Role of Numerical Modeling in Remedy Selection and Remedial Performance Evaluation

Dan Goode, USGS

with Claire Tiedeman, Allen Shapiro, and others

USEPA-USGS Fractured Rock Workshop

EPA Region 10

September 11-12, 2019

Modeling – Outline

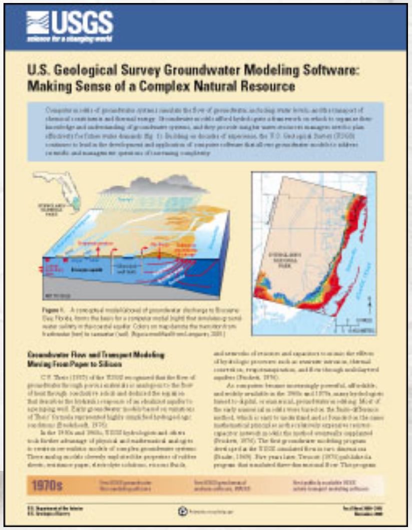
- MODELS Я USGS
  - 2 ‘Simple’ Examples
- NAS Recommendations
- EPA Guidance Highlights
- Capture Zones: Pump & Treat
  - 3D Water-Level Contouring
  - Contaminant Pathways

USGS
science for a changing world

Fact Sheet 2009-3105

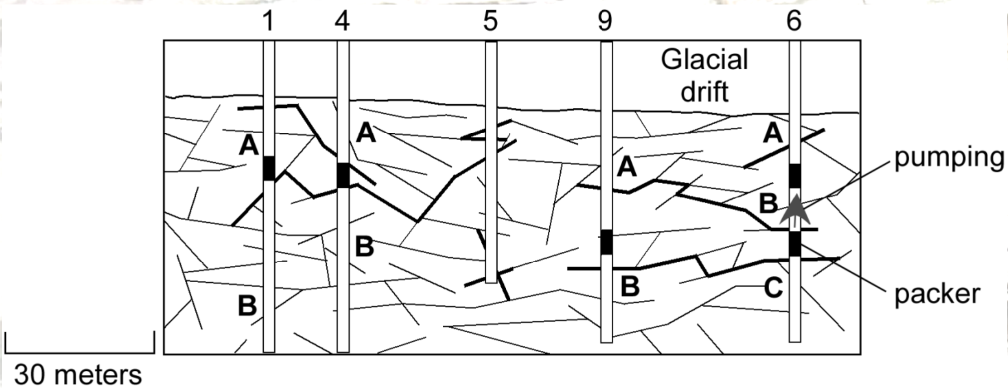
U.S. Geological Survey Groundwater Modeling Software: Making Sense of a Complex Natural Resource

"Groundwater models afford hydrologists a framework on which to organize their knowledge and understanding of groundwater systems, and they provide insights water-resources managers need to plan effectively . . . USGS software will continue to provide the tools they need."


USGS
U.S. Geological Survey Groundwater Modeling Software:
Making Sense of a Complex Natural Resource
1970s

