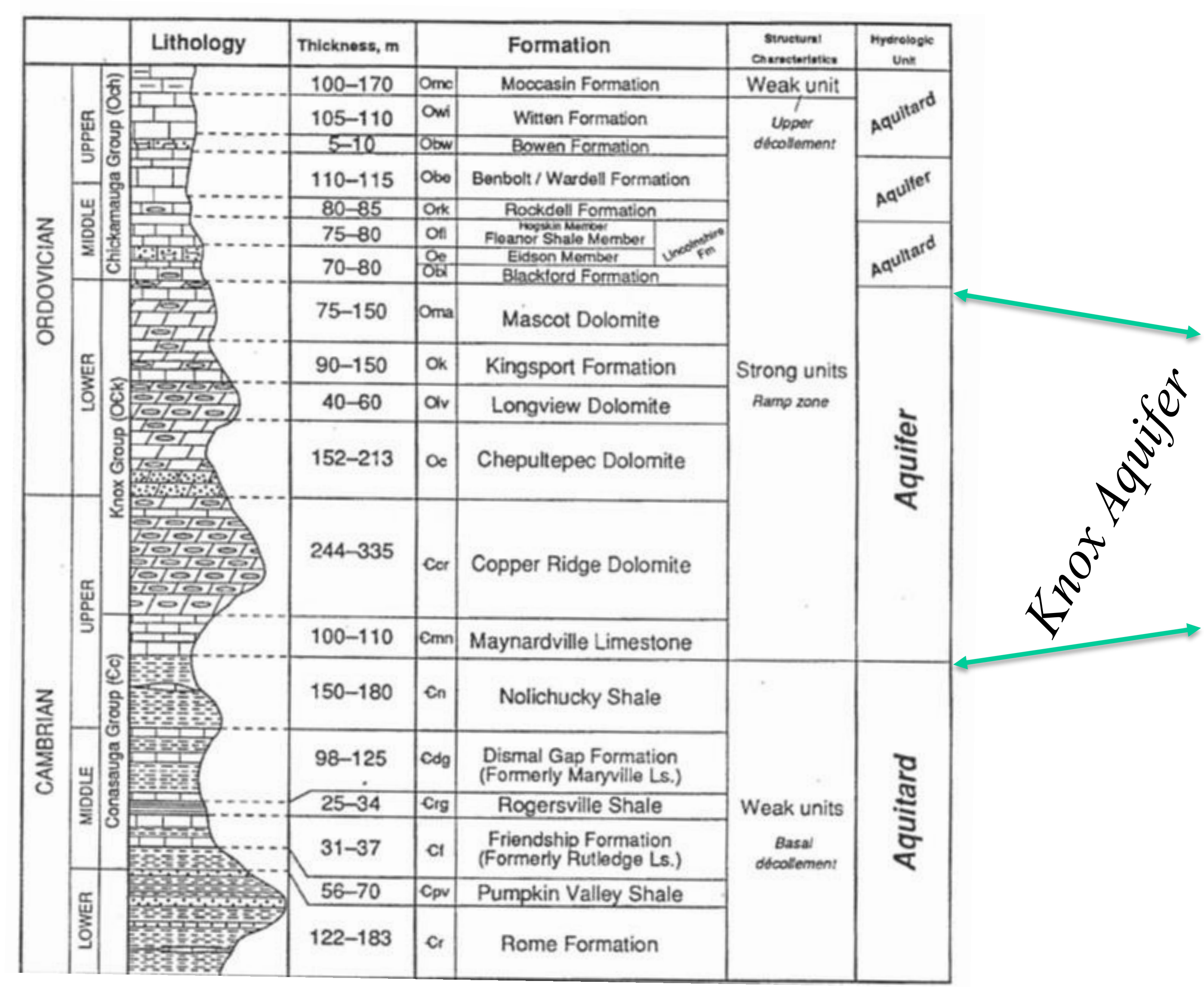
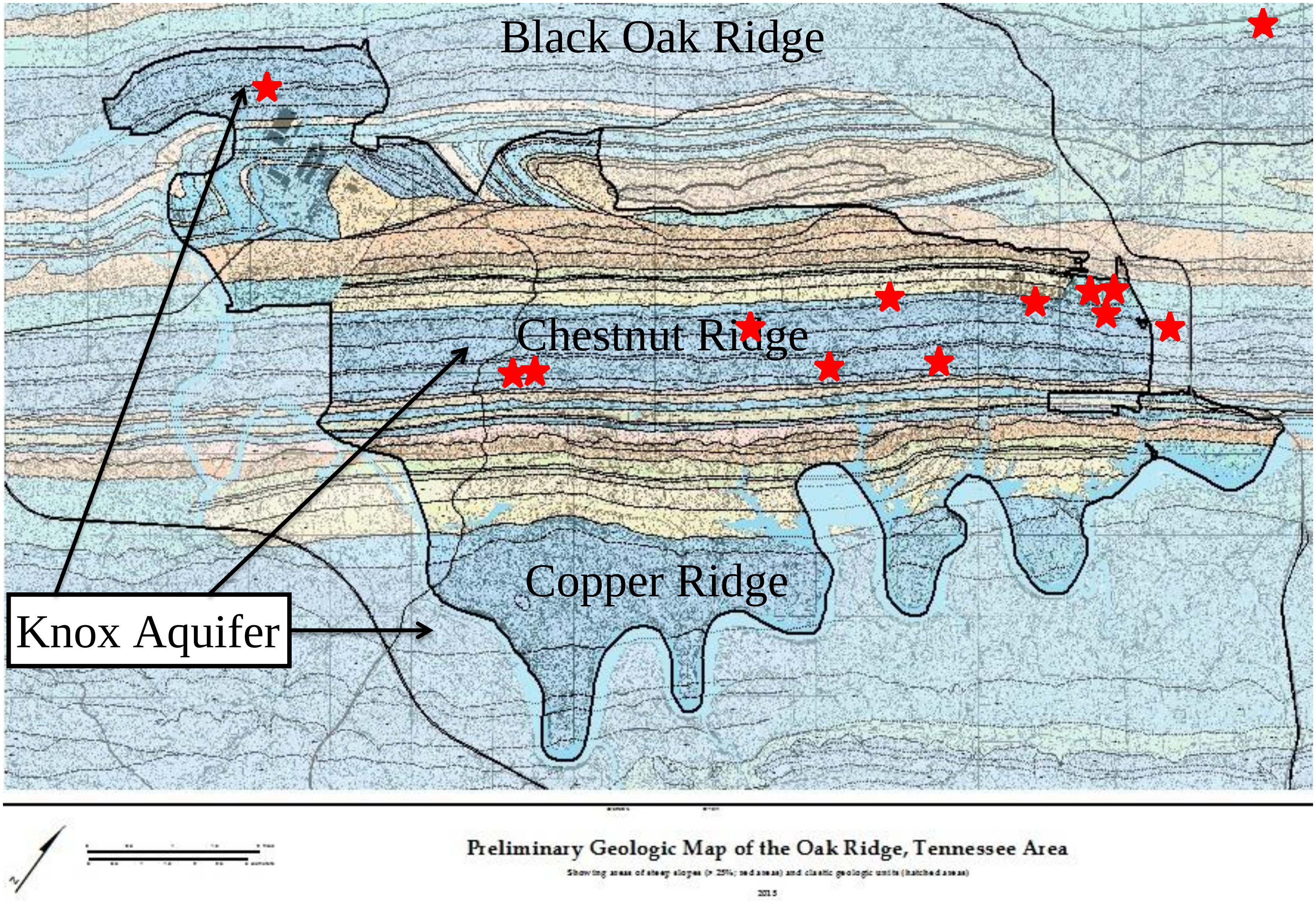
Solute and sediment transport in the Knox Aquifer near Oak Ridge, TN

Acknowledgements: Some of this work was supported by Tennessee Environment and Conservation and the UTK Department of Earth and Planetary Science. Robert Benfield, Gareth Davies, and Terri Brown contributed significantly to unfunded tracing studies

Knox aquifer developed in 5 named units of Knox Group and Maynardville Limestone



Stratigraphic column as given by Hatcher and Lemiszki in Chapter 3 of Hatcher and others, 1992, ORNL/TM 12074, Status Report on the Geology of the Oak Ridge Reservation



Carbonates are shown in blue, red stars show location of tracing studies

Background – general observations concerning the Knox Aquifer

Karst features are present throughout the carbonates of the Knox Group and the underlying Maynardville Limestone. The entrance passage in Copper Ridge Cave, the largest known cave on the Oak Ridge Reservation, is shown here.

Karst features on the ORR (Oak Ridge Reservation) :

- **Sinkholes (>550)**
- **Caves (>45)**

Numerous springs and seeps identified by USGS and Y12 staff

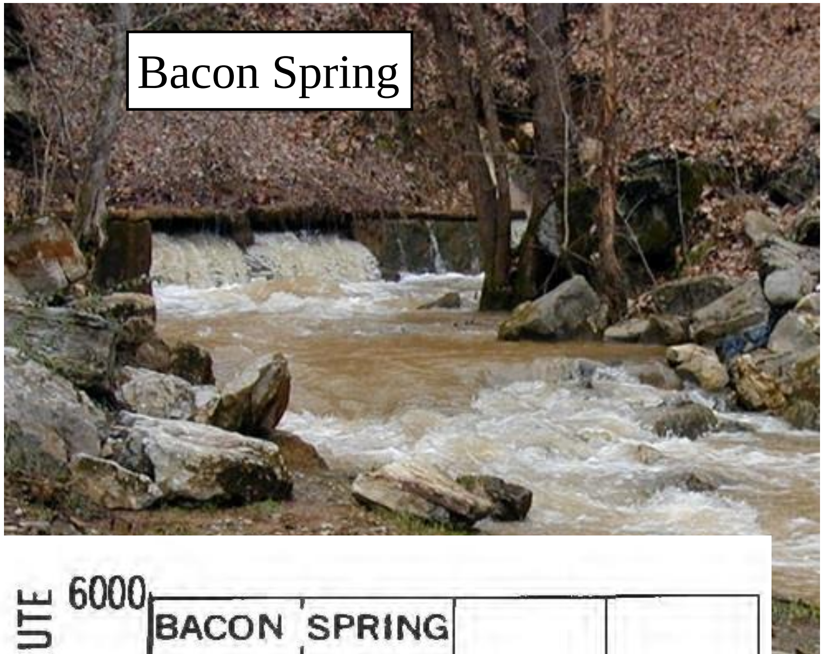
Degree of karstification in the Knox varies in East Tennessee, depends on:

- the proportion of limestone versus dolomite (Jonesboro limestone is more soluble than dolomitic units near Oak Ridge)
- amount of insoluble rock, primarily chert
- dip of rocks (shallow dip typically allows development of larger recharge areas for a given spring)
- percentage autogenic versus allogenic recharge (concentrated flow off clastic units enhances cavern development)

Pinnacle in Copper Ridge Formation in borrow area in Oak Ridge

Discharge is frequently concentrated at springs:

- Knox springs around Oak Ridge are relatively small, no known first or second magnitude springs, Bacon Spring has largest recorded discharge in Anderson and Roane counties
- Flow varies over about one order of magnitude, and springs may become turbid



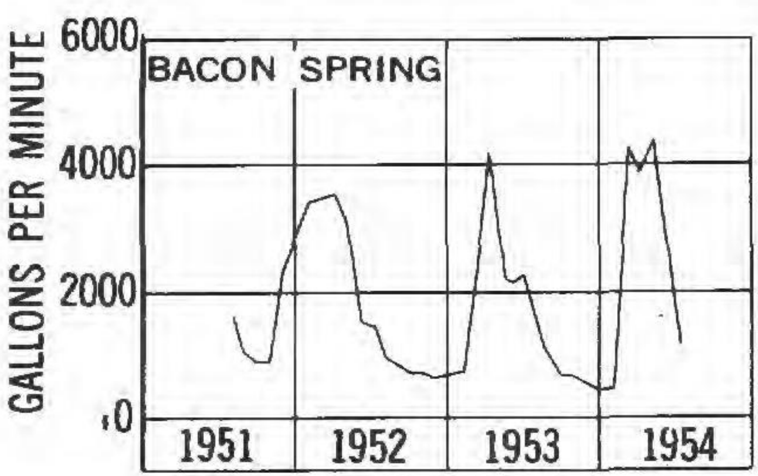
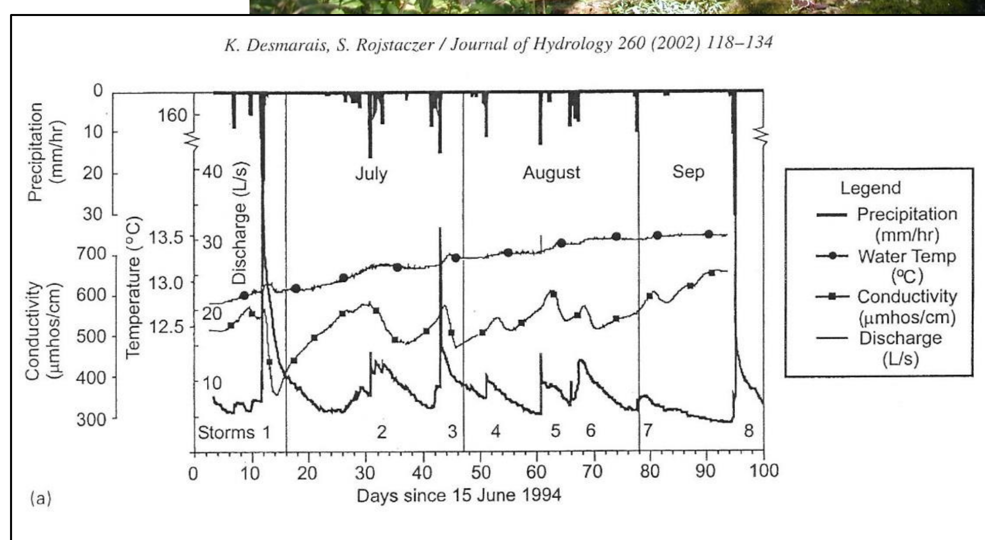


Figure from Large Springs of East Tennessee,
Sun et al., 1963 USGS Water Supply Paper 1755

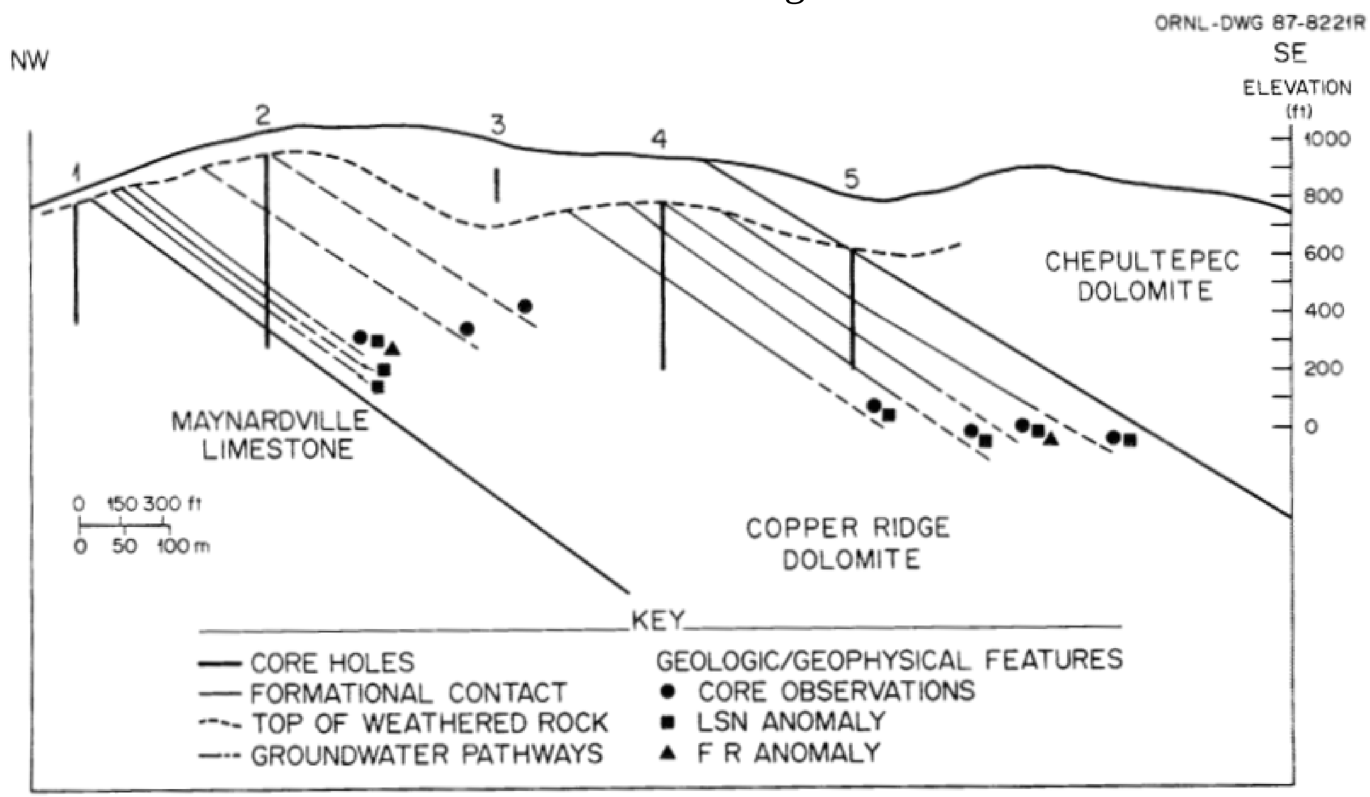


Preferential flow parallel to strata in the Knox aquifer:

- Differences in dissolution rates between beds
- Differences in fracturing between beds leading to differences in inception pathways for karst development

Strata-bound nature of preferential flow tends to result in flow down dip in vadose zone and along geologic strike in saturated zone when dip on bedrock is steeper than topography

Figure from Lee and Ketelle, 1987 (ORNL/TM 10479) who present evidence for stratigraphic control of groundwater flow at a well-studied site in the Copper Ridge formation on Chestnut Ridge west of highway 95 and east of the Clinch River within the Oak Ridge Reservation boundaries.



