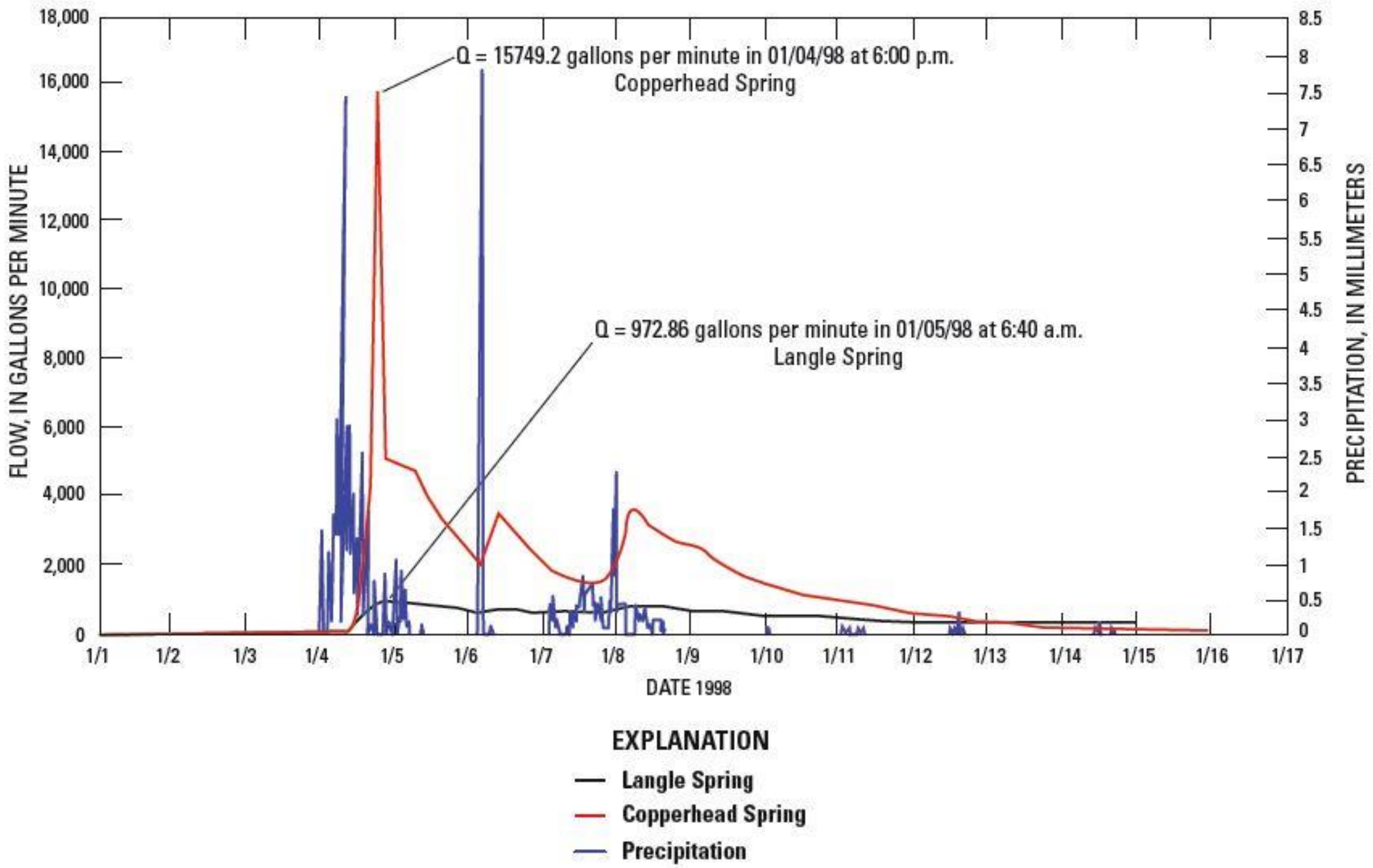
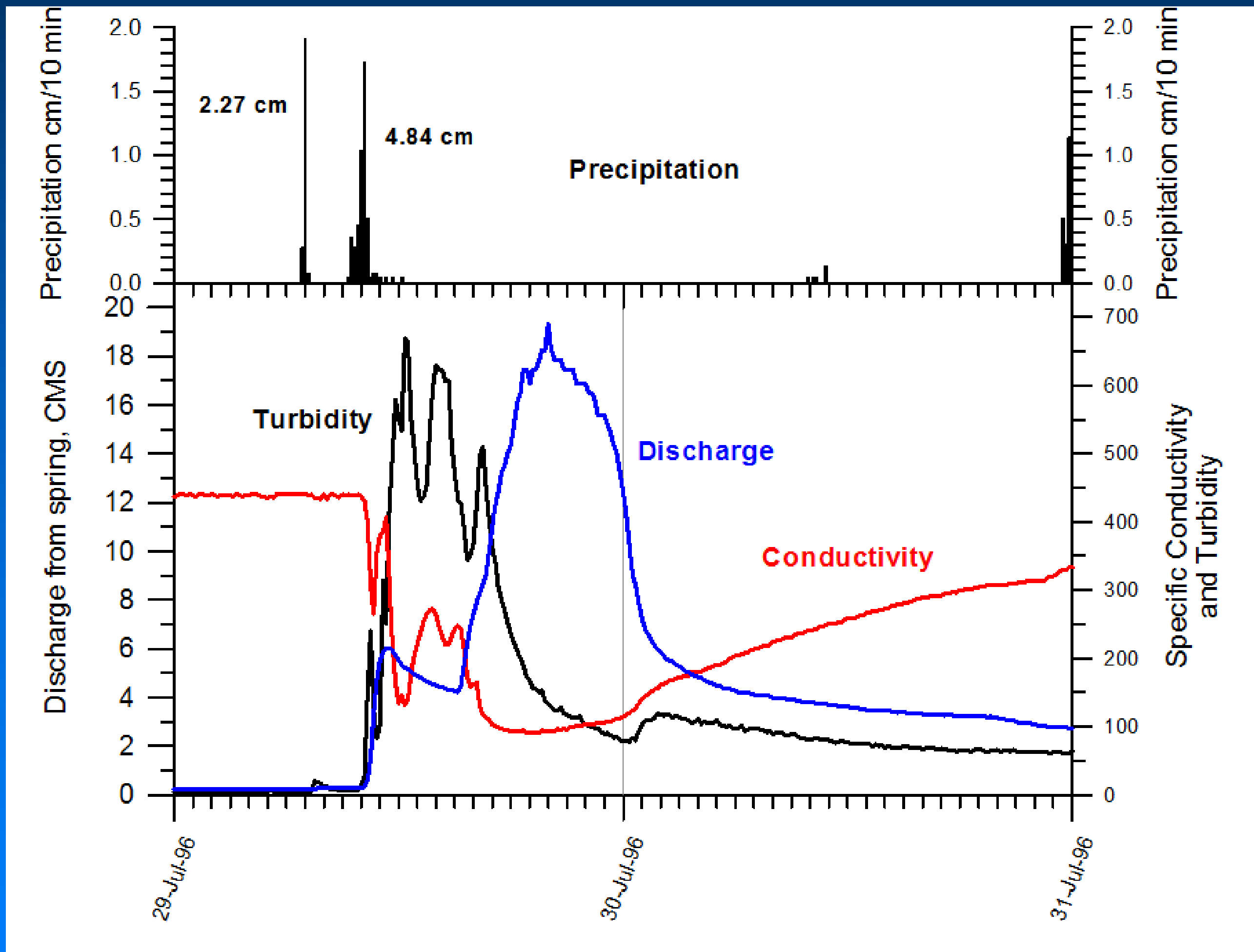
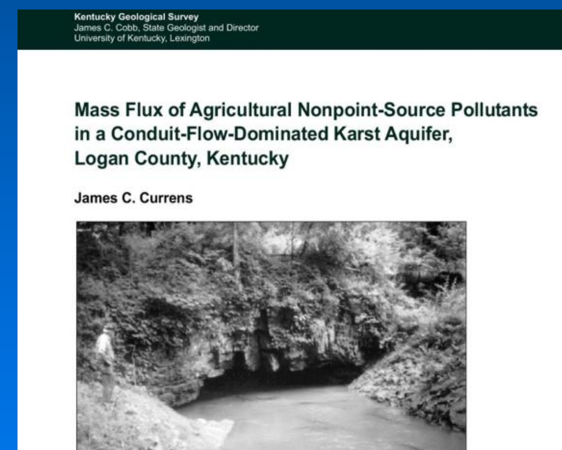