Mirror Lake NH Example: A Simple Model

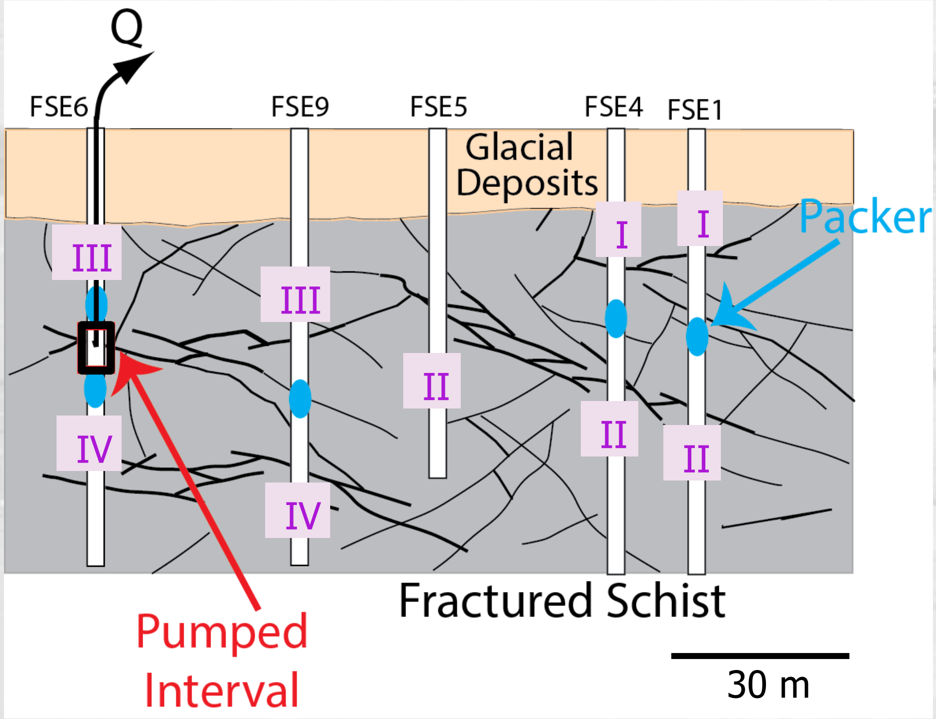
Granite and schist, Mirror Lake, NH



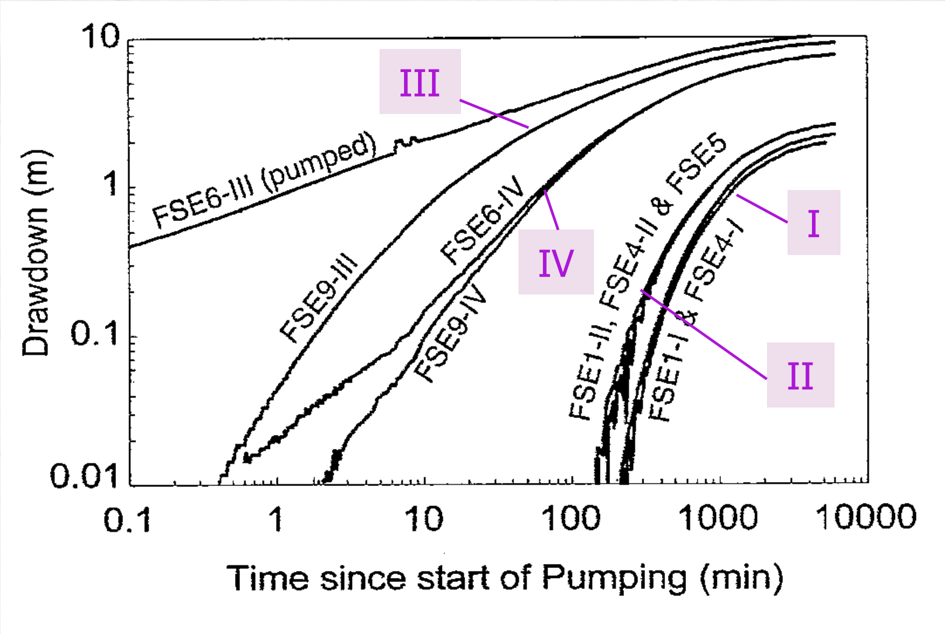
It is not necessary to identify every fracture in defining groundwater pathways. . .

But important pathways for scale of interest should be explicitly accounted for.

Cross-Hole Test in Fractured Schist



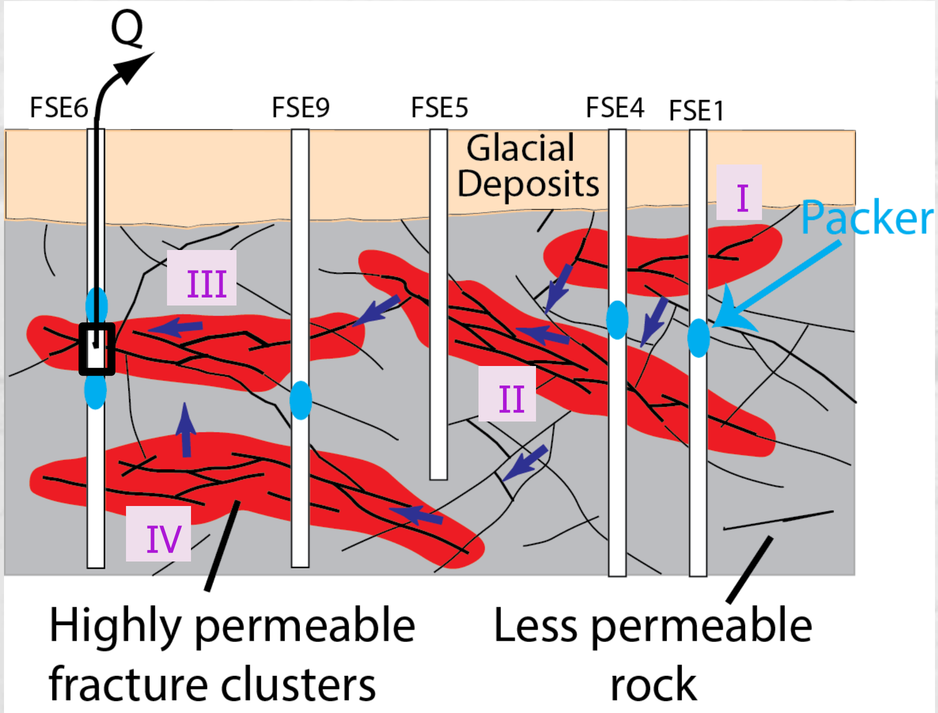
- **Observed Drawdown:**



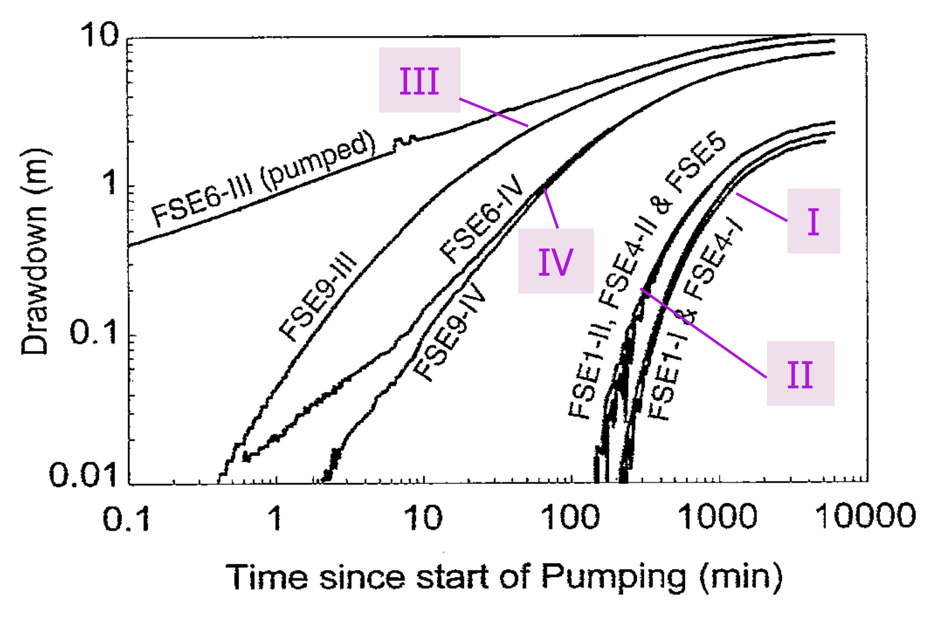
(Hsieh et al. 1999; Hsieh 2000)