Typical chemistry of Knox groundwater
from Haase, King, and Gillis, 1987.
(Y12 report # Y/TS-272)

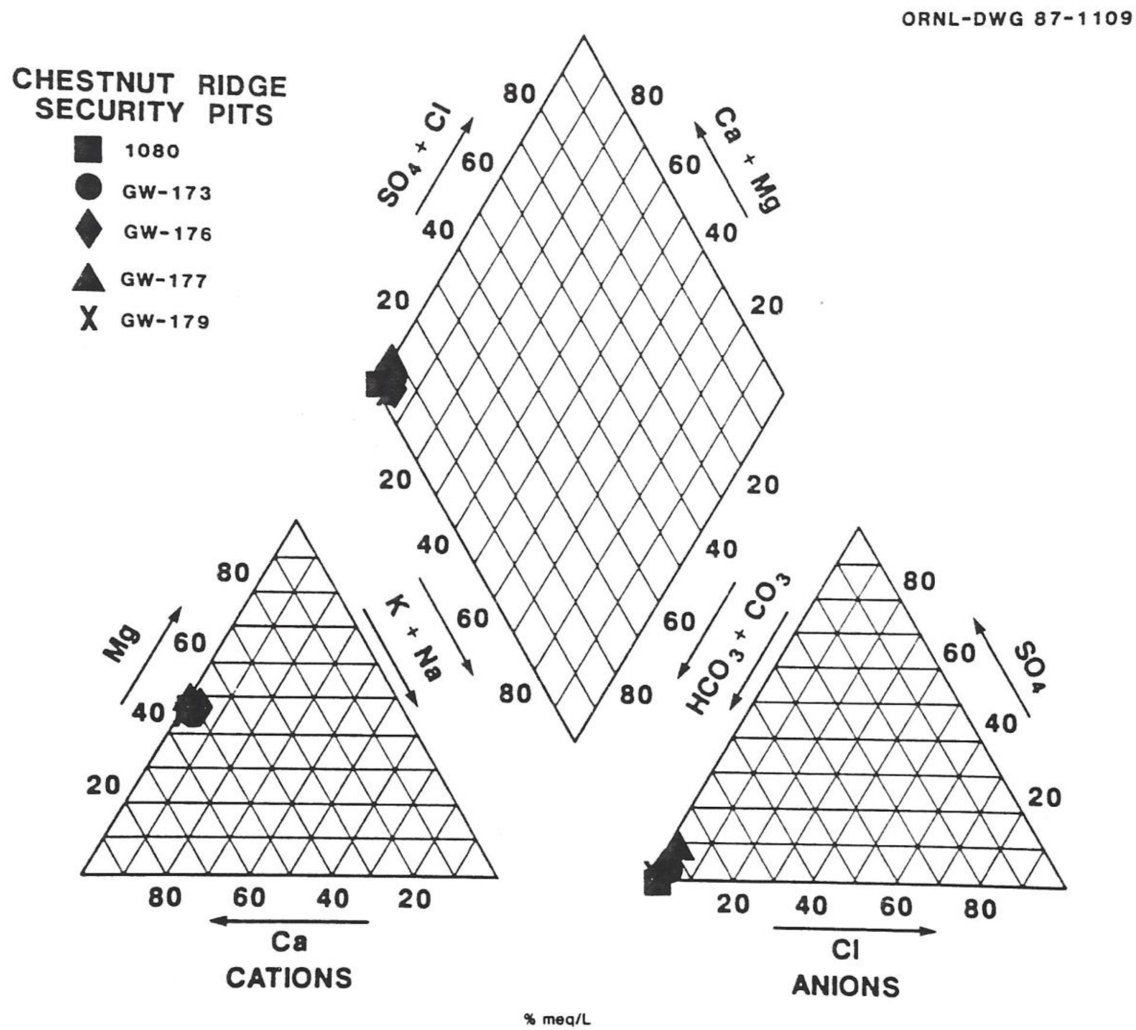


Fig. 7. Piper diagram plot of the compositions of groundwaters from the Chestnut Ridge Security Pits site. Chemical data are plotted on the basis of milliequivalents per liter.

Waters recharged through the Maynardville Limestone have similar anion distribution but higher ratio of Calcium to Magnesium ions

The initial motivation for much of the work was to better understand the nature and extent of groundwater contamination on and around the Oak Ridge Reservation. At the time tracing studies were initiated by TDEC in the 1990s, DOE's conceptual framework for Oak Ridge hydrogeology did not seem to adequately address important questions concerning the potential for rapid flow of groundwater in preferential channels formed by dissolution of bedrock. Note below the unusual caveat in the Foreword of *ORNL/TM-12026*, *Status Report: A Hydrologic Framework for the Oak Ridge Reservation*

FOREWORD

The conceptual hydrologic framework for the Oak Ridge Reservation is still evolving. The description of the framework in this status report represents the best current thinking on the properties and processes affecting contaminant migration in an extremely complicated setting. Confidence in the general framework is high, but a number of as yet unproved, and thus conjectural, assertions are made. These are not made to mislead the reader but to catalyze the further identification and investigation of properties and processes believed to be keys to quantifying contaminant transport.

Hydrologic Units as proposed in ORNL/TM-12026, Status Report: Hydrologic Framework for the Oak Ridge Reservation

Aquifer

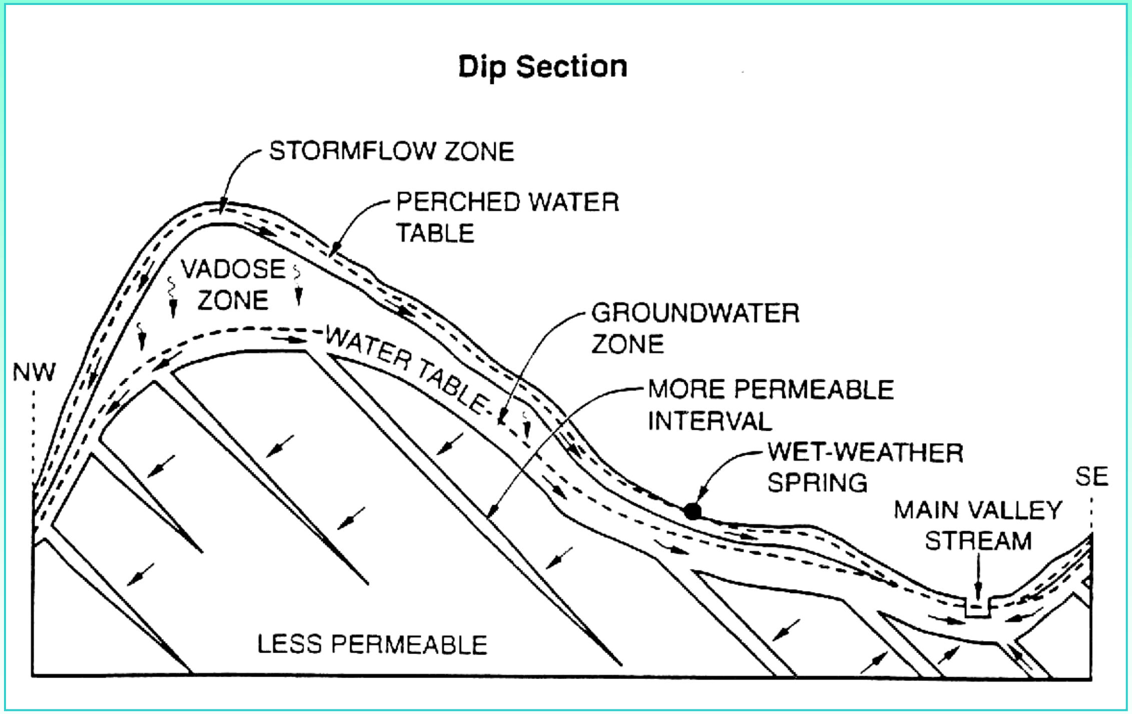
- **Knox Group Dolostones and Maynardville Limestone**
  - *Flow in fractures and conduits*

Aquitard

- **All other formations, but still including some with significant carbonates.**
  - *Flow in fractures*

Aquiclude

The conceptual model for Oak Ridge hydrogeology of the 1990s, including the hydrogeology of the Knox Aquifer focused on the importance of flow in the shallow stormflow zone

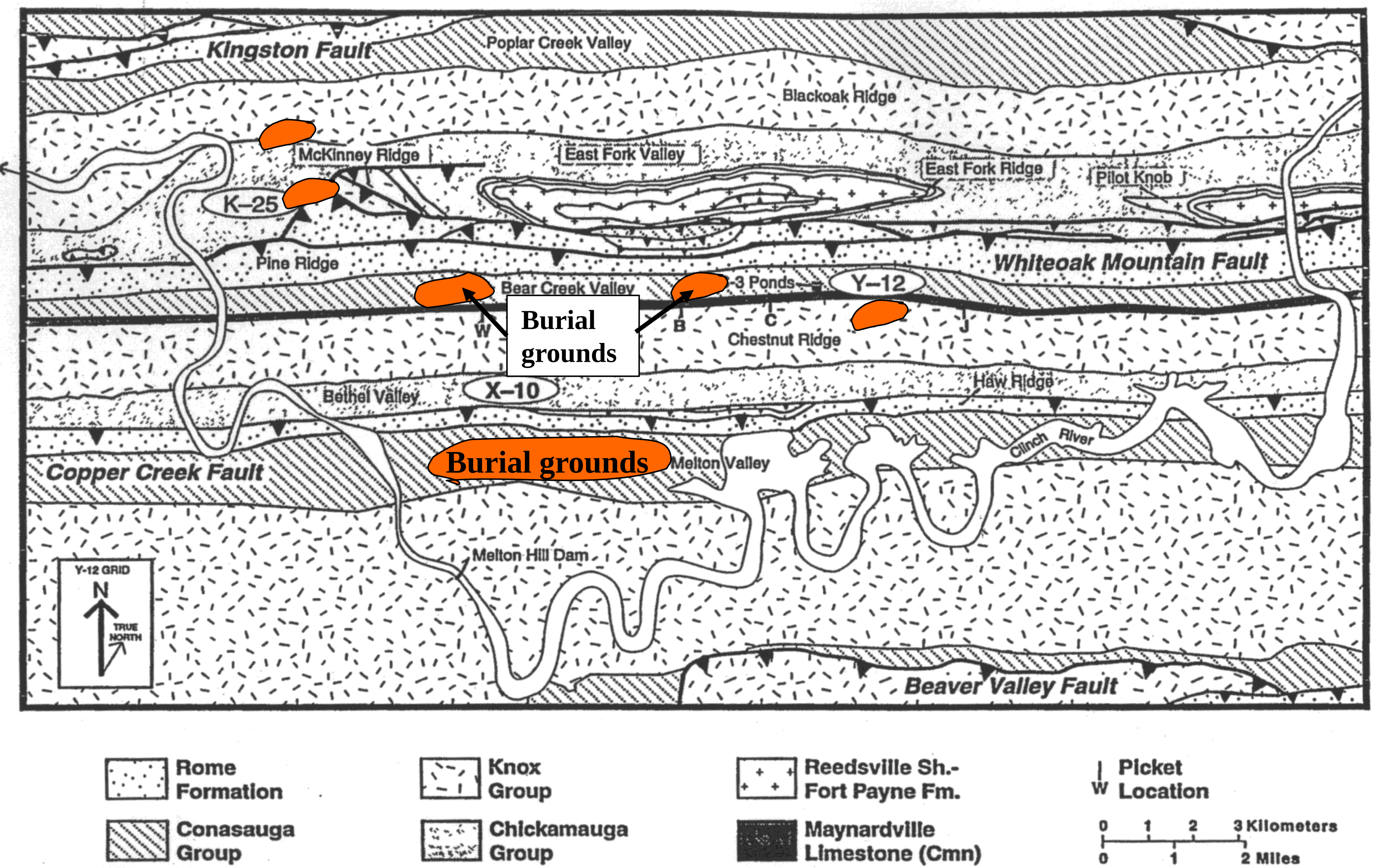


- Storm - 90% of flow
- Vadose Zone
- Groundwater

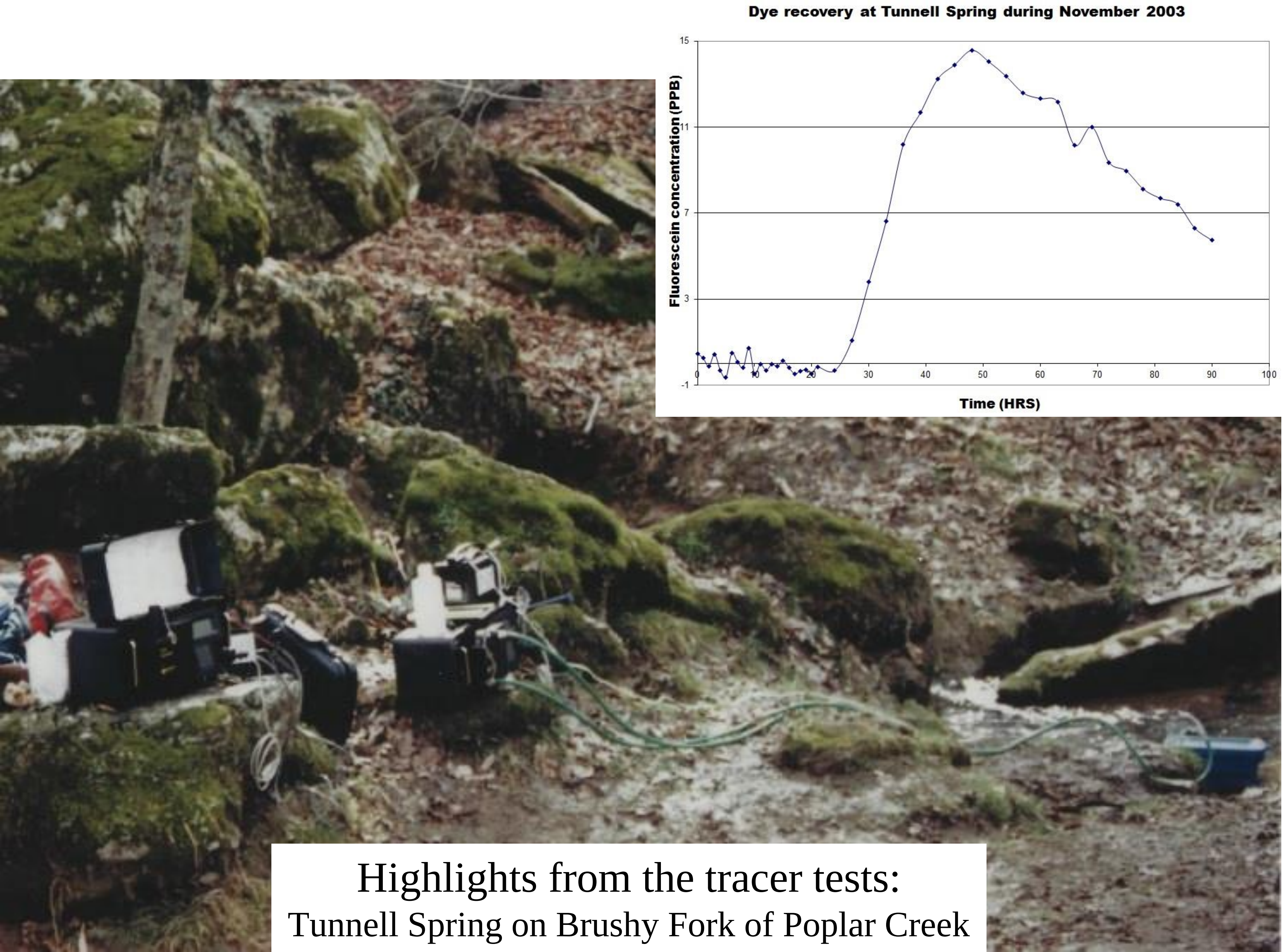
Aquifer/Aquitard designation was primarily based on a comparison of hydraulic conductivity from slug and packer tests in various stratigraphic groupings. This approach correctly identified the Knox as the most important aquifer in the area, but classified other carbonate units as aquitards.

The conceptual model was later revised somewhat with the percentage of subsurface flow in the bedrock varying from about 10% to 50% as documented in the ORNL Environmental Sciences Division Groundwater Program Office Report for Fiscal Years 1995-1997.

More recent efforts to understand and model groundwater hydrology in Oak Ridge have considered the effects of dissolution on permeability. DOE's current Groundwater Strategy is not based on the old conceptual model, but there have been no efforts to replace the "Status Report" with a new document, and it is sometimes still referenced as the authoritative source for fundamental information concerning the hydrogeology in Oak Ridge.