Figure 7. Variable response of springs to precipitation. Copperhead Spring hydrograph shows rapid conduit-dominated flow response. Langle Spring hydrograph shows slow diffuse-dominated flow response. These are related to the relative proportion of conduit permeability to nonconduit permeability (courtesy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

Spring Storm-Pulse Water-Quality Monitoring



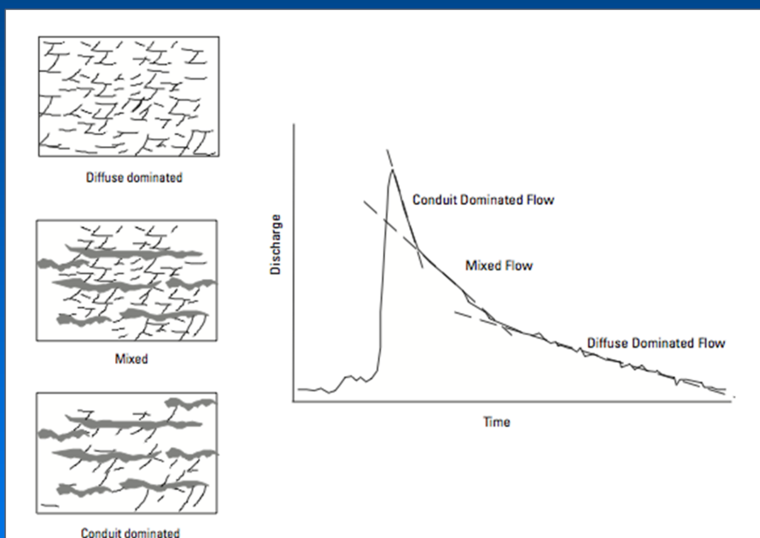
Discharge hydrograph and chemograph for the July 1996 high-flow event at Pleasant Grove Spring.



Spring Discharge Recession Analysis

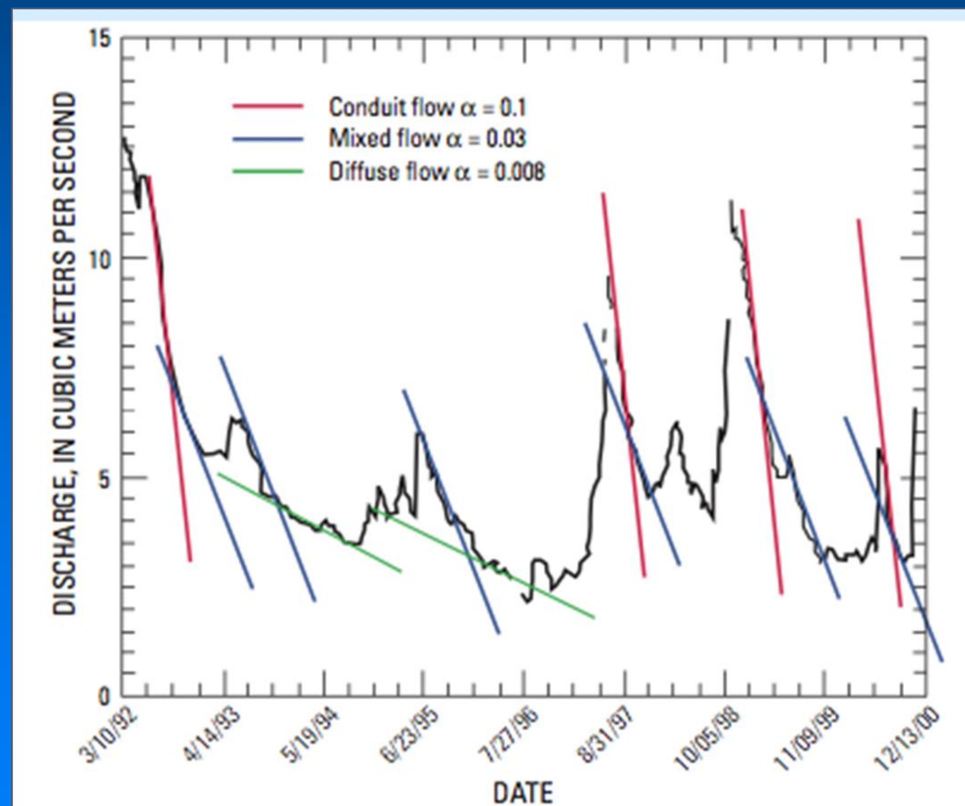
Has been used to calculate discharge and storage related to the triple permeability components of karst aquifers.