Cross-Hole Test in Fractured Schist

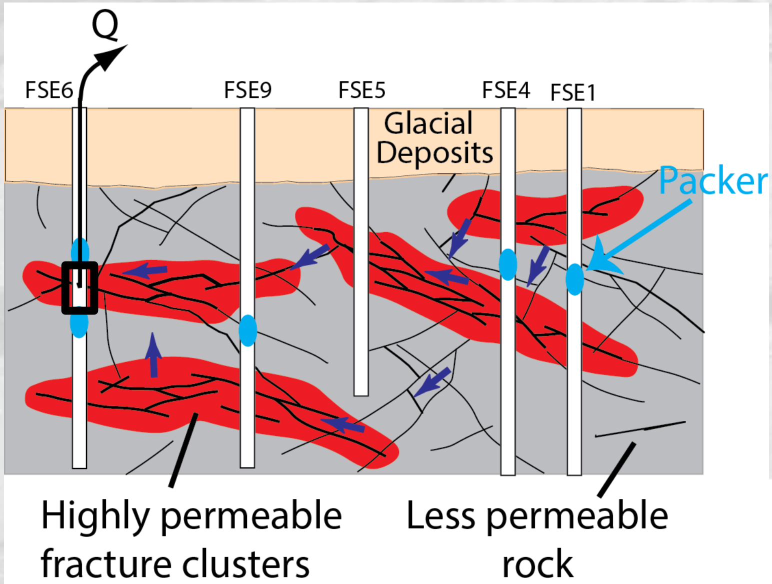
- **Conceptual Model:**

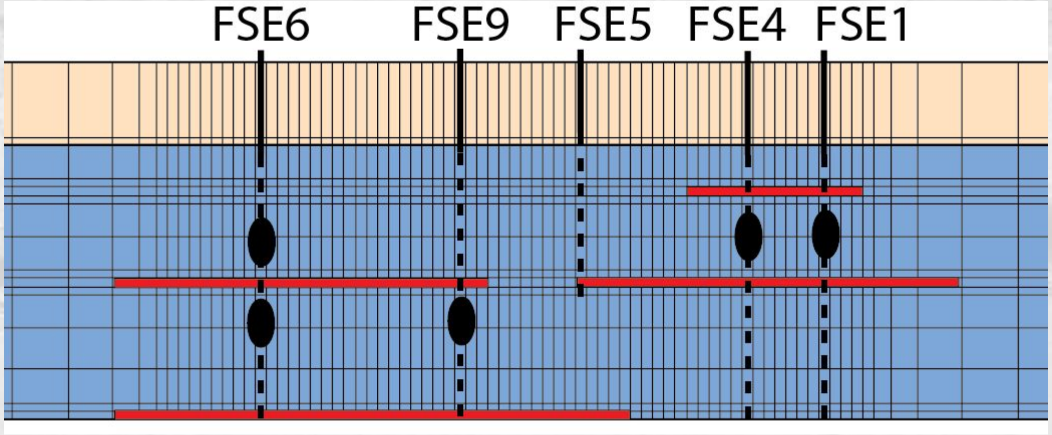


- **Observed Drawdown:**

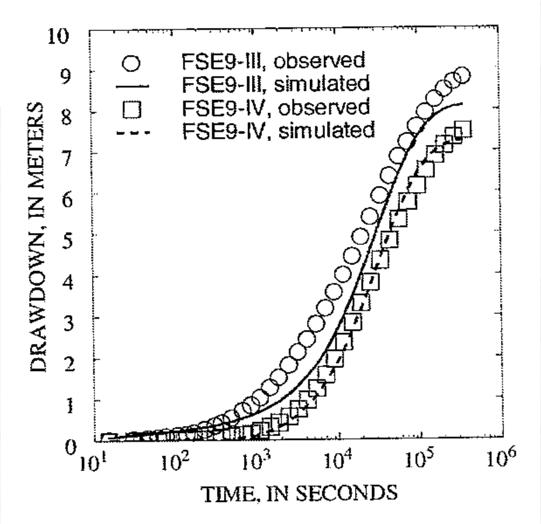


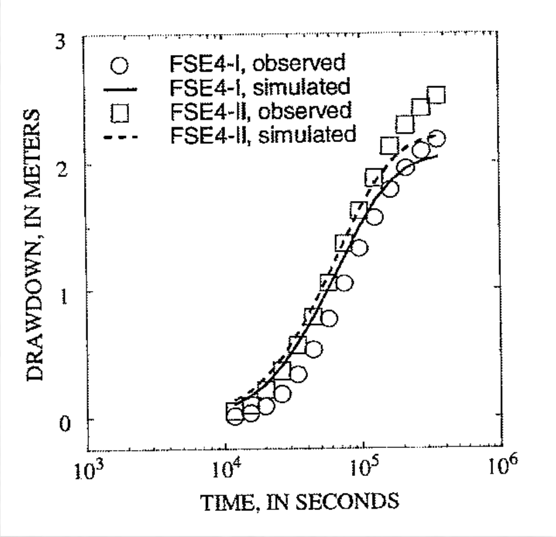
Analysis With Simple Numerical Model





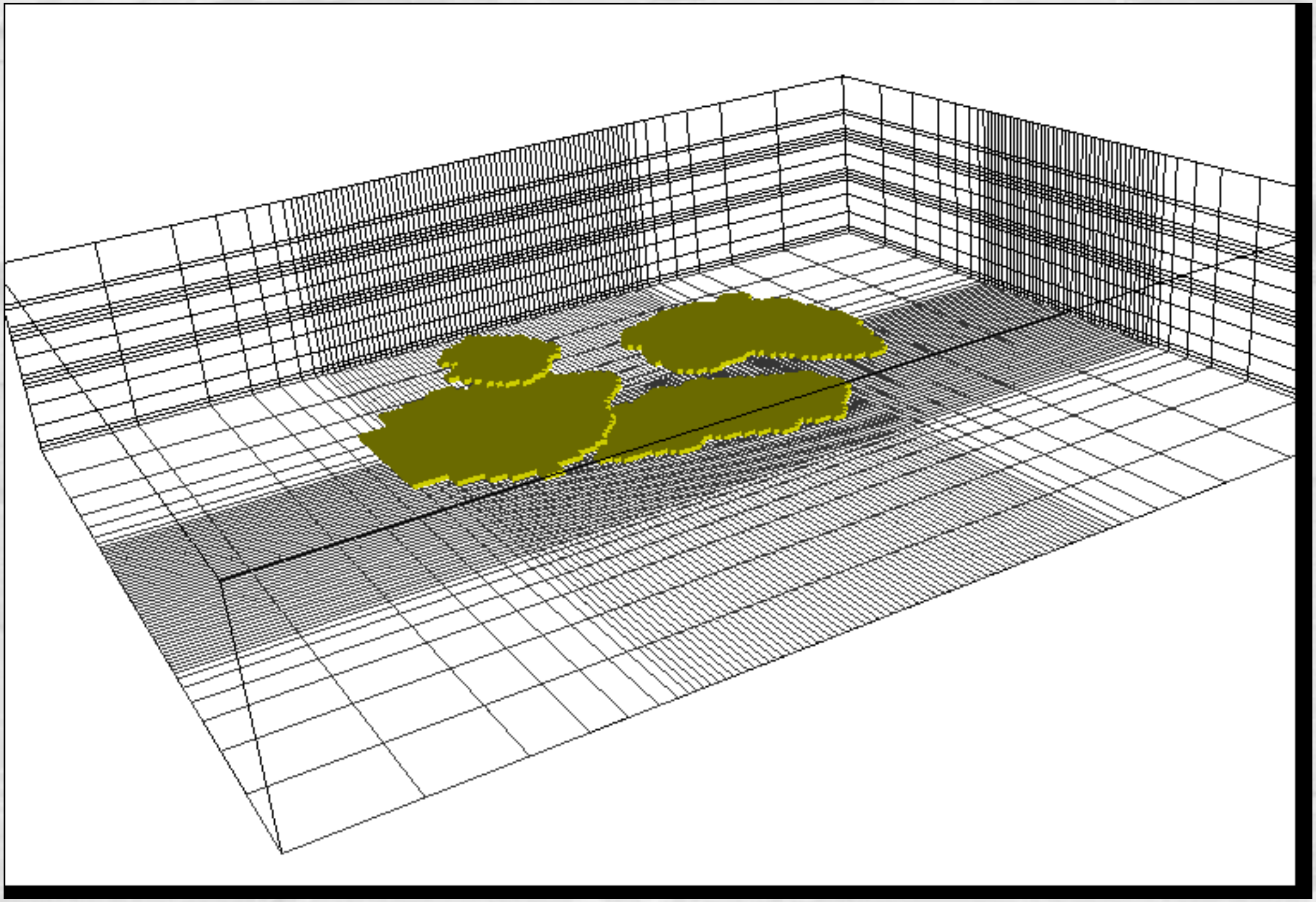
- **Simple numerical model:**