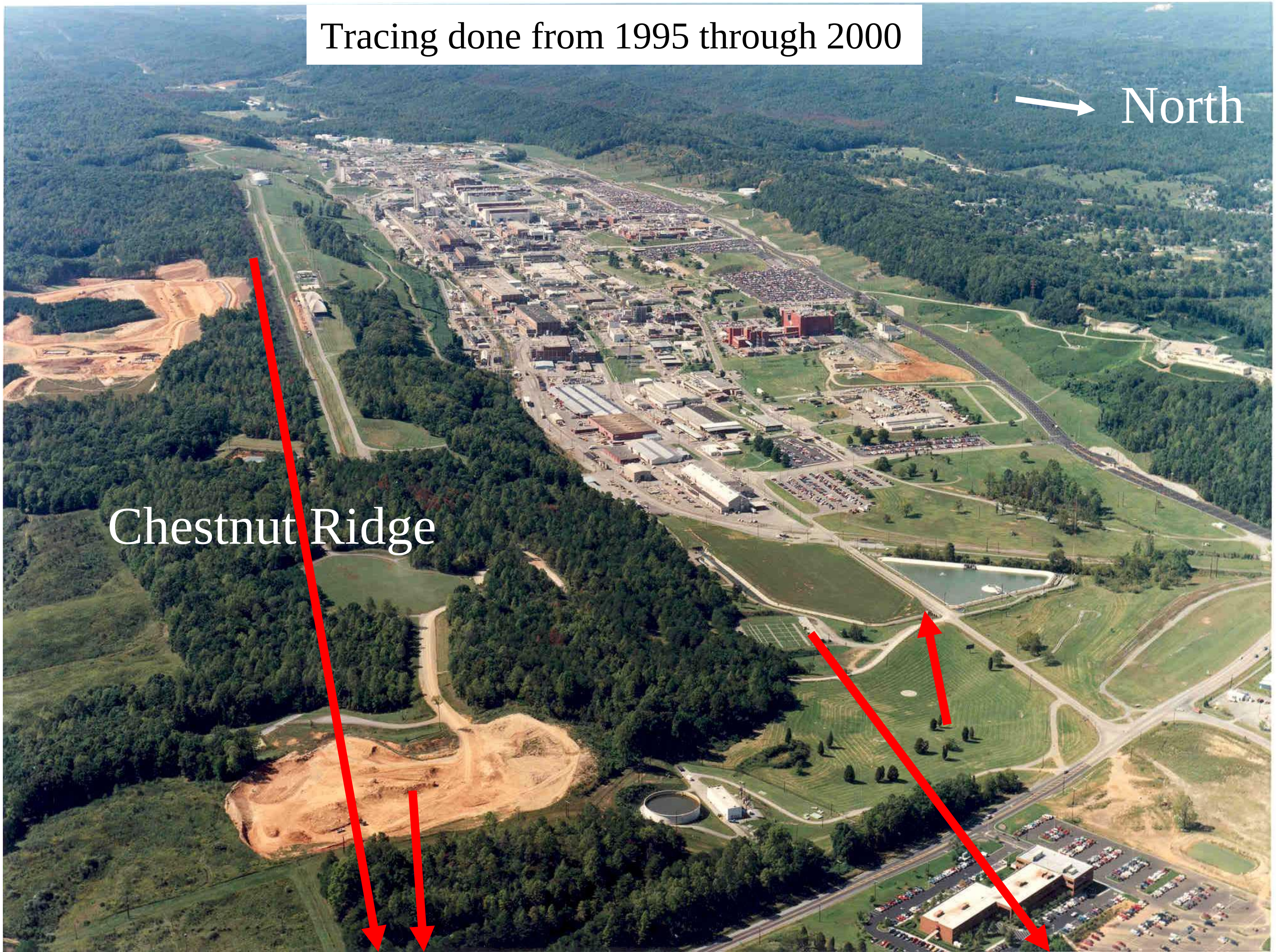
Oak Ridge Reservation geology (modified from Hatcher et al, 1992), showing location of major burial grounds in color. Note that most do not overlie the Knox Aquifer, a testament to benefits of studies done on geology and hydrology in the 1950s & 1960s.



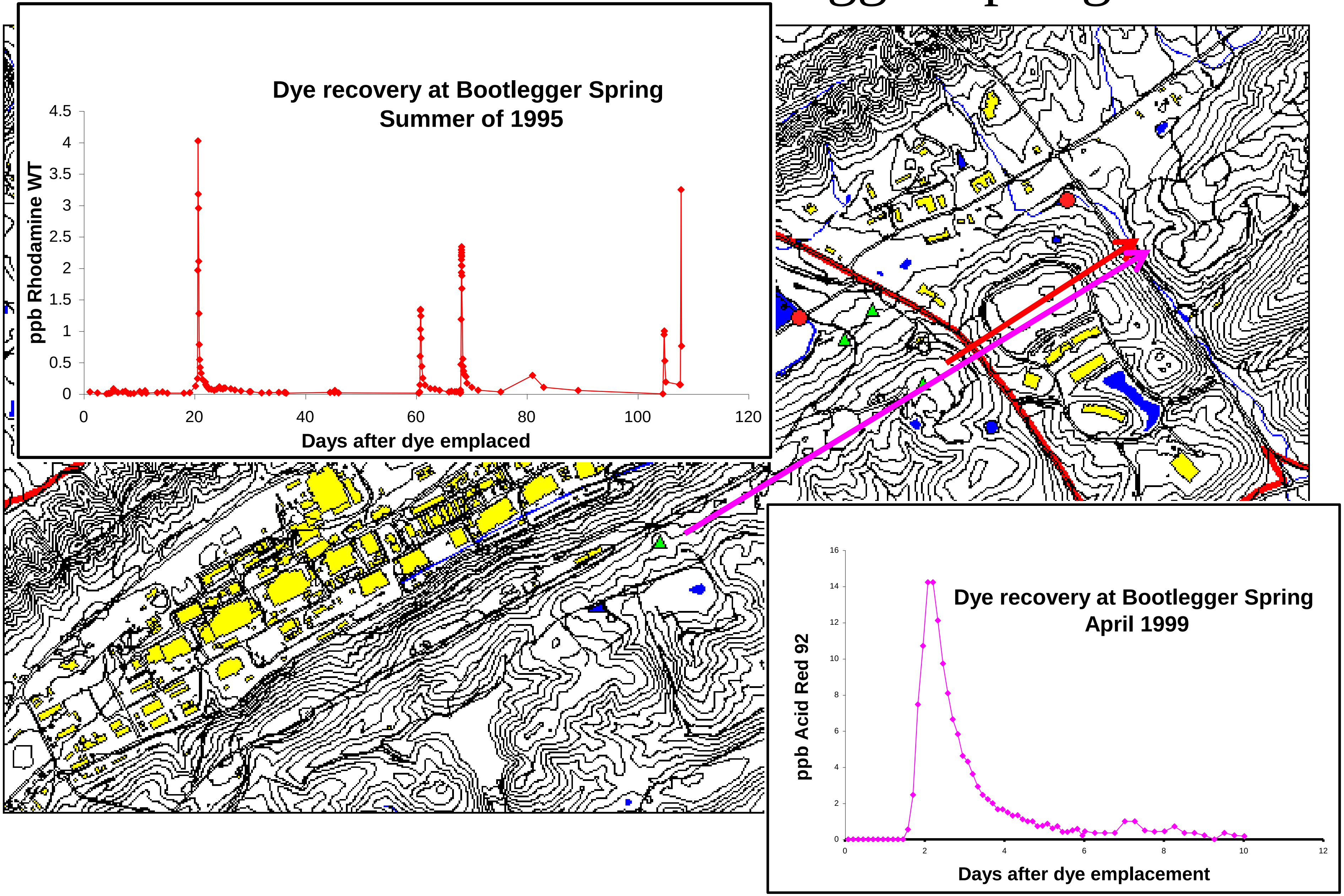
Highlights from the tracer tests:

Tunnell Spring on Brushy Fork of Poplar Creek

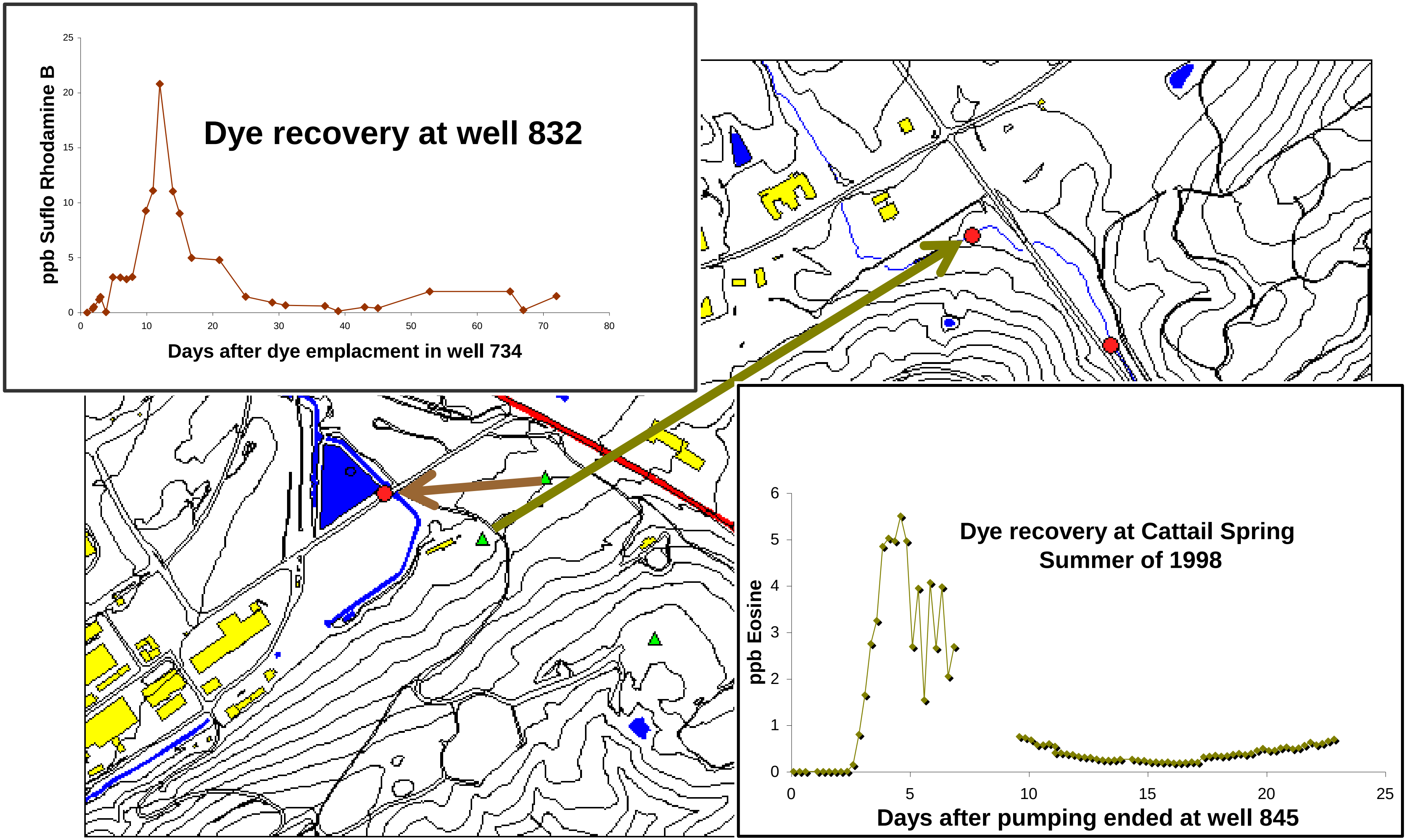
East end of Y12 Plant, looking down Bear Creek Valley