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



α[1]	Prevailing flow regime
0.0018	Slow-flow or diffuse-flow
0.0058, 0.006	Mixed (intermediate) flow
0.25, 0.13, 0.038	Quick-flow or conduit-dominated flow

[1]Range of characteristic α's from literature (Baedke and Krothe, 2001; Shevenell, 1996; Padilla and others, 1994, Sauter, 1992; and Milanović, 1981a, b).



from: Taylor and Greene, 2008

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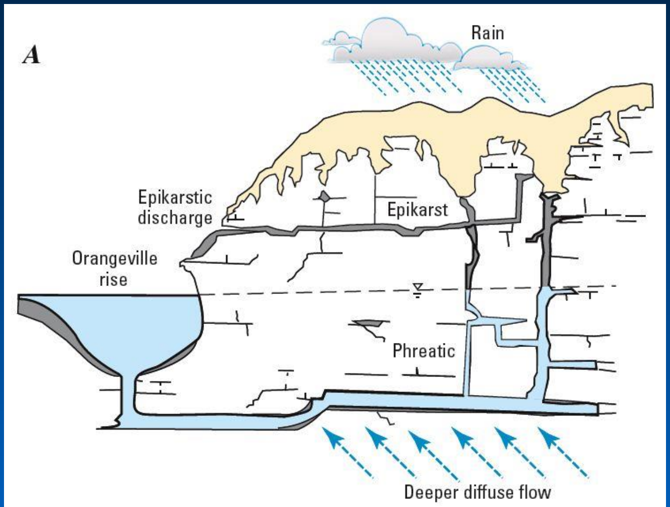
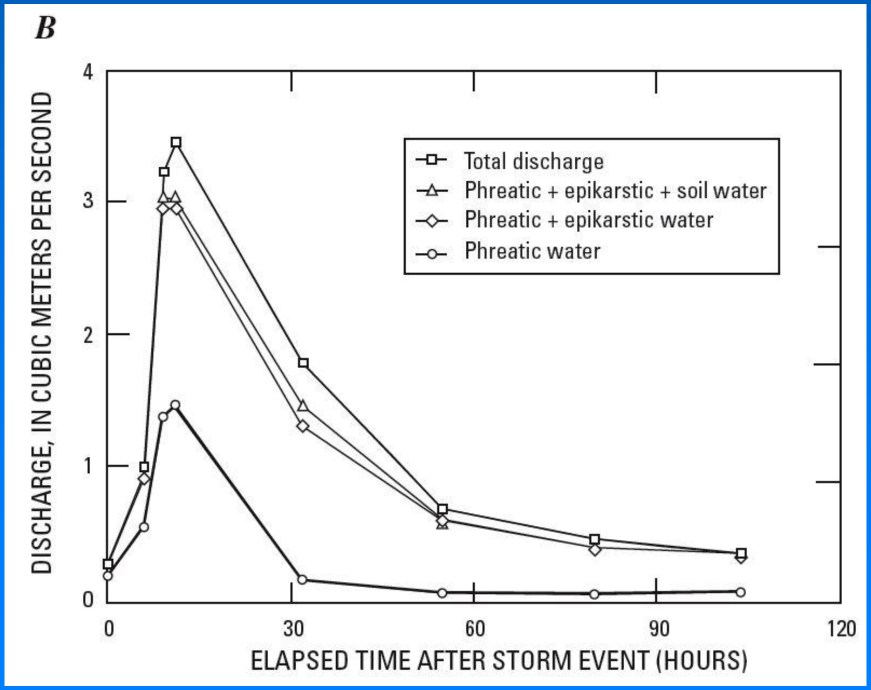
Spring Chemical-Hydrograph Separation

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.