  - **Confirms conceptual model**
  - **Captures primary heterogeneities**
  - **Is basis for transport model**
  - **Not unique**
  - **Has uncertainties**





Analysis With Simple Numerical Model

- **3D view of model**



From Hsieh (2000)

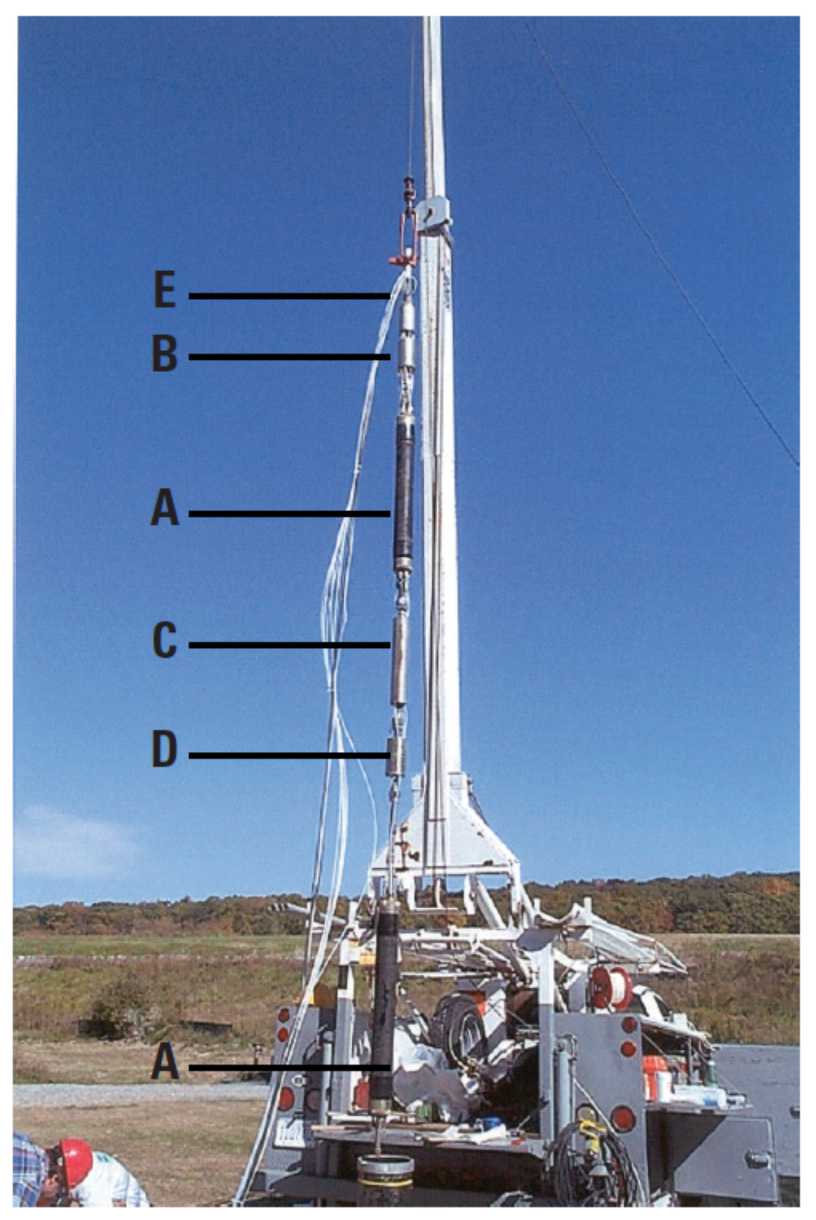
Using Hydraulic Information to Characterize Capture Zones