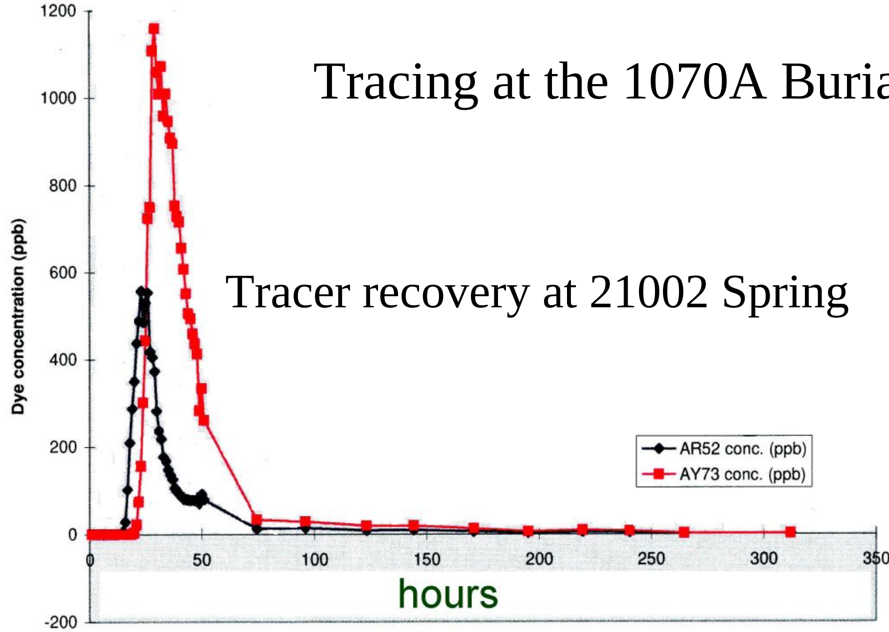
Chestnut Ridge to Bootlegger Spring

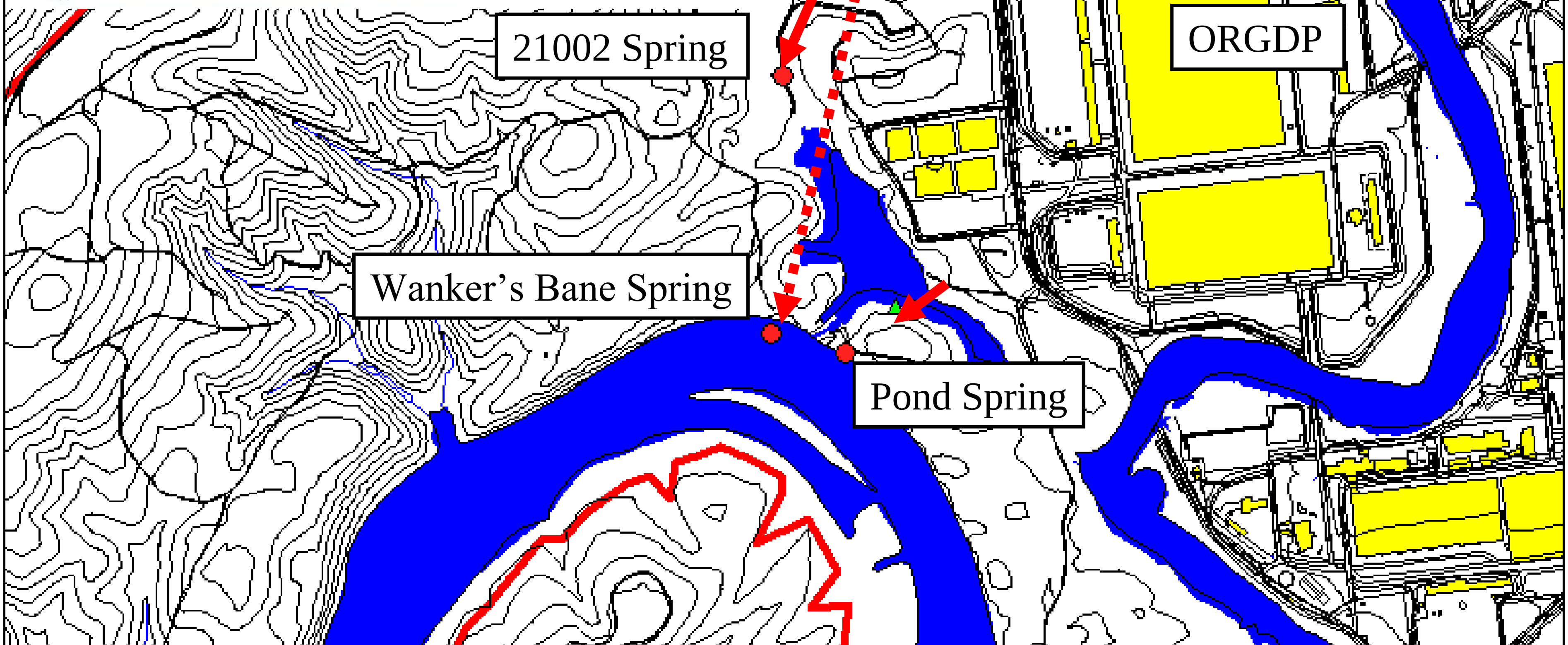


Union Valley tracing

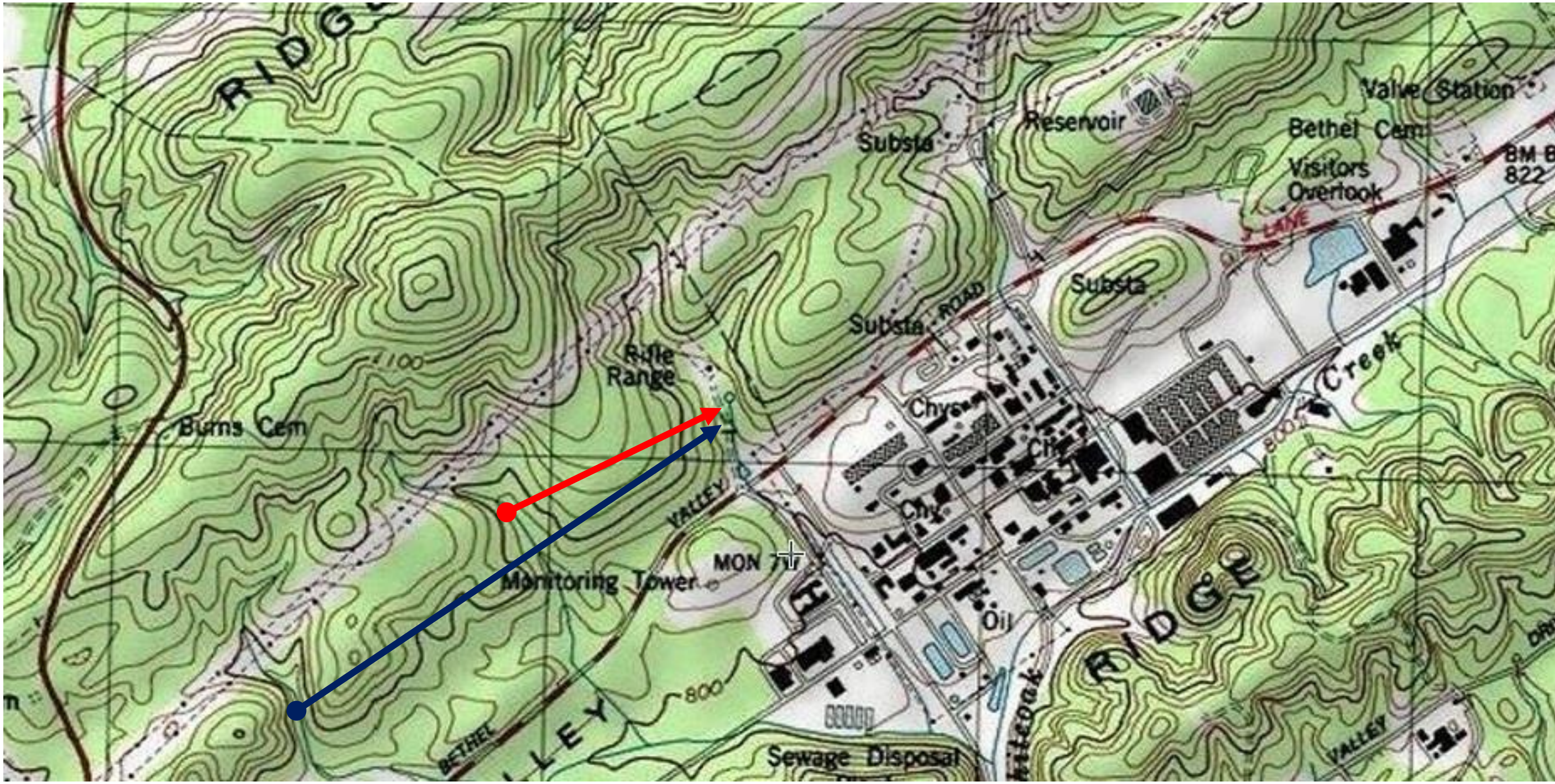


Tracing at the 1070A Burial Ground & 901 Pond in 1996 and 1997

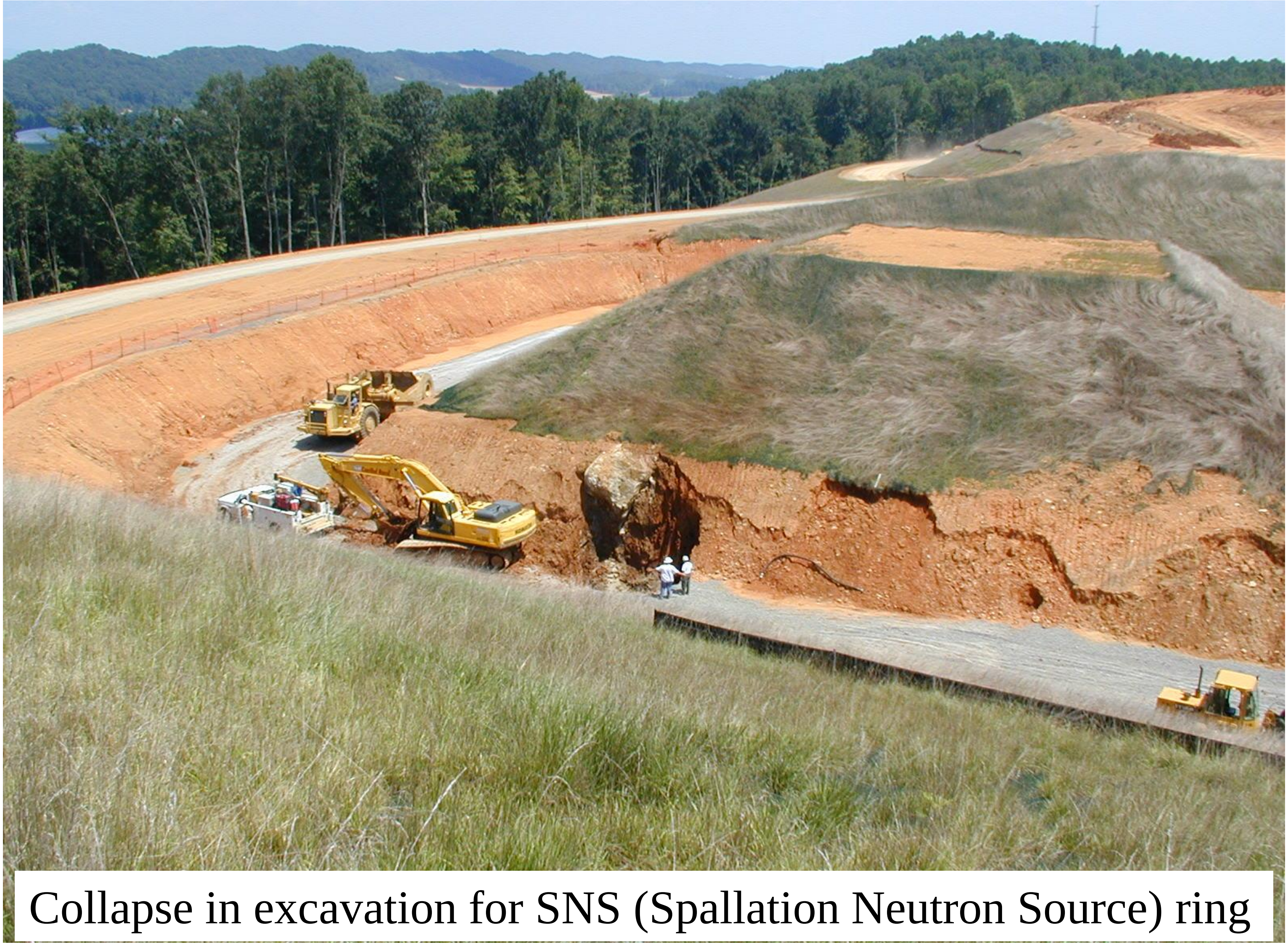




Northwest Tributary to First Creek in 1999



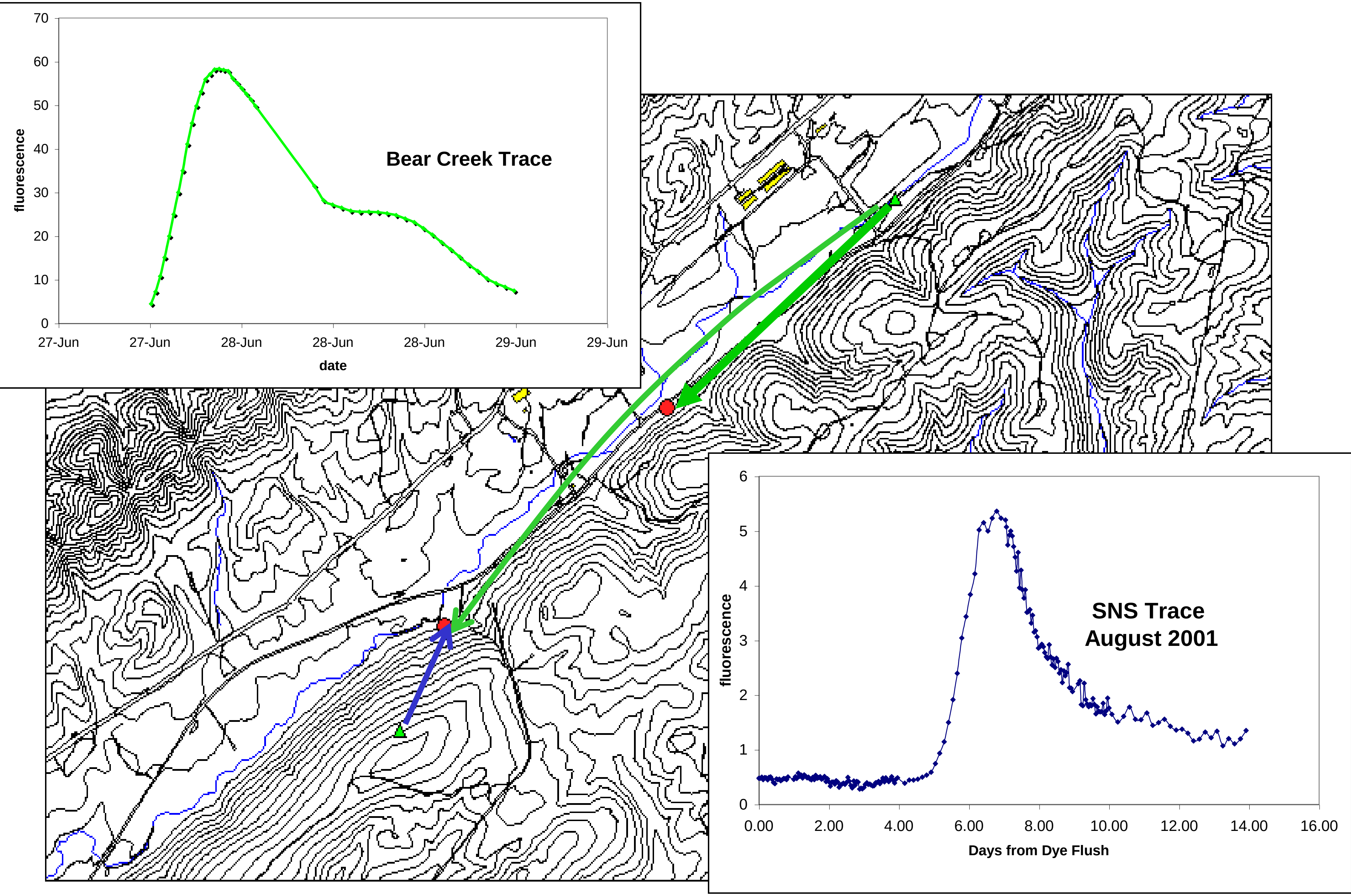
Muddy Spring in Bear Creek Valley in 2001



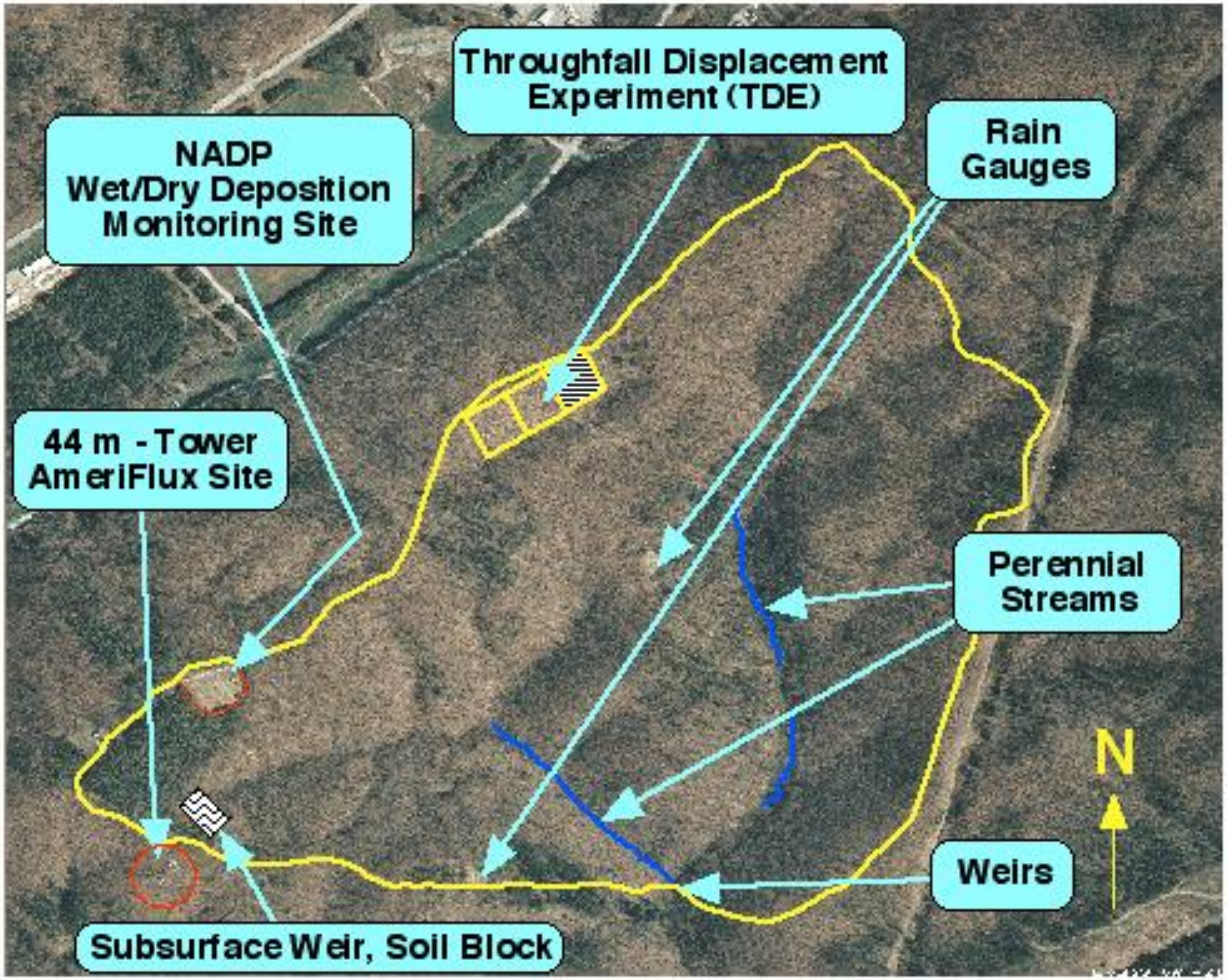
Collapse in excavation for SNS (Spallation Neutron Source) ring