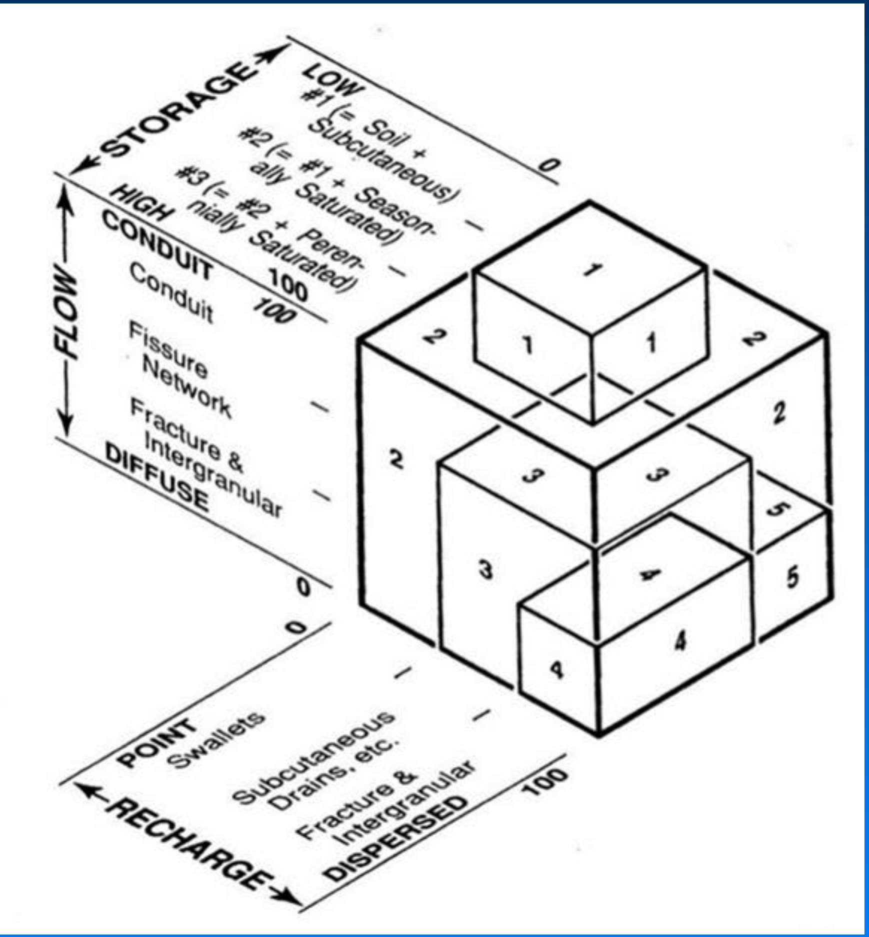


Collective Results of Many Karst Aquifer Studies Using Tracer Tests and Various Types of Spring Hydrograph Analysis