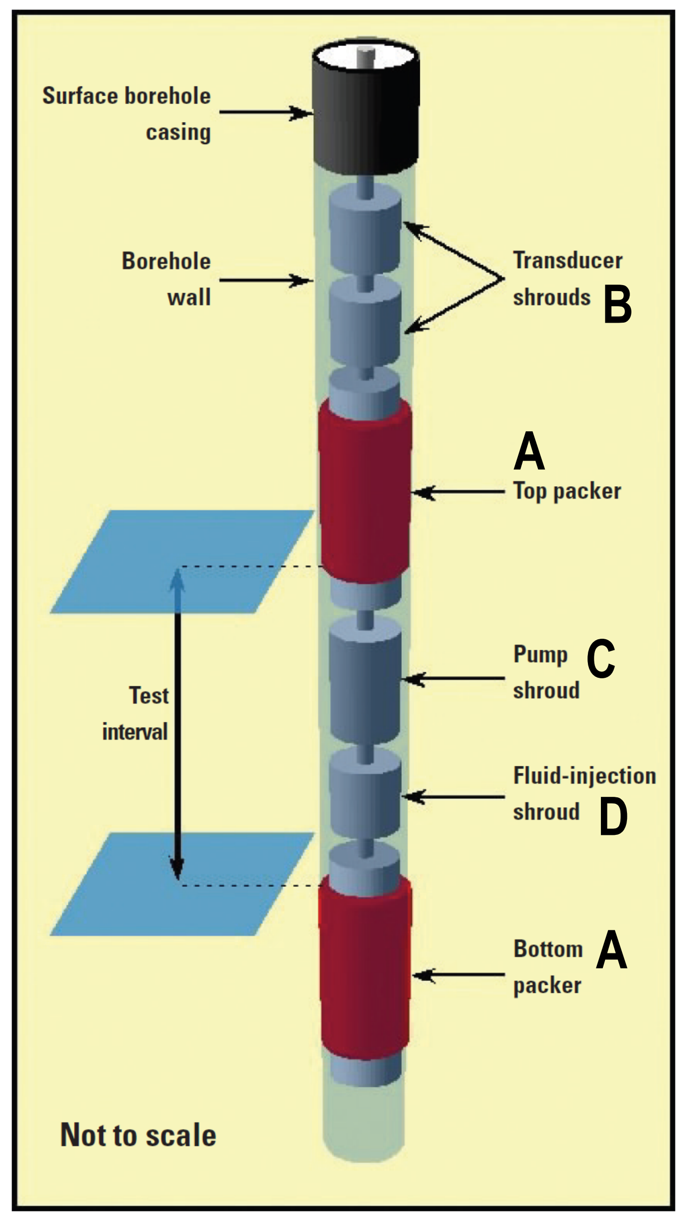
Evaluating Capture Zones in Fractured-Rock Aquifers
EPA TSP Ground Water Forum Workshop
Orlando November 16, 2010