Tracer flushed into the collapse

Bear Creek and SNS Traces in 2001



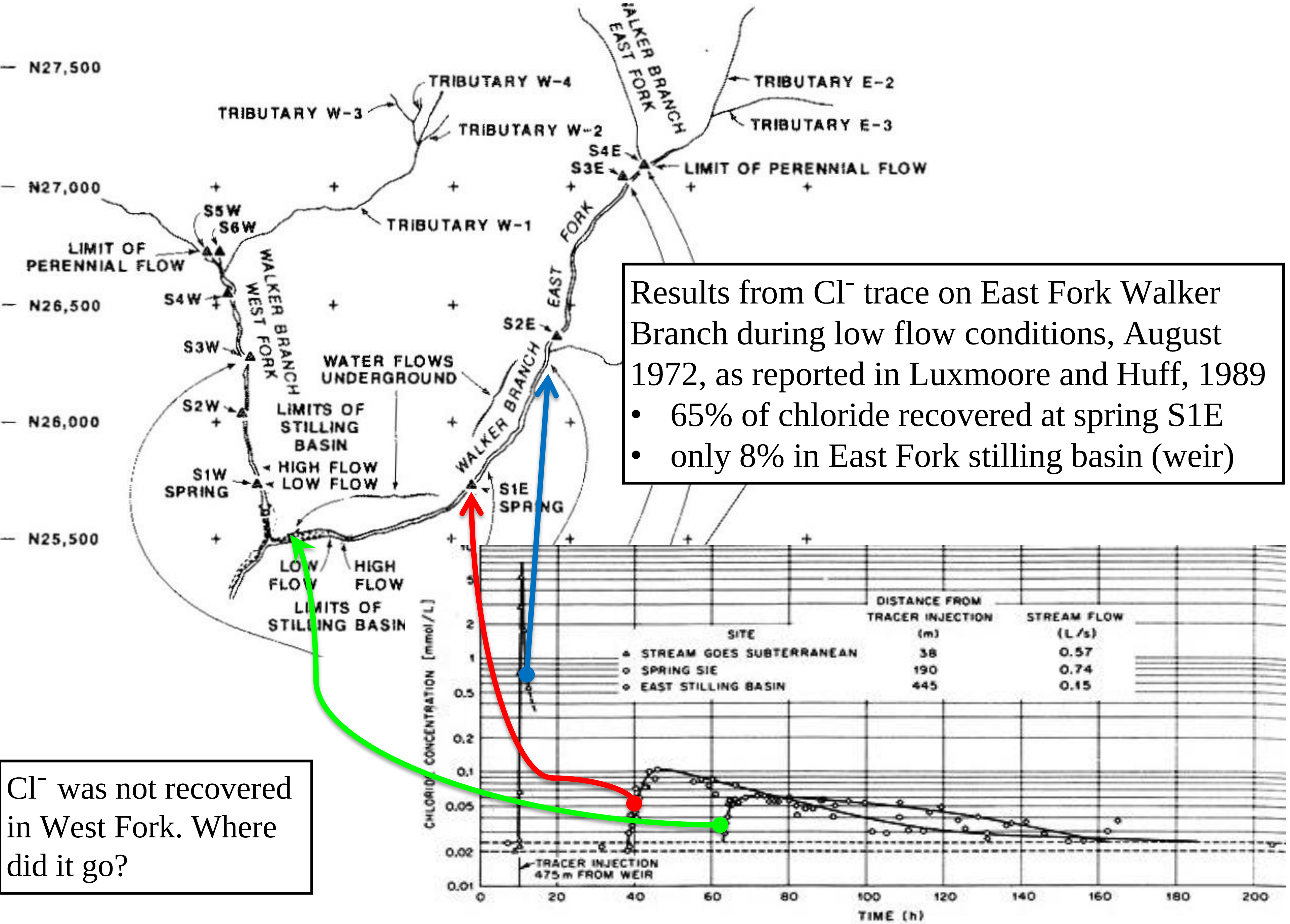
Walker Branch Research Site



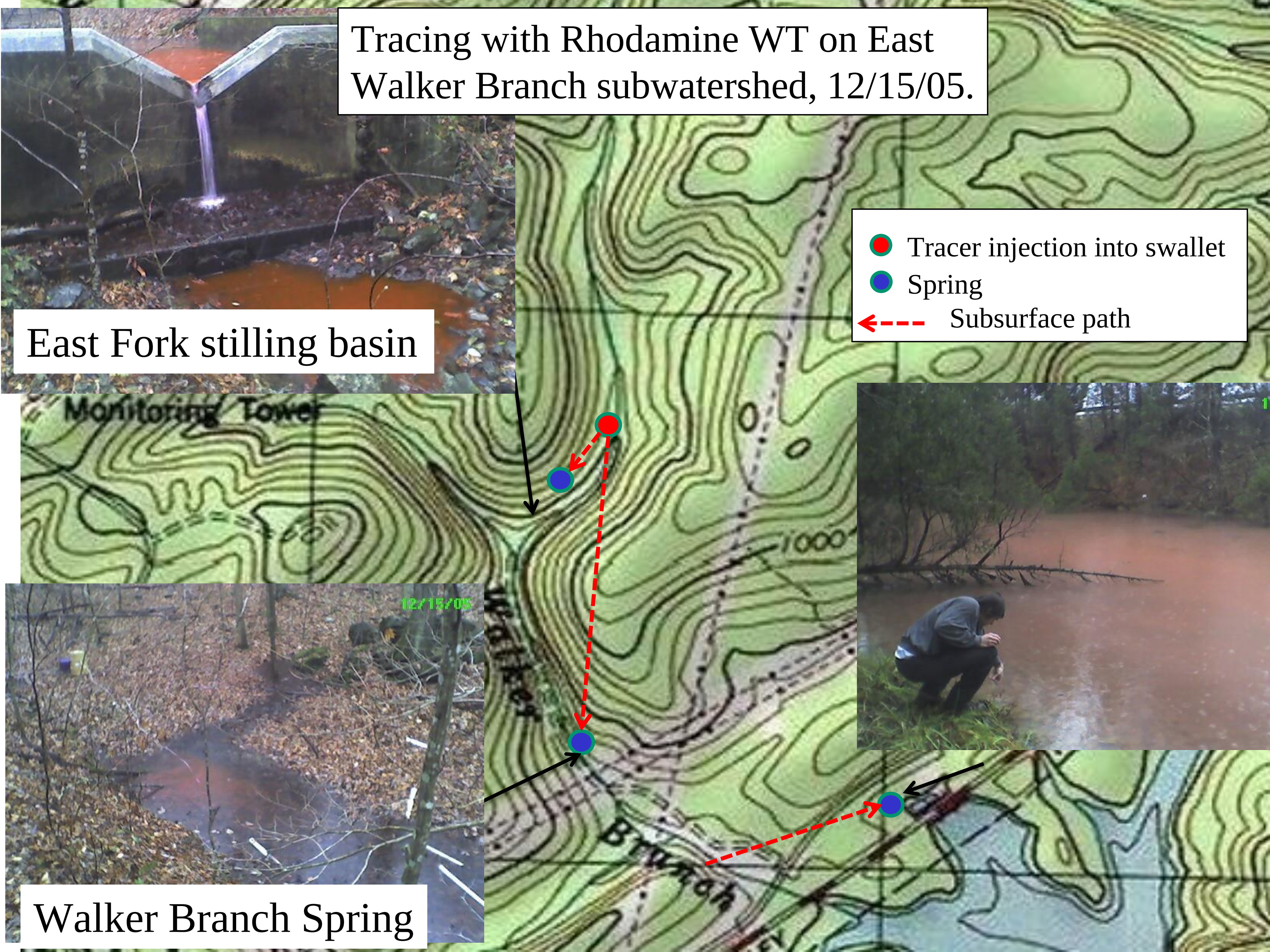
Results from Cl⁻ trace on East Fork Walker Branch during low flow conditions, August 1972, as reported in Luxmoore and Huff, 1989

- 65% of chloride recovered at spring S1E
- only 8% in East Fork stilling basin (weir)

Cl⁻ was not recovered in West Fork. Where did it go?



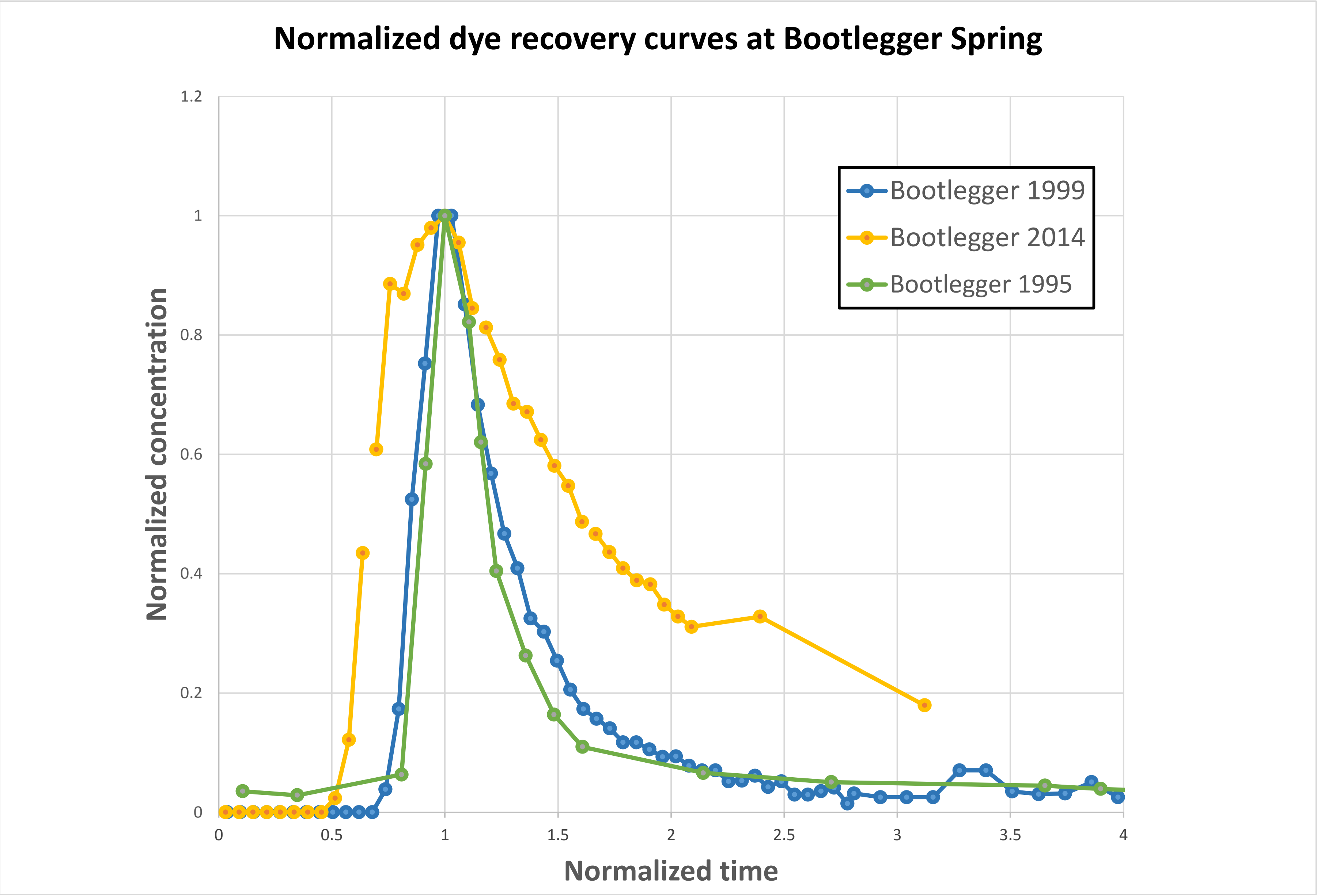
Tracing with Rhodamine WT on East Walker Branch subwatershed, 12/15/05.



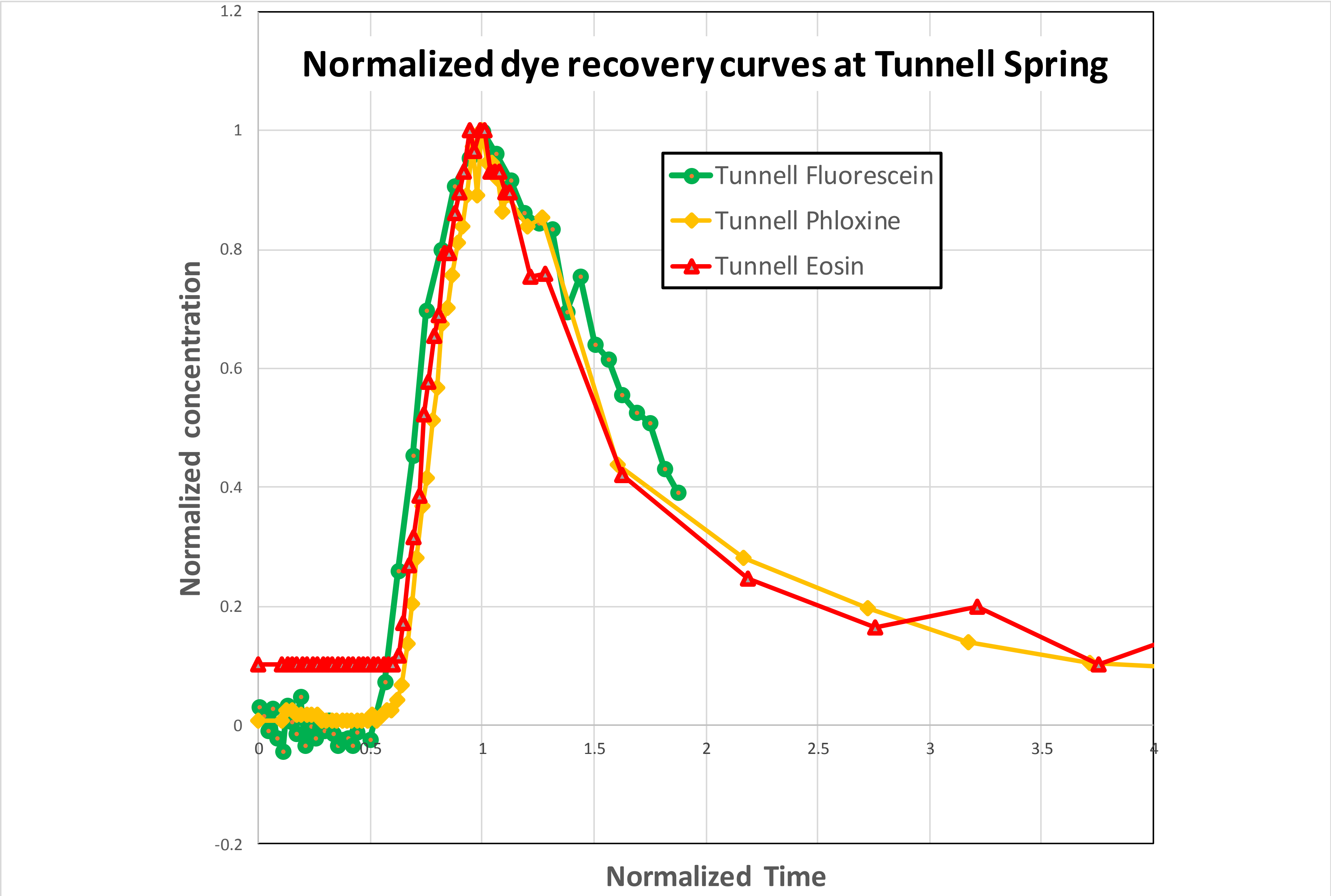
What can be learned about solute transport in the preferential flow paths of the Knox Aquifer from these studies ?

- Length of subsurface flow paths
- Travel time to peak arrival and inferred groundwater velocity
- Mass recovery
- Dispersion

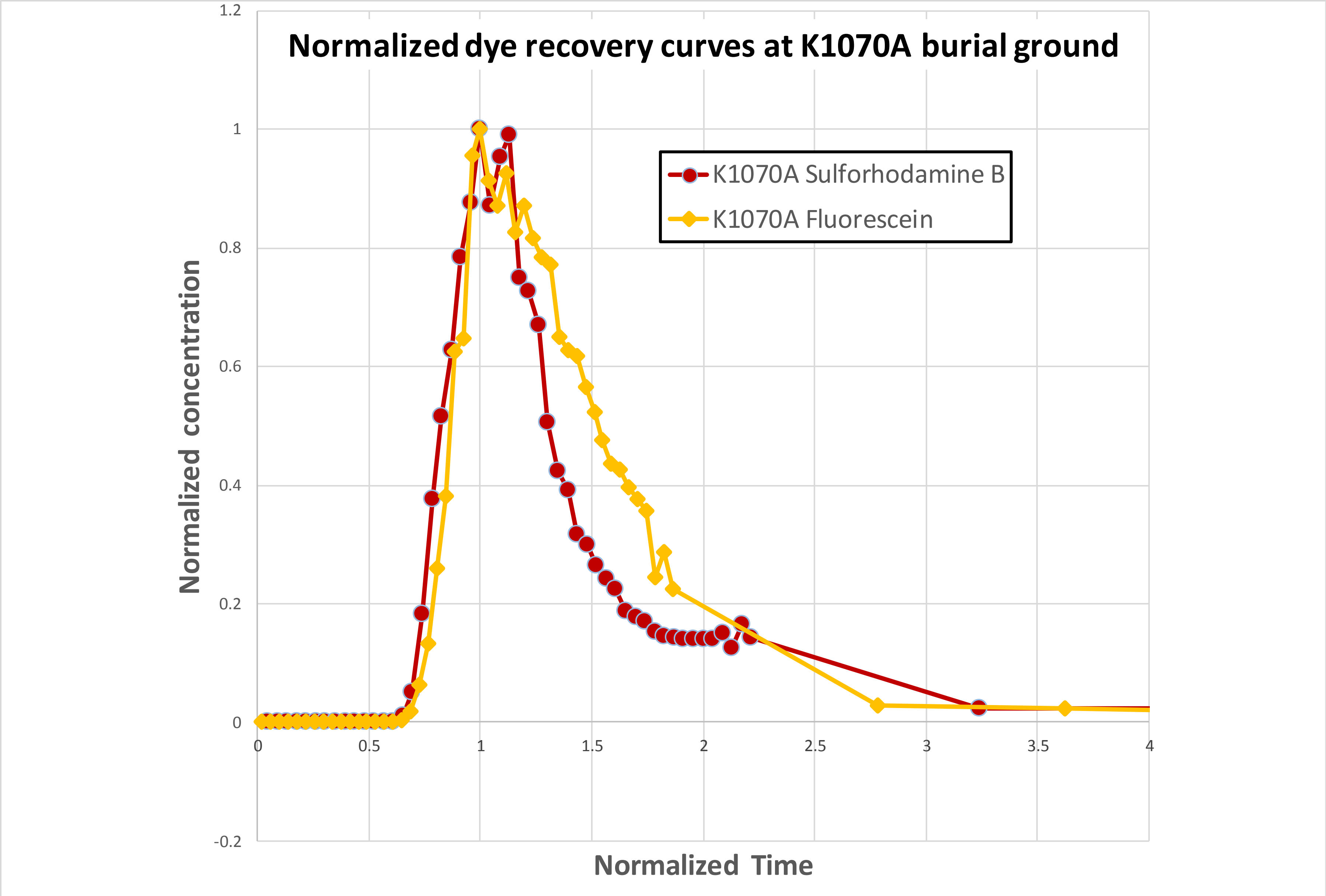
Site	Date	Distance (m)	Injection point	Time to Peak (hr)	Velocity (m/d)	Mass recovery
Landfill 2 area	9/14/1999	230	Sinking stream	44	125	Unknown
East End Y12 Plant	3/10/97	300	Bedrock Well	288	25	Unknown
Spallation Neutron Source	8/15/2001	360	Stormwater Swallet	126	70	Unknown
Tunnell	11/13/2003	400	Sinking stream	48	200	Unknown
ORNL First Creek	6/14/1999	560	Sinking stream	22	610	>50%
Walker Branch	12/13/2005	575	Sinking stream	72	190	Unknown
Commerce Park Borrow area	11/16/2014	830	Stormwater Swallet	16	1250	5%
K1070A Burial Ground	1/16/1996	640	Unconsolidated Well	25.5	600	30%
K1070A Burial Ground	1/16/1996	640	Bedrock Well	23	670	10%
Bear Creek	6/26/2001	970	Sinking stream	35.5	660	Unknown
Chestnut Ridge East Borrow area	6/1/1995	1010	Stormwater Swallet	10 (after rain)	2500	1% (total)
Union Valley	7/11/1998	1080	Bedrock Well	110	240	Unknown
ORNL First Creek	6/14/1999	1220	Sinking stream	68.5	425	>50%
Chestnut Ridge Security Pits area	4/12/1999	2250	Stormwater Swallet	54	1000	5%



Normalized dye recovery curves at Bootlegger Spring
Normalized concentration
Normalized time
Bootlegger 1999
Bootlegger 2014
Bootlegger 1995
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
2.5
3
3.5
4