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

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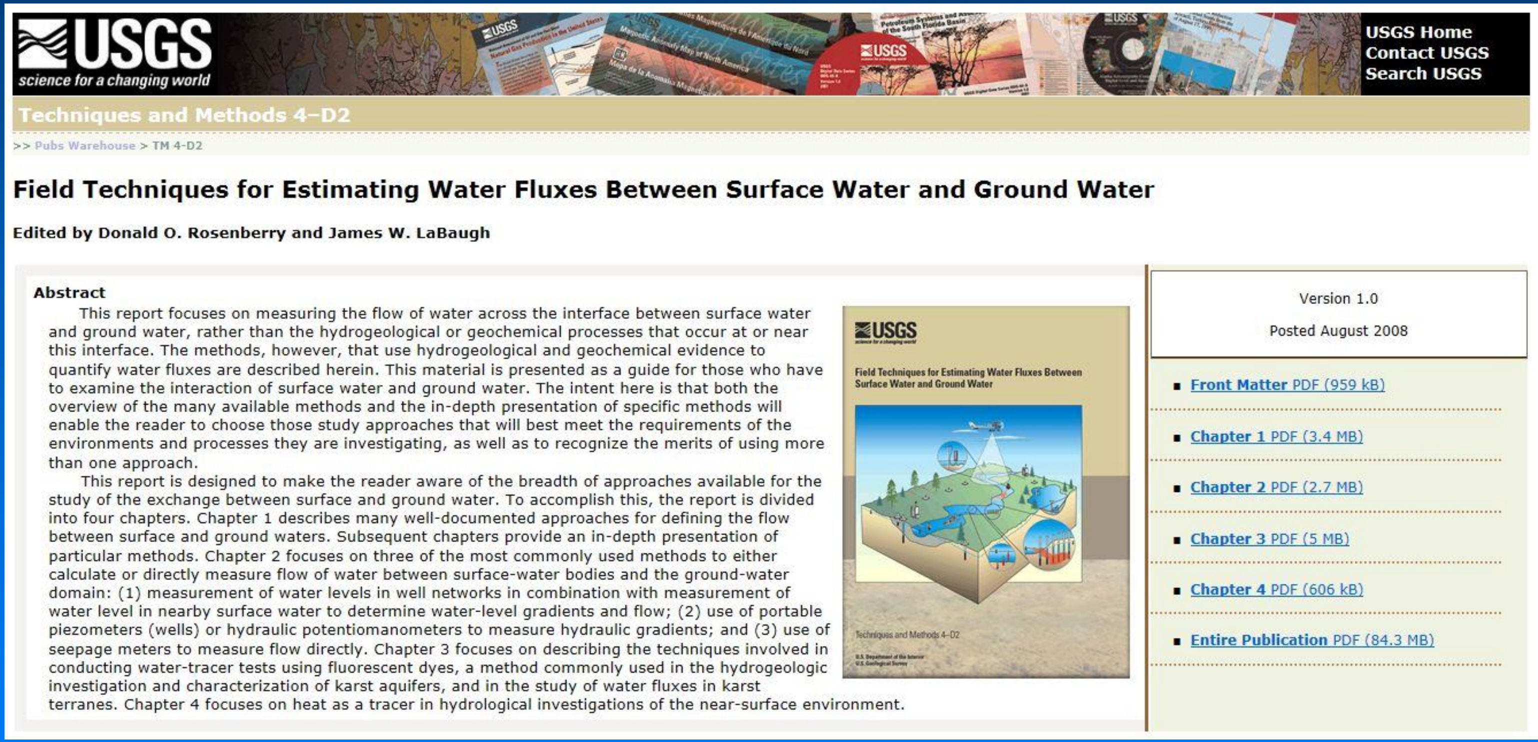
Summary:

- 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)



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Field Techniques for Estimating Water Fluxes Between Surface Water and Ground Water

Edited by Donald O. Rosenberry and James W. LaBaugh

Abstract

This report focuses on measuring the flow of water across the interface between surface water and ground water, rather than the hydrogeological or geochemical processes that occur at or near this interface. The methods, however, that use hydrogeological and geochemical evidence to quantify water fluxes are described herein. This material is presented as a guide for those who have to examine the interaction of surface water and ground water. The intent here is that both the overview of the many available methods and the in-depth presentation of specific methods will enable the reader to choose those study approaches that will best meet the requirements of the environments and processes they are investigating, as well as to recognize the merits of using more than one approach.

This report is designed to make the reader aware of the breadth of approaches available for the study of the exchange between surface and ground water. To accomplish this, the report is divided into four chapters. Chapter 1 describes many well-documented approaches for defining the flow between surface and ground waters. Subsequent chapters provide an in-depth presentation of particular methods. Chapter 2 focuses on three of the most commonly used methods to either calculate or directly measure flow of water between surface-water bodies and the ground-water domain: (1) measurement of water levels in well networks in combination with measurement of water level in nearby surface water to determine water-level gradients and flow; (2) use of portable piezometers (wells) or hydraulic potentiomanometers to measure hydraulic gradients; and (3) use of seepage meters to measure flow directly. Chapter 3 focuses on describing the techniques involved in conducting water-tracer tests using fluorescent dyes, a method commonly used in the hydrogeologic investigation and characterization of karst aquifers, and in the study of water fluxes in karst terranes. Chapter 4 focuses on heat as a tracer in hydrological investigations of the near-surface environment.