U.S. Department of the Interior
U.S. Geological Survey

Packer Testing in Open Boreholes

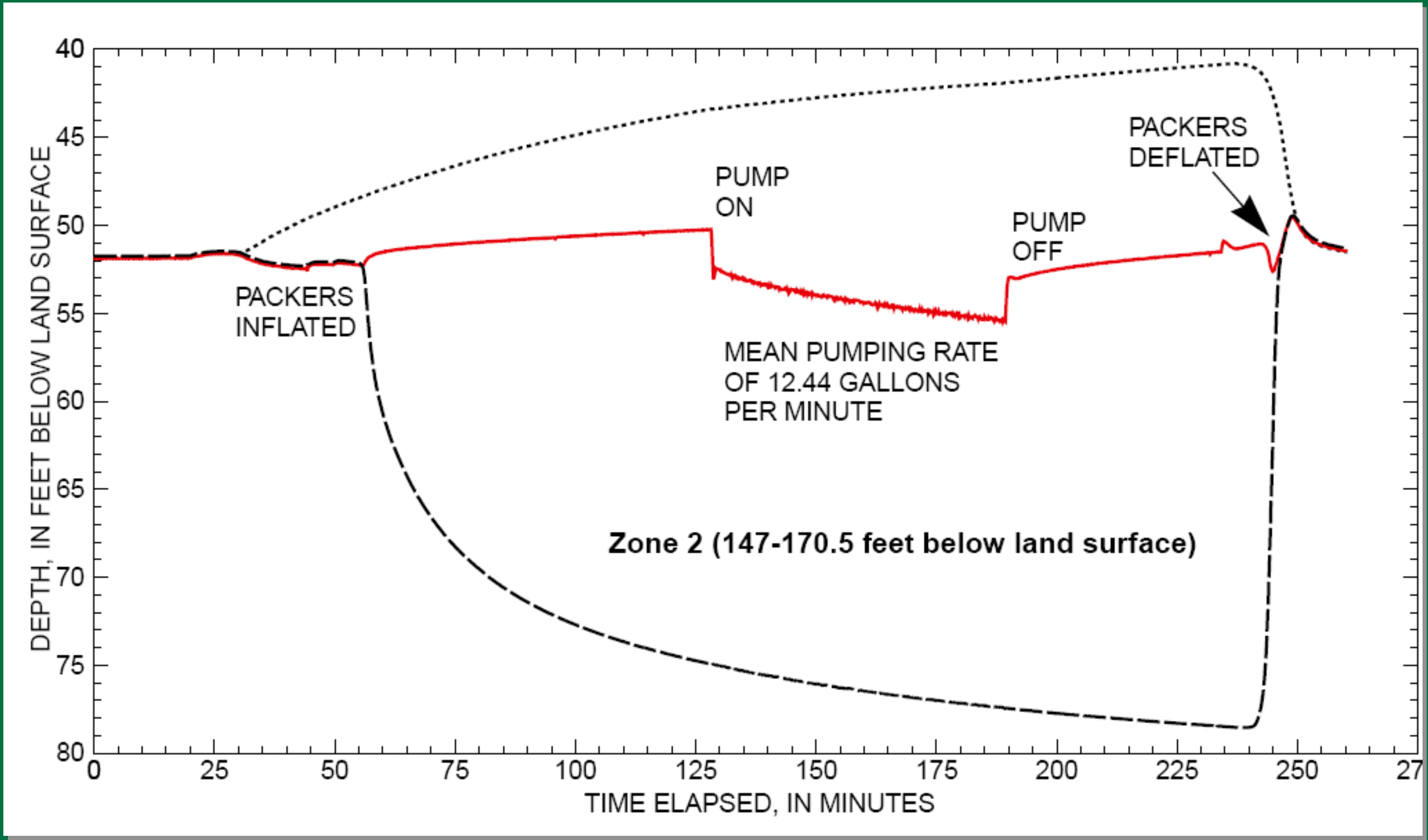
Shapiro





USGS

Packer test of Production Well



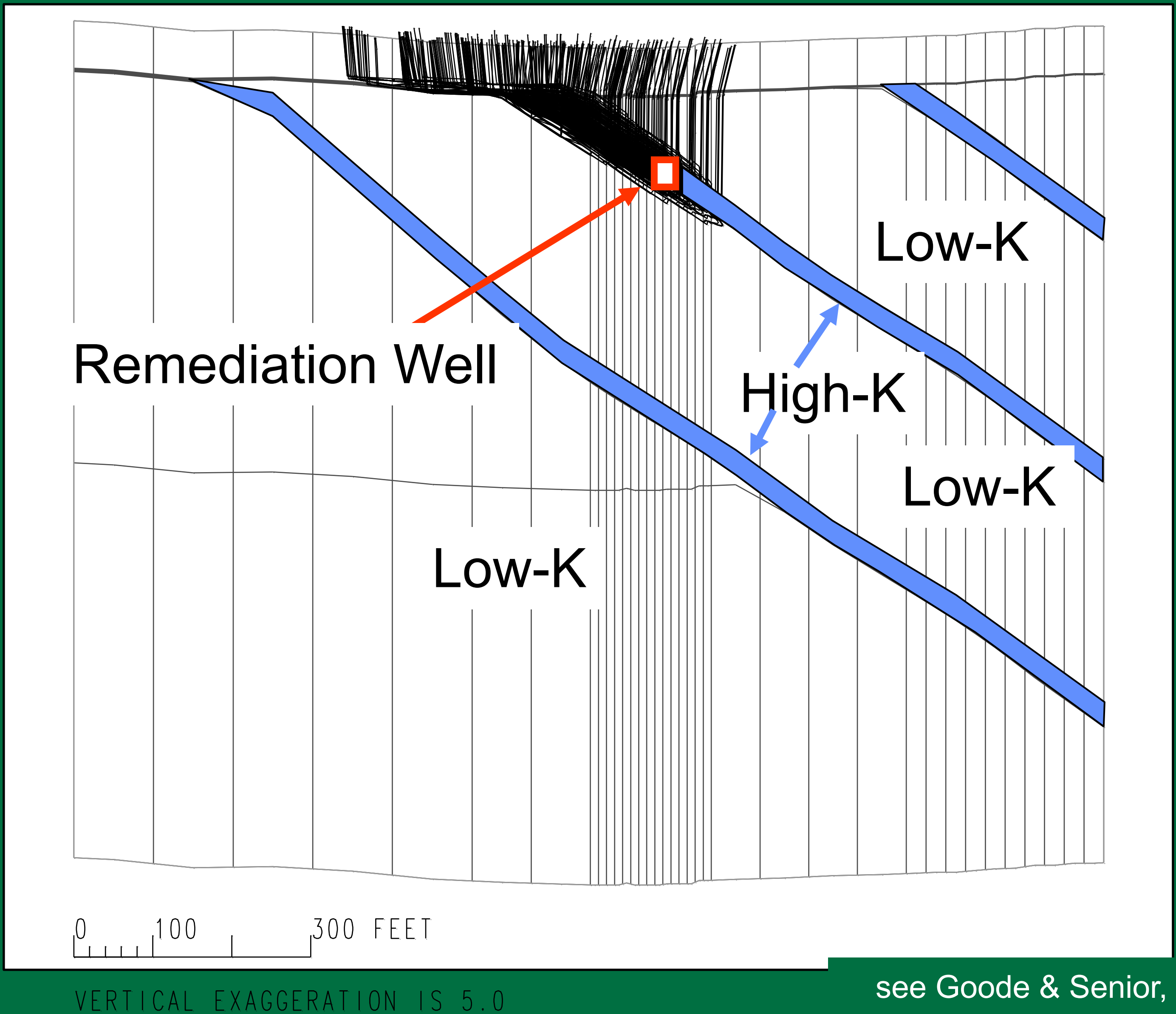
Well MG-202 (L-22)

USGS

from Senior and others (2005)

North Penn Area 6, Lansdale Pa (R3)

This information is preliminary or provisional and is subject to revision. It is being provided to meet the need for timely best science. The information has not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.



USGS

see Goode & Senior, 2000

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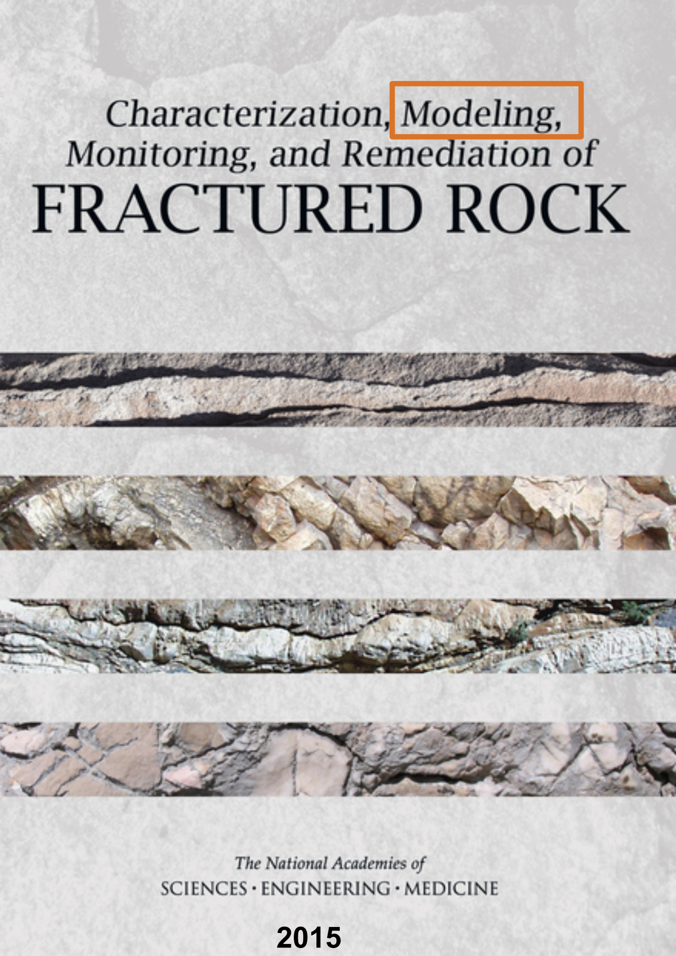