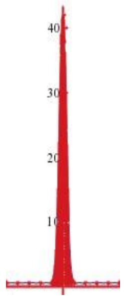


Normalized dye recovery curves at Tunnell Spring
Tunnell Fluorescein
Tunnell Phloxine
Tunnell Eosin
Normalized concentration
Normalized Time
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
2.5
3
3.5
4


Normalized dye recovery curves at K1070A burial ground
K1070A Sulforhodamine B
K1070A Fluorescein
Normalized concentration
Normalized Time
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
2.5
3
3.5
4

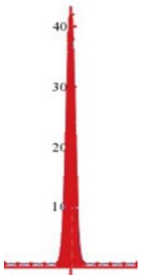
A very simple conceptual model for transport of solute

Instantaneous impulse source

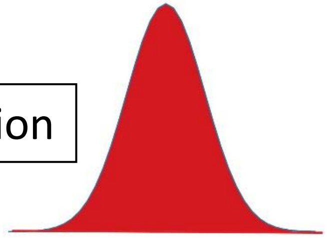


Transport through the subsurface

Advection

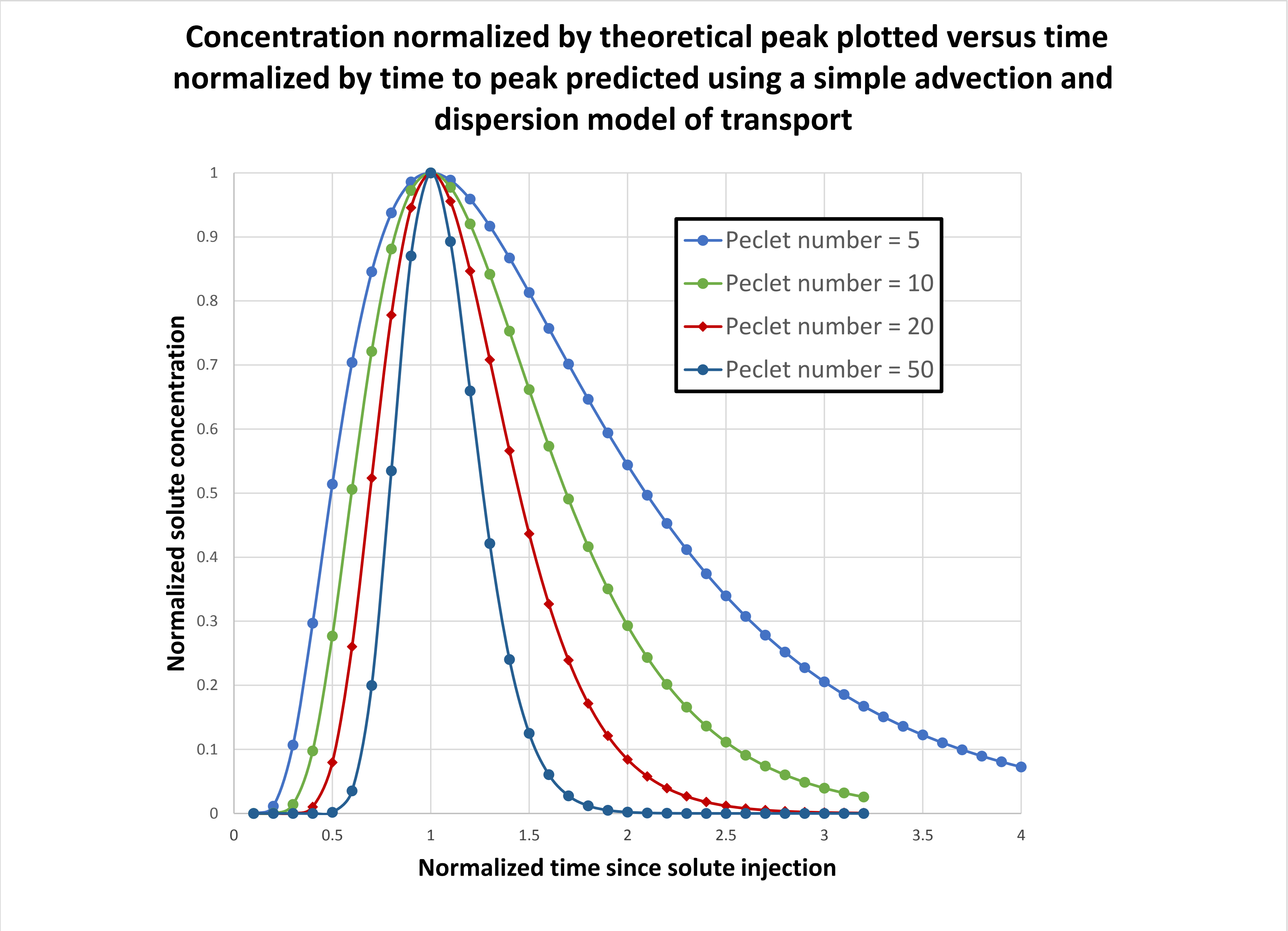


Dispersion

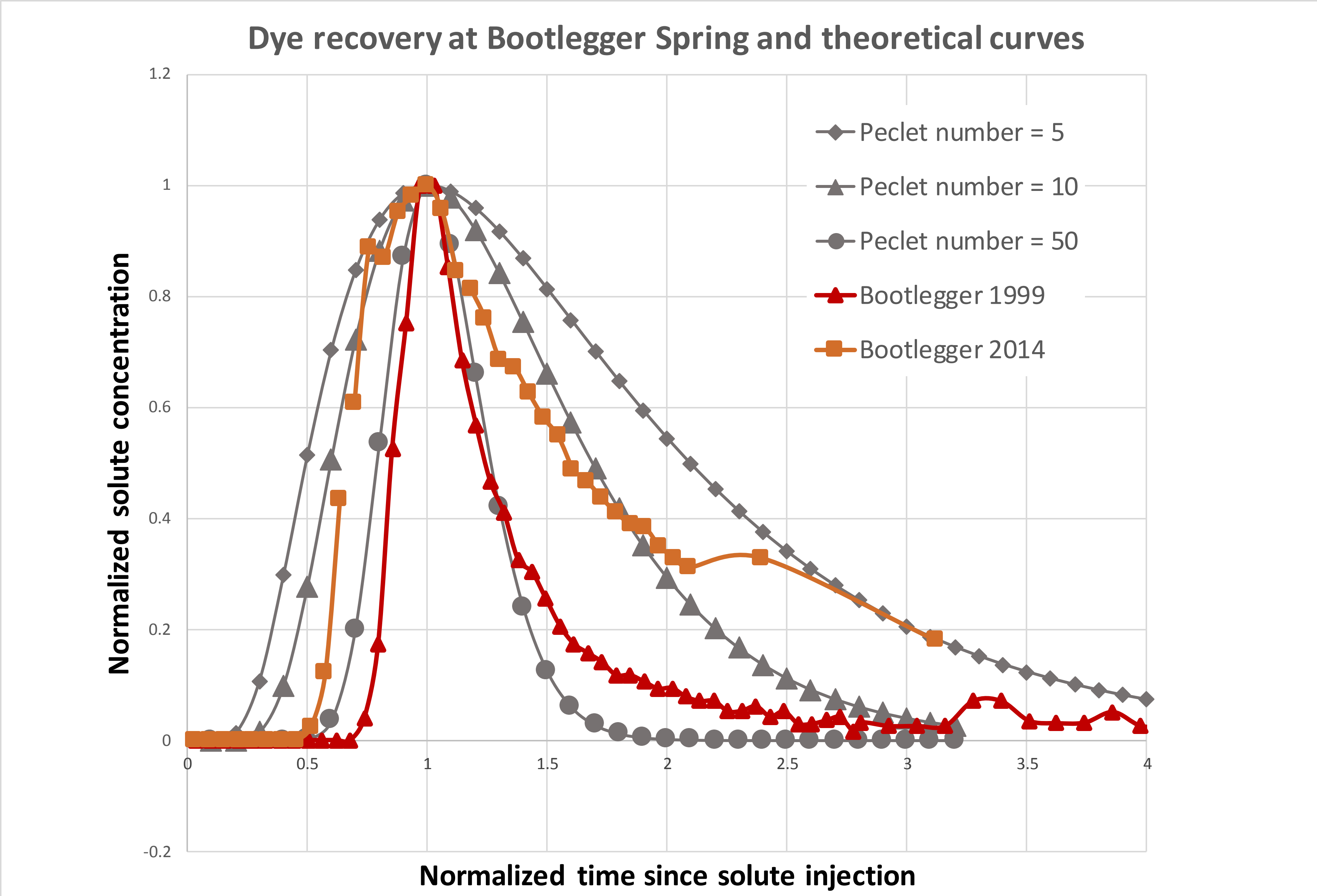


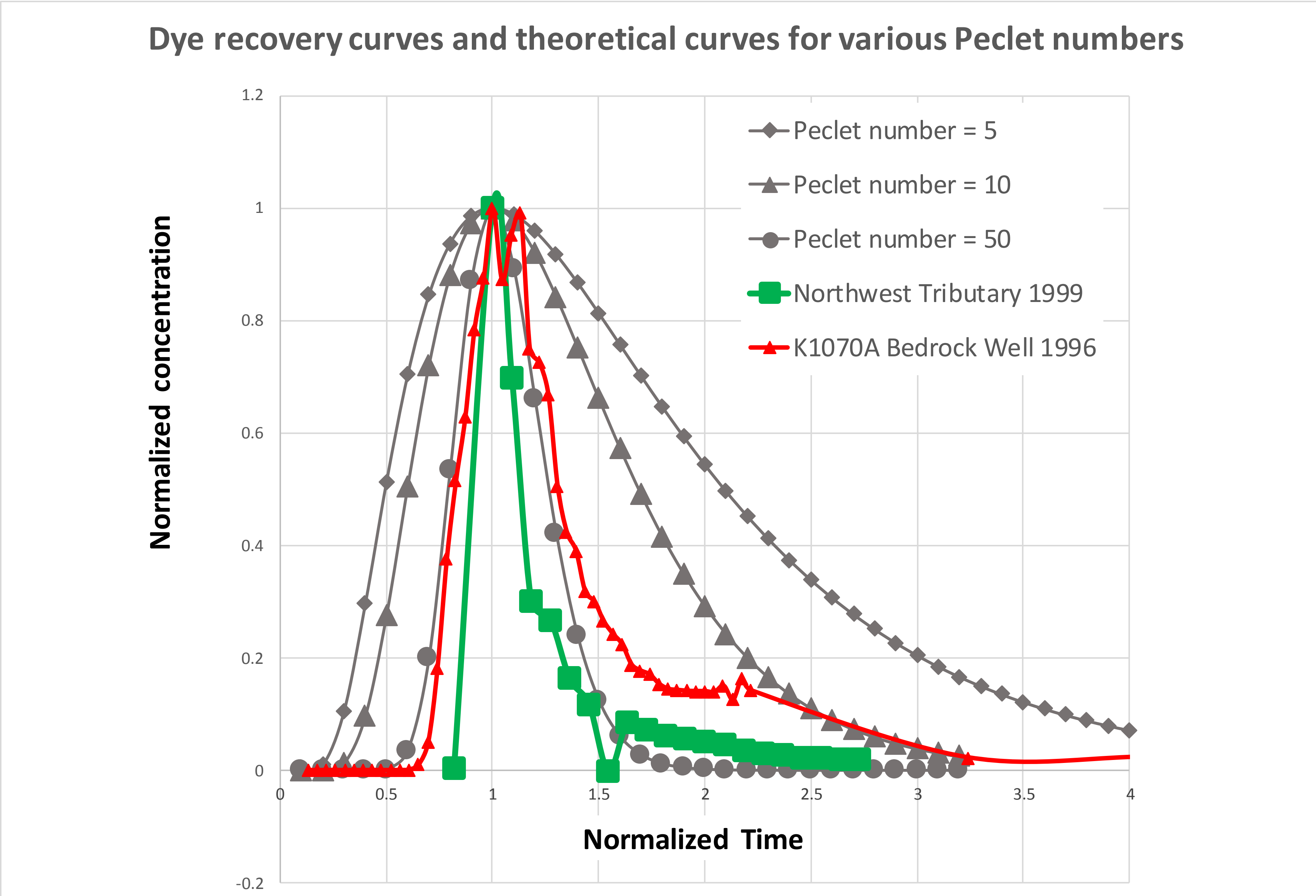
Mass lost irreversibly to subsurface from source

$$C(dimensionless) = \frac{\sqrt{x_D}}{\sqrt{4\pi t_D}} e^{-\left(\frac{X_D(1-t_D)^2}{4t_D}\right)}$$



In the simple model, the shape of the normalized curves depends only on the Peclet number, which is the distance traveled X, multiplied by mean velocity V, divided by the dispersion coefficient D.


Dye recovery at Bootlegger Spring and theoretical curves
Normalized solute concentration
Normalized time since solute injection
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
Peclet number = 5
Peclet number = 10
Peclet number = 50
Bootlegger 1999
Bootlegger 2014

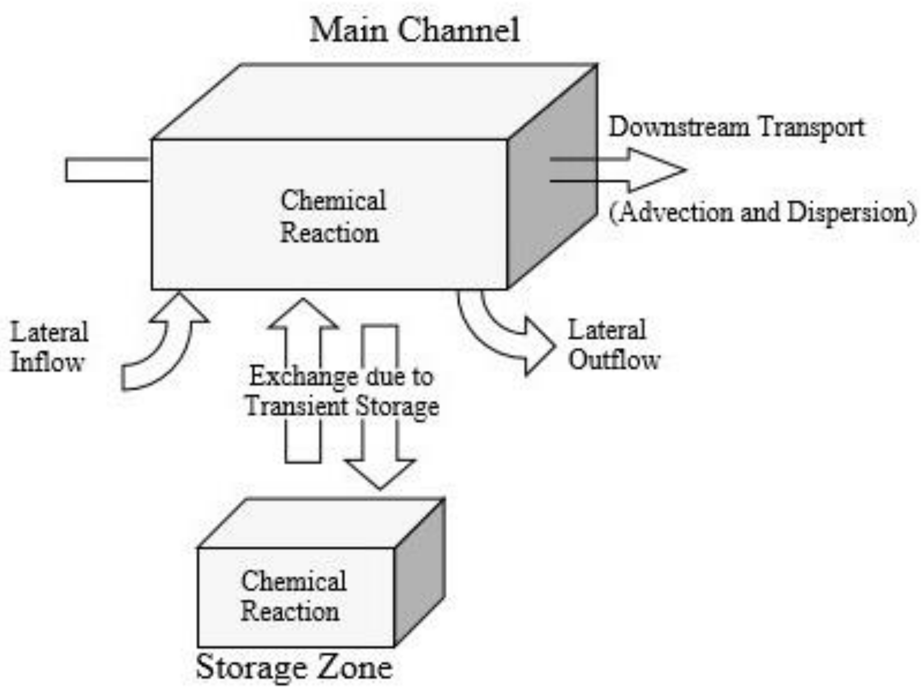


Dye recovery curves and theoretical curves for various Peclet numbers
Normalized concentration
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
Normalized Time
Peclet number = 5
Peclet number = 10
Peclet number = 50
Northwest Tributary 1999
K1070A Bedrock Well 1996

- Peclet numbers for our traces are relatively high, in the range of 10 to 100, so effects of dispersion are relatively small. Loss of mass that is not recovered during the trace may effect the peak concentrations more than dispersion in some cases.

- Normalized concentration curves from these studies are typically more asymmetric than the theoretical curves, with an abrupt concentration increase with a tail that decays more slowly. This is consistent with many results from tracing of surface streams and is often explained (and modeled) using the notion of exchange between an active flow zone and transient storage zones where the stream velocity is essentially zero.

Conceptual Model: Main Channel and Storage Zone



ONE-DIMENSIONAL TRANSPORT WITH INFLOW AND STORAGE (OTIS): A SOLUTE TRANSPORT MODEL FOR STREAMS AND RIVERS

By **Robert L. Runkel**

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 98–4018

Transient storage models have been applied to tracer recovery curves in karst as well, as shown below in this figure extracted from a 2008 paper in *Groundwater* by Goppert and Goldscheider in a trace through a cave stream to a single spring.