Version 1.0

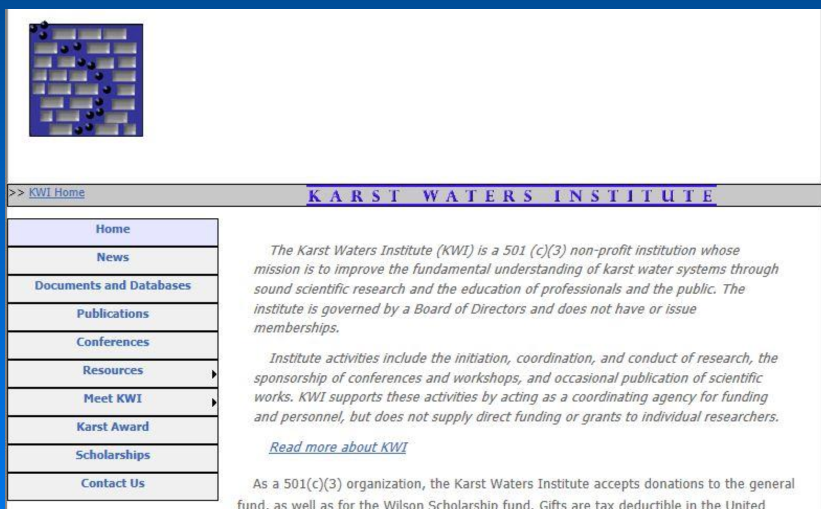
Posted August 2008

- **Front Matter** PDF (959 kB)
- **Chapter 1** PDF (3.4 MB)
- **Chapter 2** PDF (2.7 MB)
- **Chapter 3** PDF (5 MB)
- **Chapter 4** PDF (606 kB)
- **Entire Publication** PDF (84.3 MB)

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/



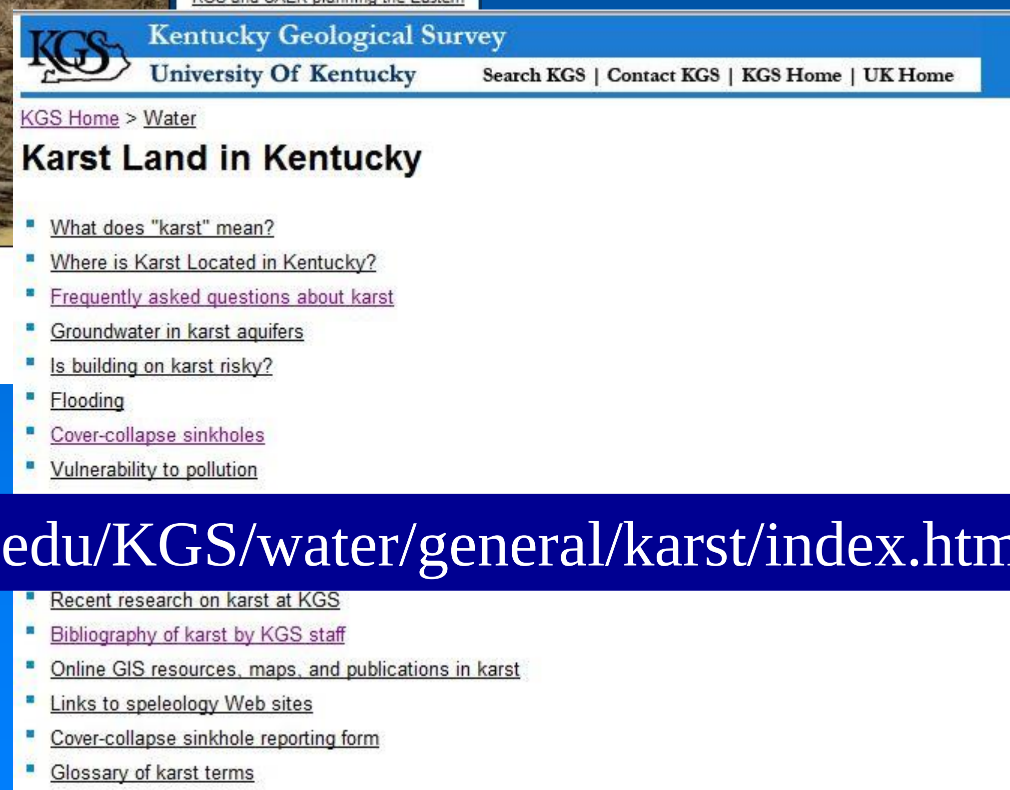
http://www.karstwaters.org/

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

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

Useful Sources of Information

http://www.uky.edu/KGS/



http://www.uky.edu/KGS/water/general/karst/index.htm

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