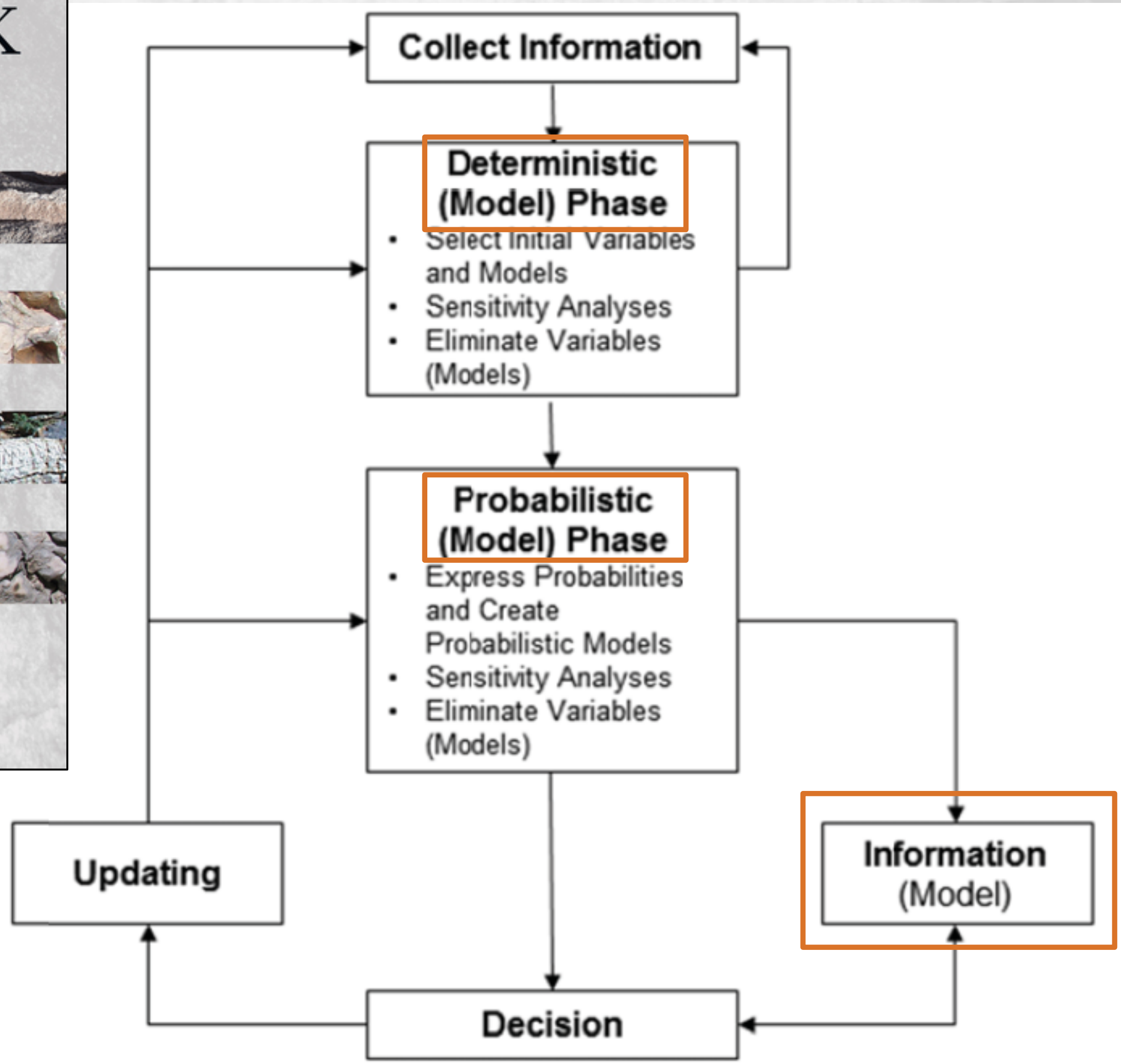
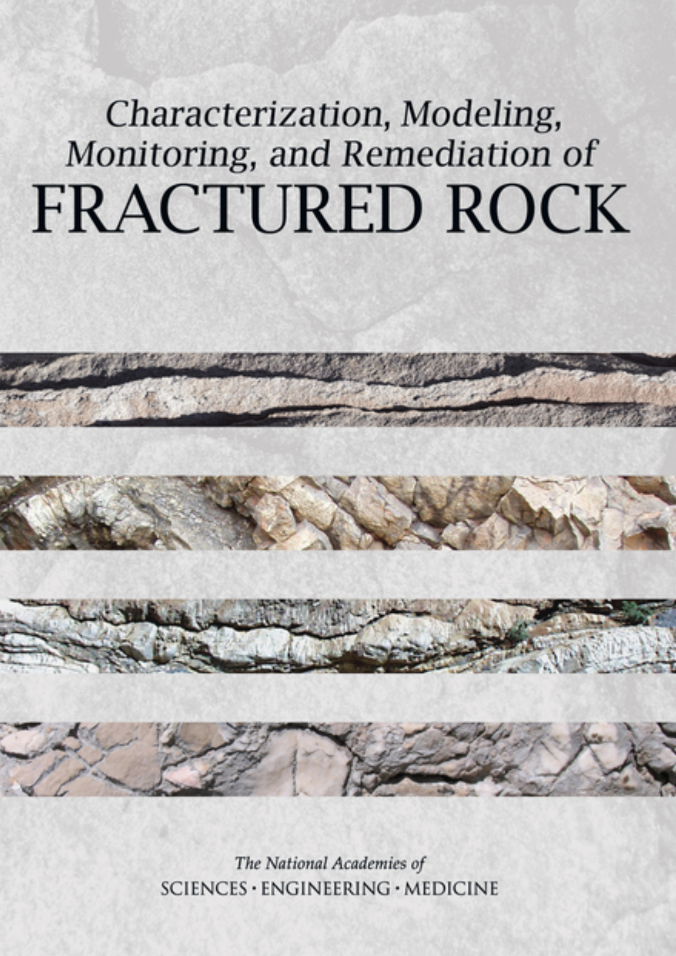


Figure 7.1 A decision analysis cycle for geotechnical engineering based on a business modeling approach. SOURCE: Modified from Einstein, 2002 after Staël von Holstein, 1974).