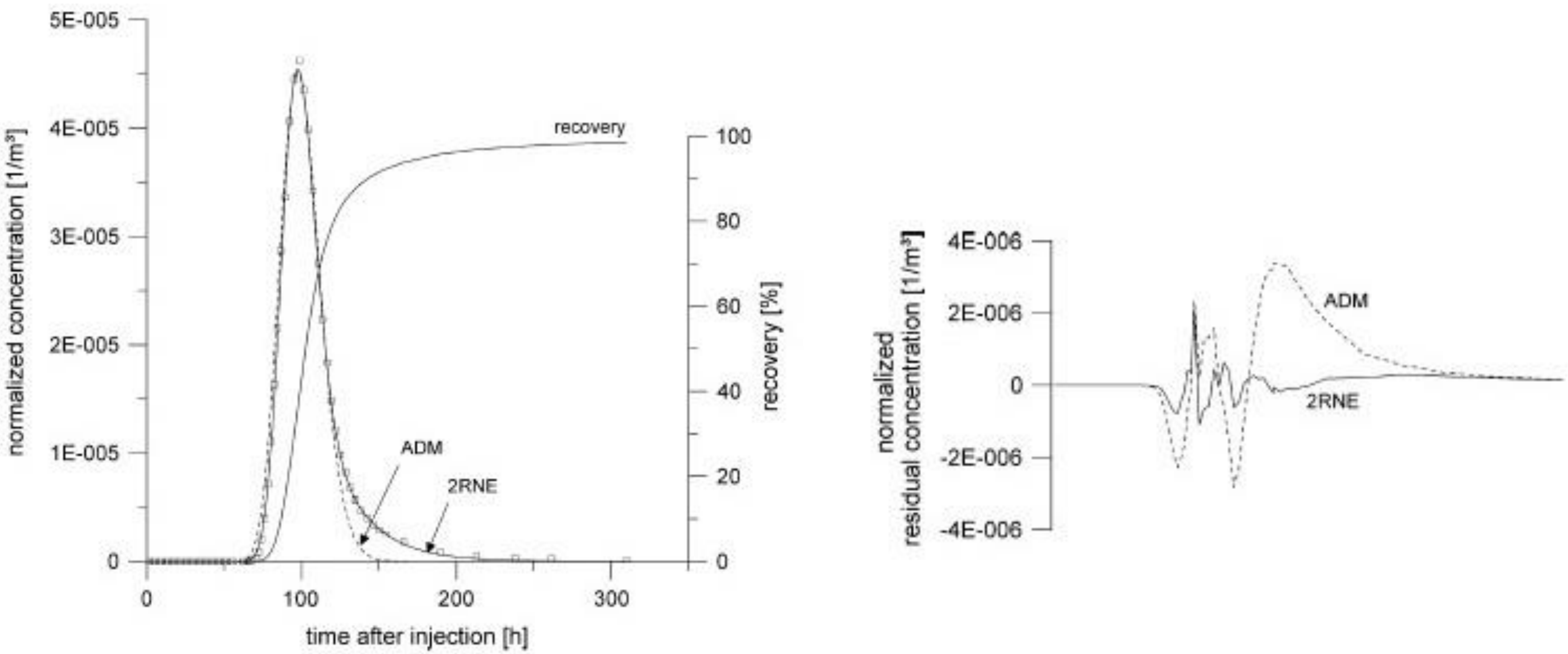
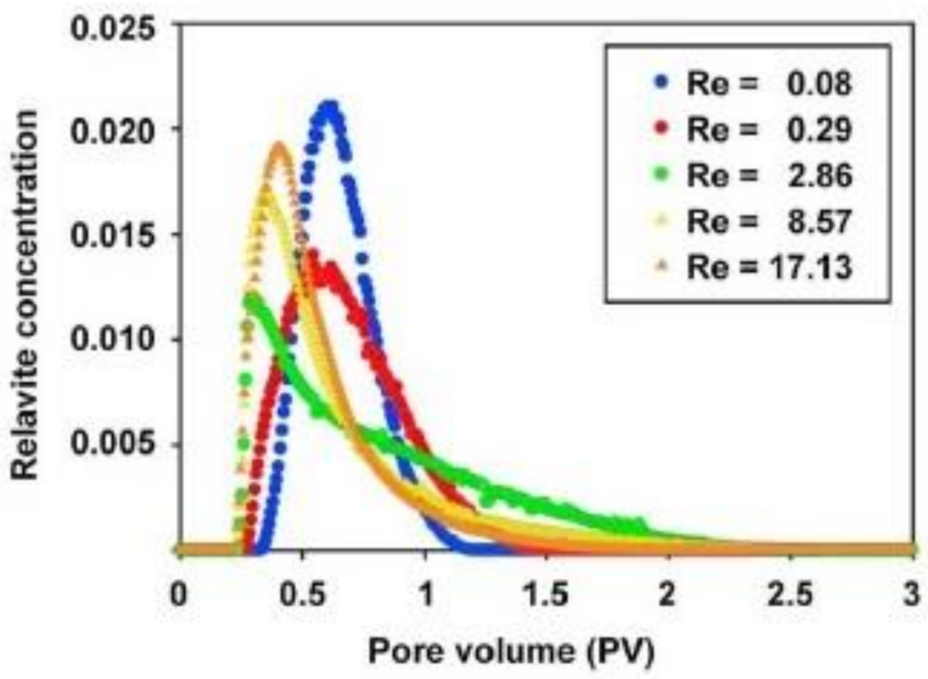


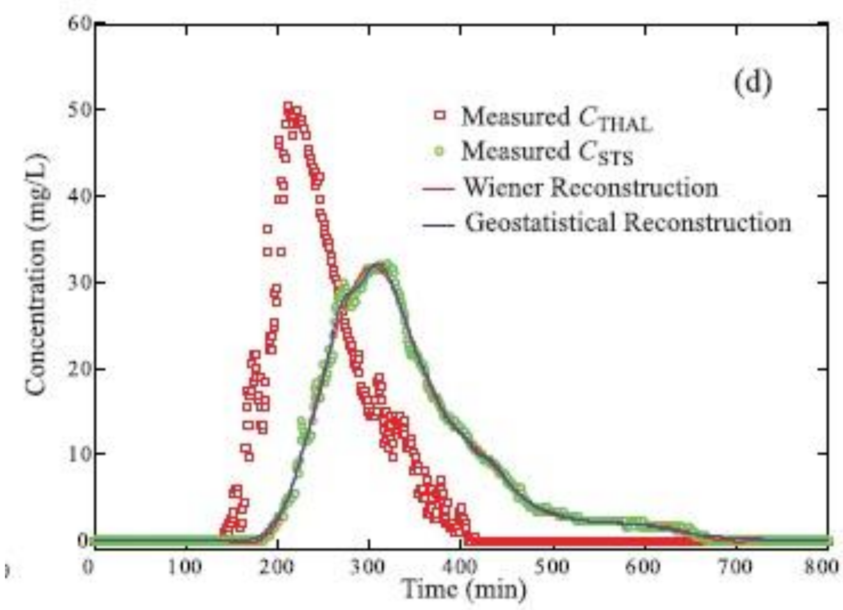
Figure 2. Results for uranine during low flow: observed values (squares), fitted models (ADM and 2RNE), residual concentrations. Constant spring discharge during the experiment: 172 L/s.

The transient storage model is the next step in modeling complexity beyond the simple model discussed before and does help explain the skewed distribution of recovery curves. However, more detailed analysis of surface water tracer tests and solute transport through variable aperture fractures have shown (as expected by tracing practitioners:

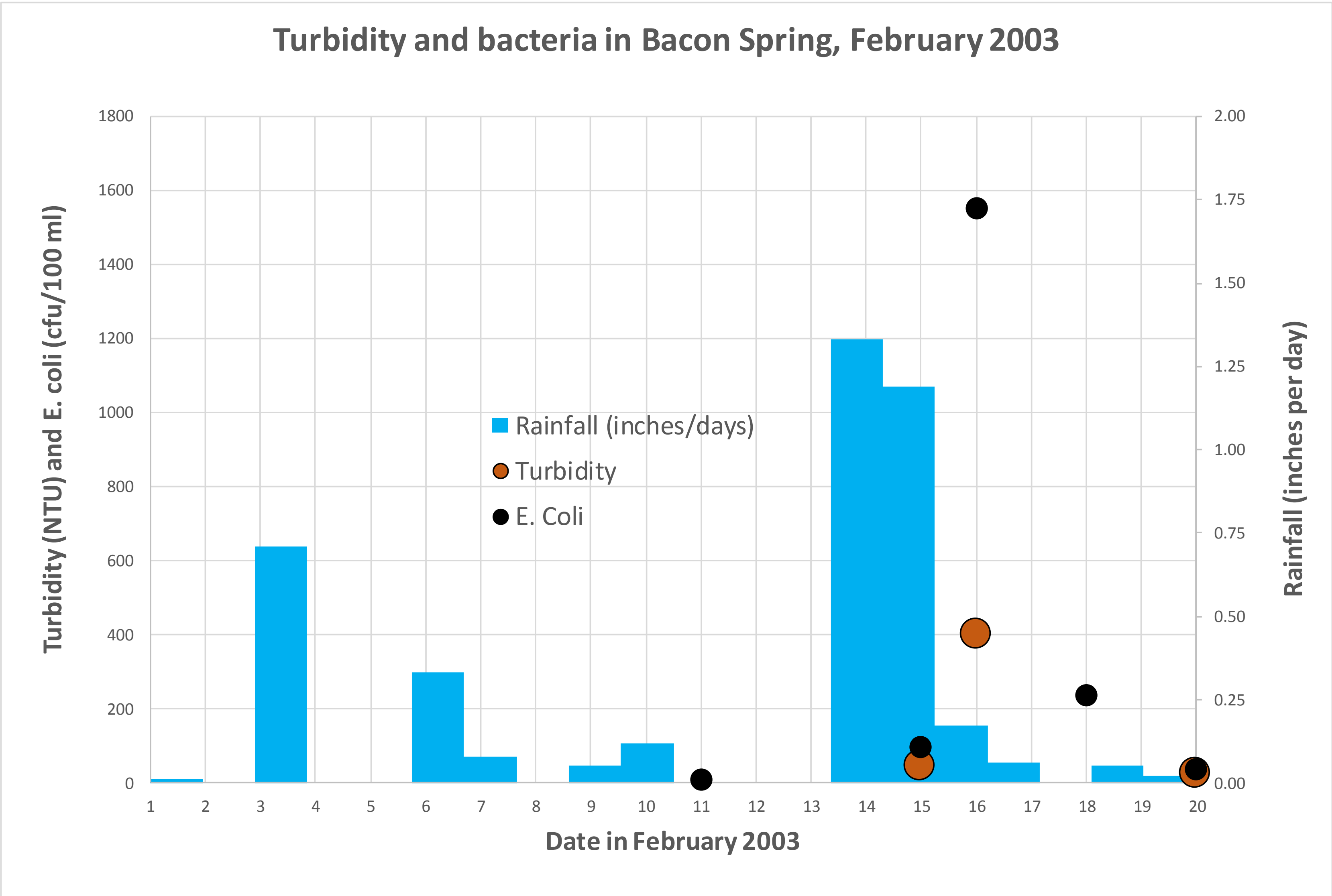
- The relative effects of transient storage depend on flow conditions (see figure on left below from Lee, et al., 2015, *Geophysical Research Letters*)

- The mass transfer processes in storage zones are more complex than those incorporated into the model (figure on right from Gooseff et al., 2011, *Water Resources Research*)





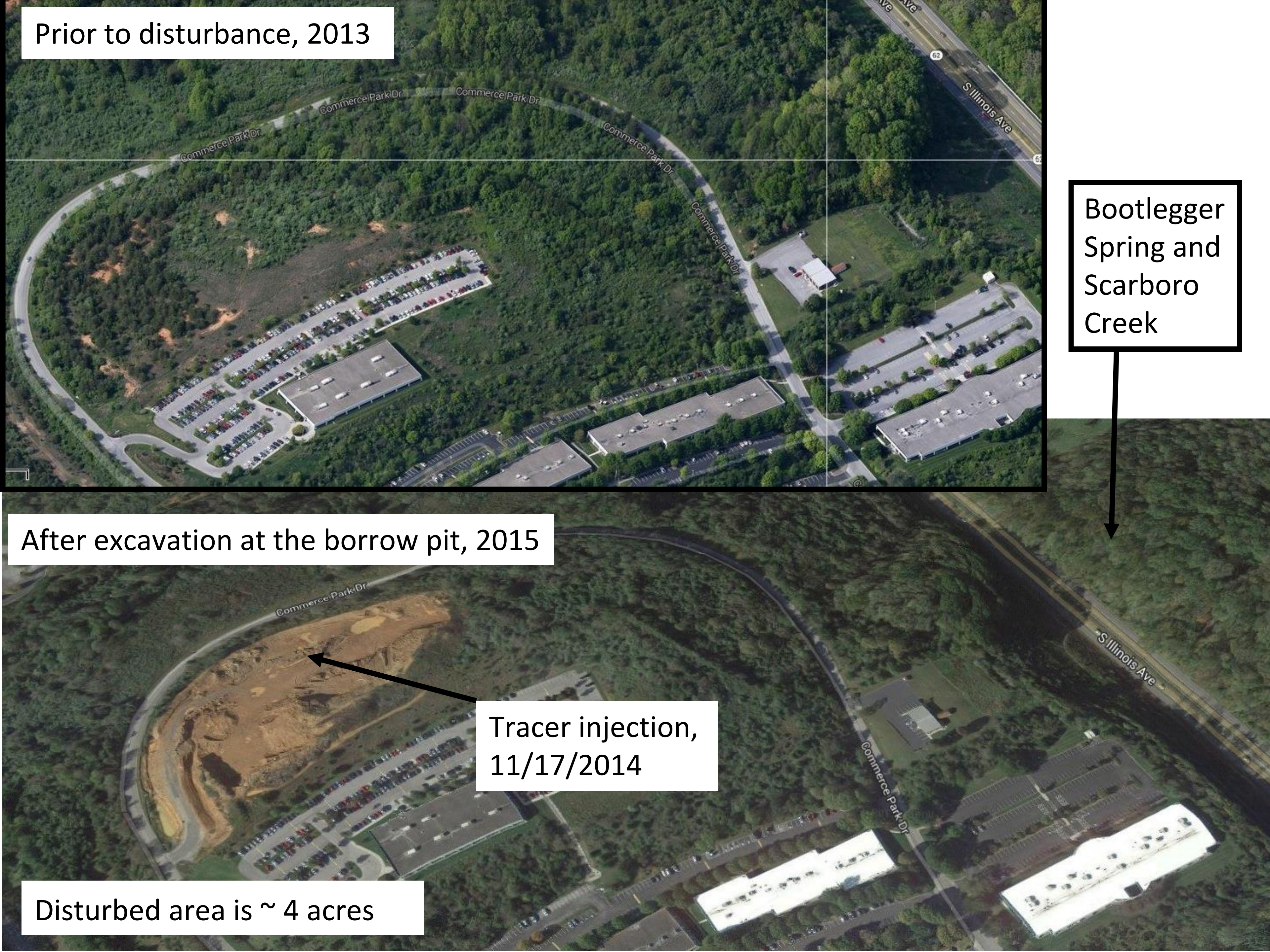
What was learned about transport of particulate through the subsurface? Bacteria and sediment transport in the Knox aquifer in a similar manner to the transport of particulate documented in other karst aquifers.



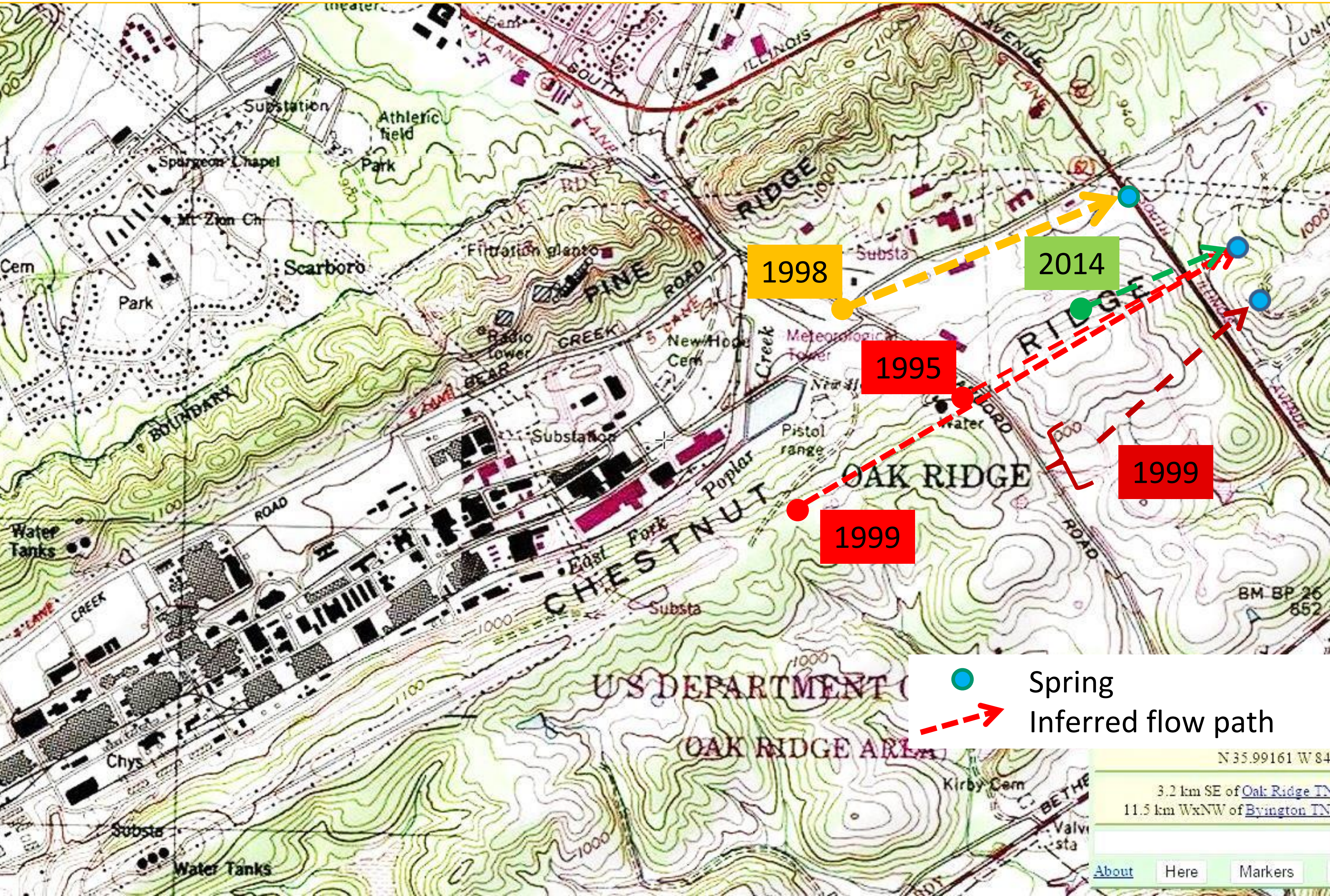

Examples already seen of construction related disturbances on Chestnut Ridge resulting in sediment in springs include the SNS ring construction and the borrow area on East Chestnut Ridge. Another example near Oak Ridge (on Black Oak Ridge) was the disturbance due to construction a single-family residence that resulted in formation of a stormwater swallet draining only about an acre but apparently impacting Bacon Spring.

In fall of 2014, Bootlegger became extremely muddy again as stormwater swallets developed in a borrow area in Commerce Park used the city of Oak Ridge. This provided an opportunity to get better estimates on the amount of sediment transported through the subsurface from a well defined source through a known and well-defined karst pathway.

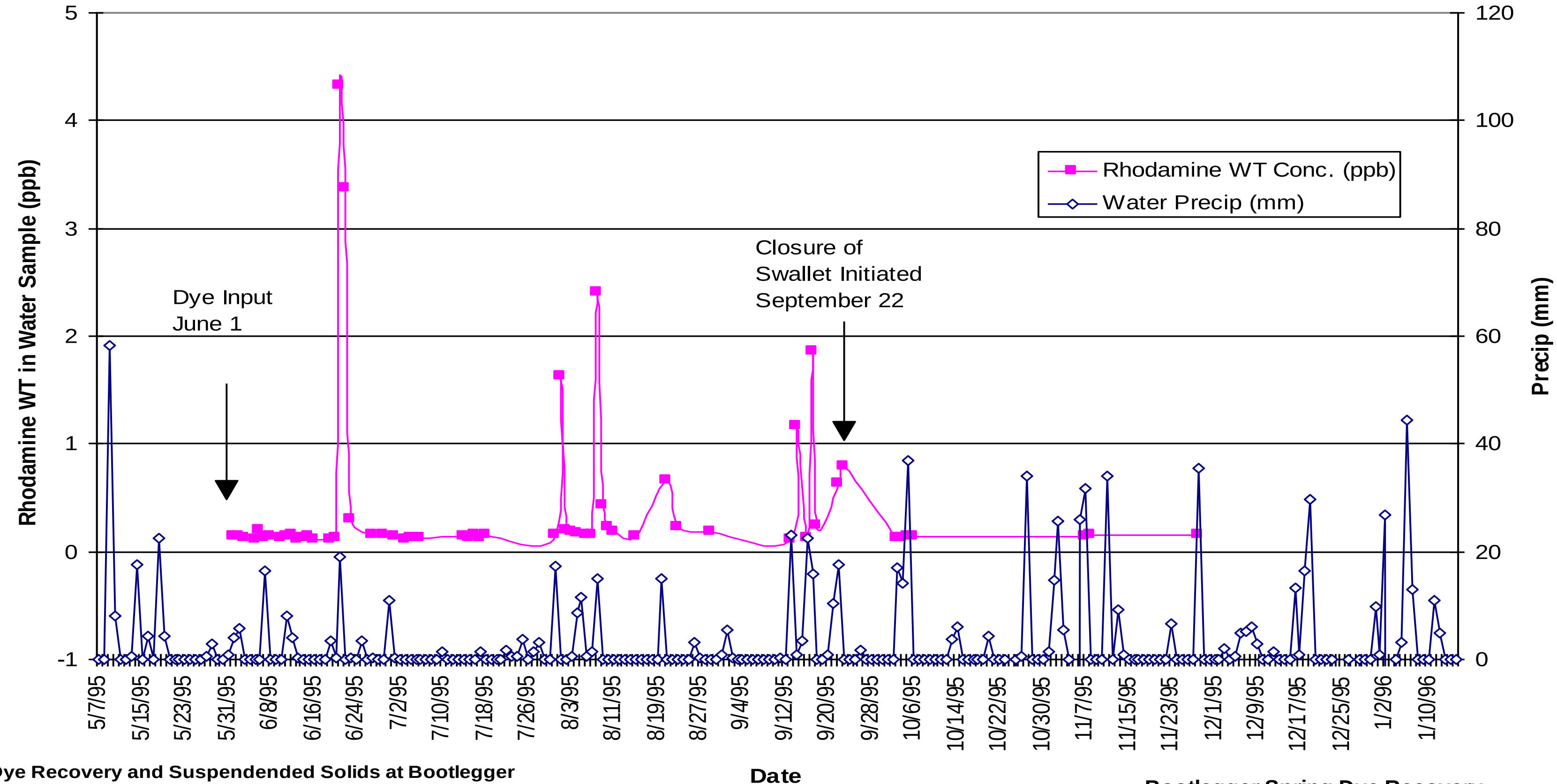
Western swallet
Trench leading to western swallet
Western swallet
Eastern swallet
Trench leading to
eastern swallet


Prior to disturbance, 2013
Commerce Park Dr
S Illinois Ave
Bootlegger Spring and Scarboro Creek
After excavation at the borrow pit, 2015
Tracer injection, 11/17/2014
Disturbed area is ~ 4 acres

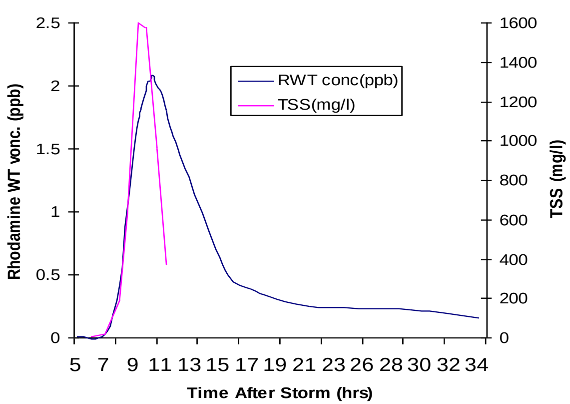
Summary of groundwater tracing to springs feeding Scarboro Creek



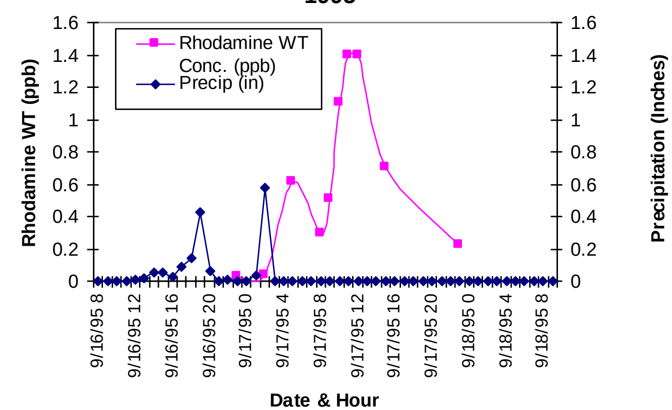
What was learned from the 1995 tracing at Bootlegger?

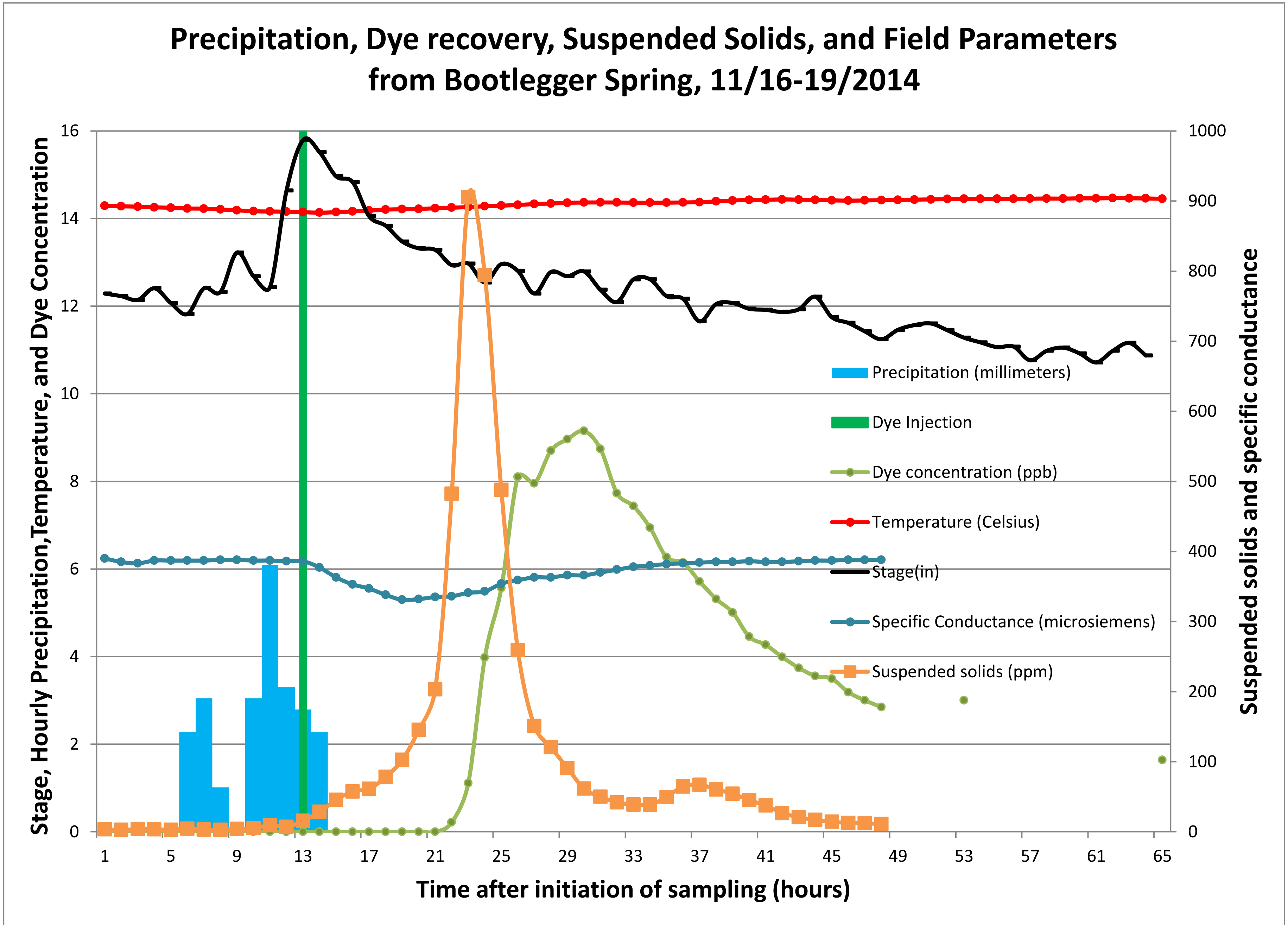


Dye Recovery and Suspendended Solids at Bootlegger Spring on 8/8/95

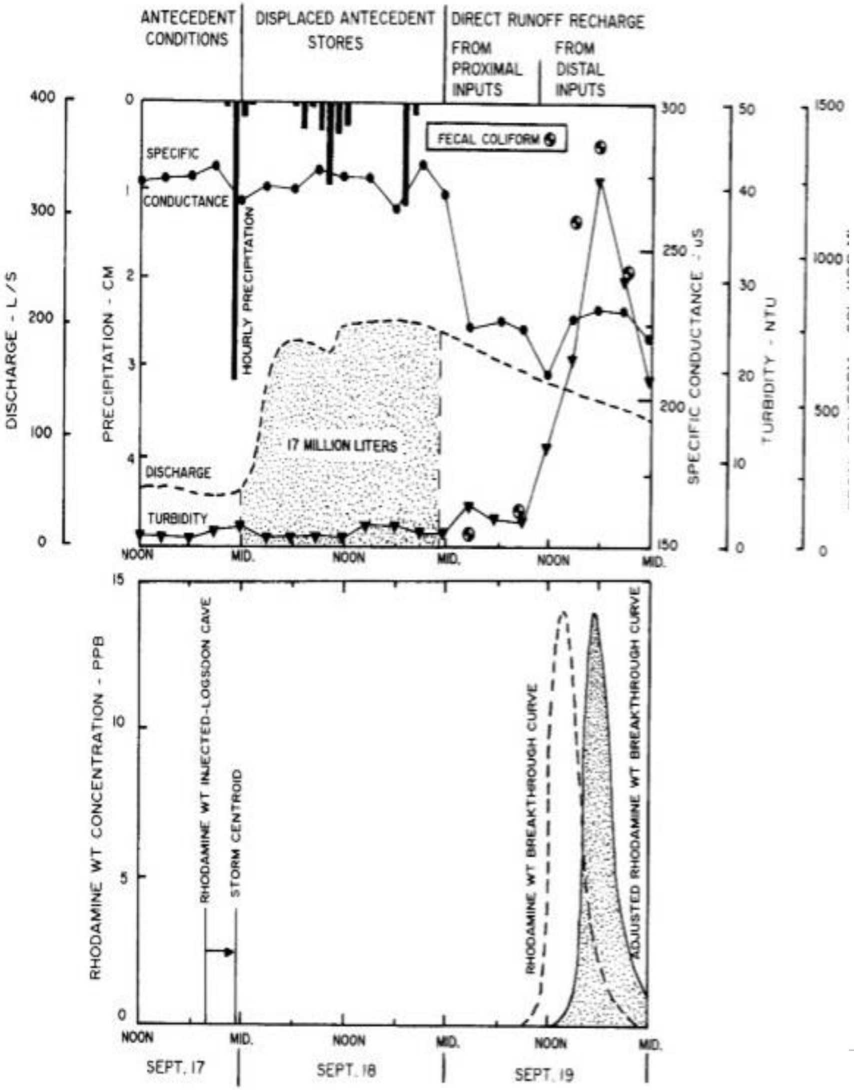


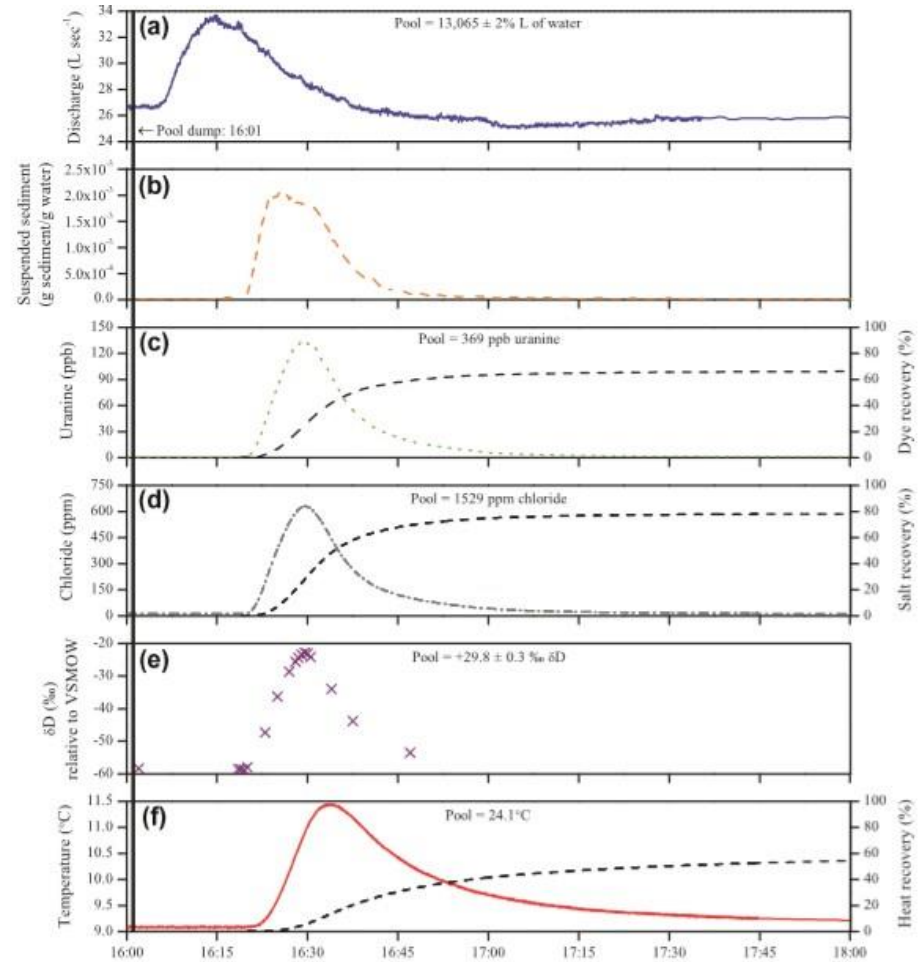
Bootlegger Spring Dye Recovery September 16 & 17 Rain Events 1995





Precipitation, Dye recovery, Suspended Solids, and Field Parameters
from Bootlegger Spring, 11/16-19/2014
Stage, Hourly Precipitation,Temperature, and Dye Concentration
Suspended solids and specific conductance
Time after initiation of sampling (hours)
Precipitation (millimeters)
Dye Injection
Dye concentration (ppb)
Temperature (Celsius)
Stage(in)
Specific Conductance (microsiemens)
Suspended solids (ppm)
16
14
12
10
8
6
4
2
0
1000
900
800
700
600
500
400
300
200
100
0
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
61
65





These data are consistent with results of Ryan and Meiman, 1996, (*Groundwater*) in the Mammoth Cave area, showing particulate concentrations respond to hydraulic loading of the aquifer, and Luhmann et al., 2012, (*Journal of Hydrology*) in Minnesota, showing they may peak earlier than solute concentrations and may decay more rapidly.

In this case the source of sediment to the spring was well defined, so an estimate of sediment yield was possible. Sediment Load to the Creek = $\int(QC)\,dt$ over the duration of the storm = ~ 200 kg

For the longer and more intense storms in October, with 2-3 inches total precipitation, suspended solids concentrations at the spring near the peak turbidity were about 7 times that for the peak in November storm. The duration of turbid conditions at the spring was also 5 to 10 times longer, and the spring discharge was generally higher. Thus a crude estimate for the sediment transported through the subsurface during major storm events is about a metric ton per acre of disturbed area