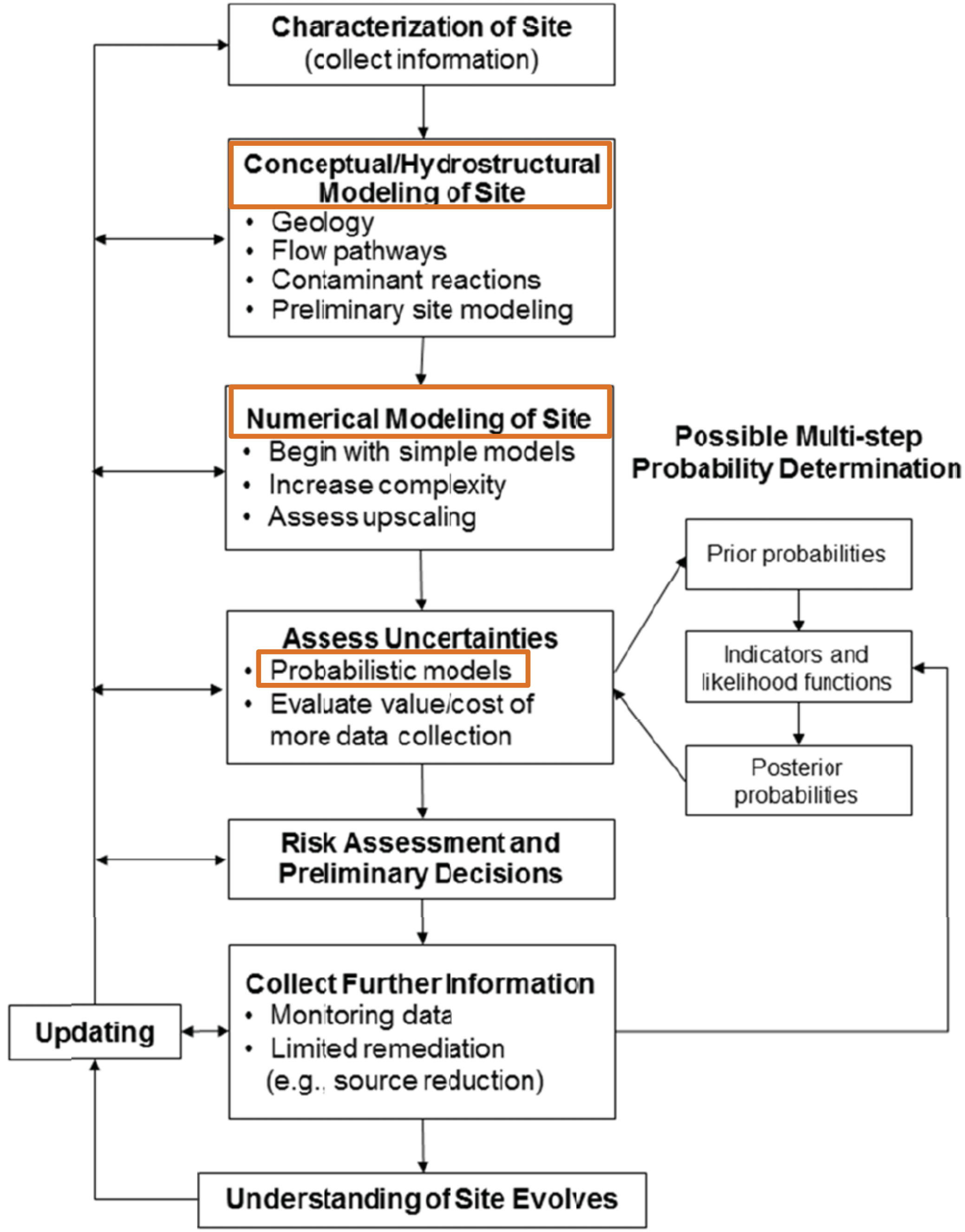


Figure 7.3 Adaptation of an observational approach to engineering at a fractured rock site.

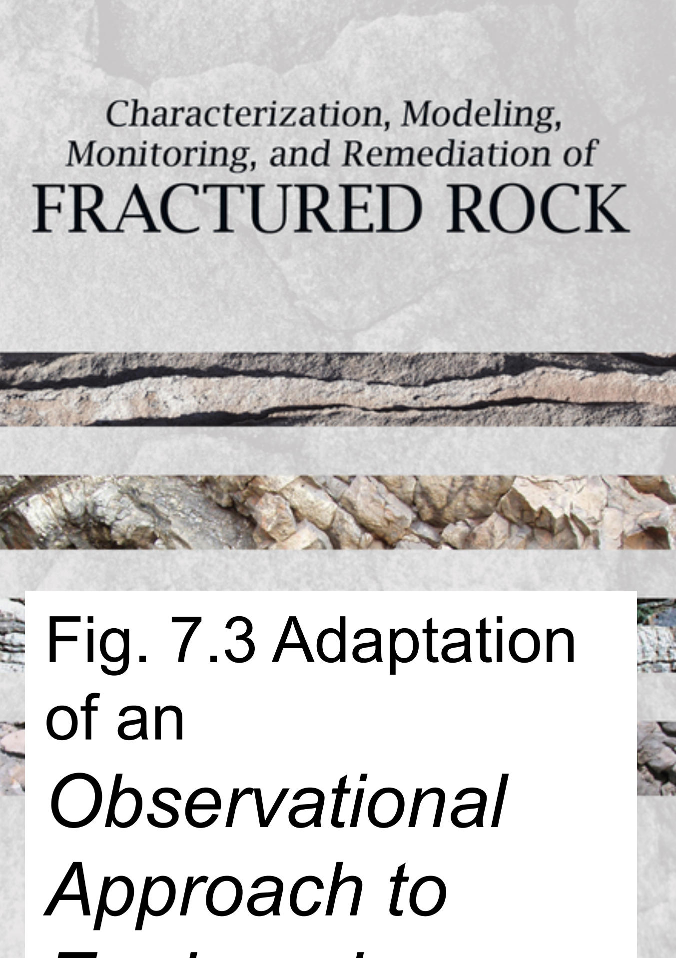


Fig. 7.3 Adaptation of an *Observational Approach to Engineering* at a Fractured Rock Site.

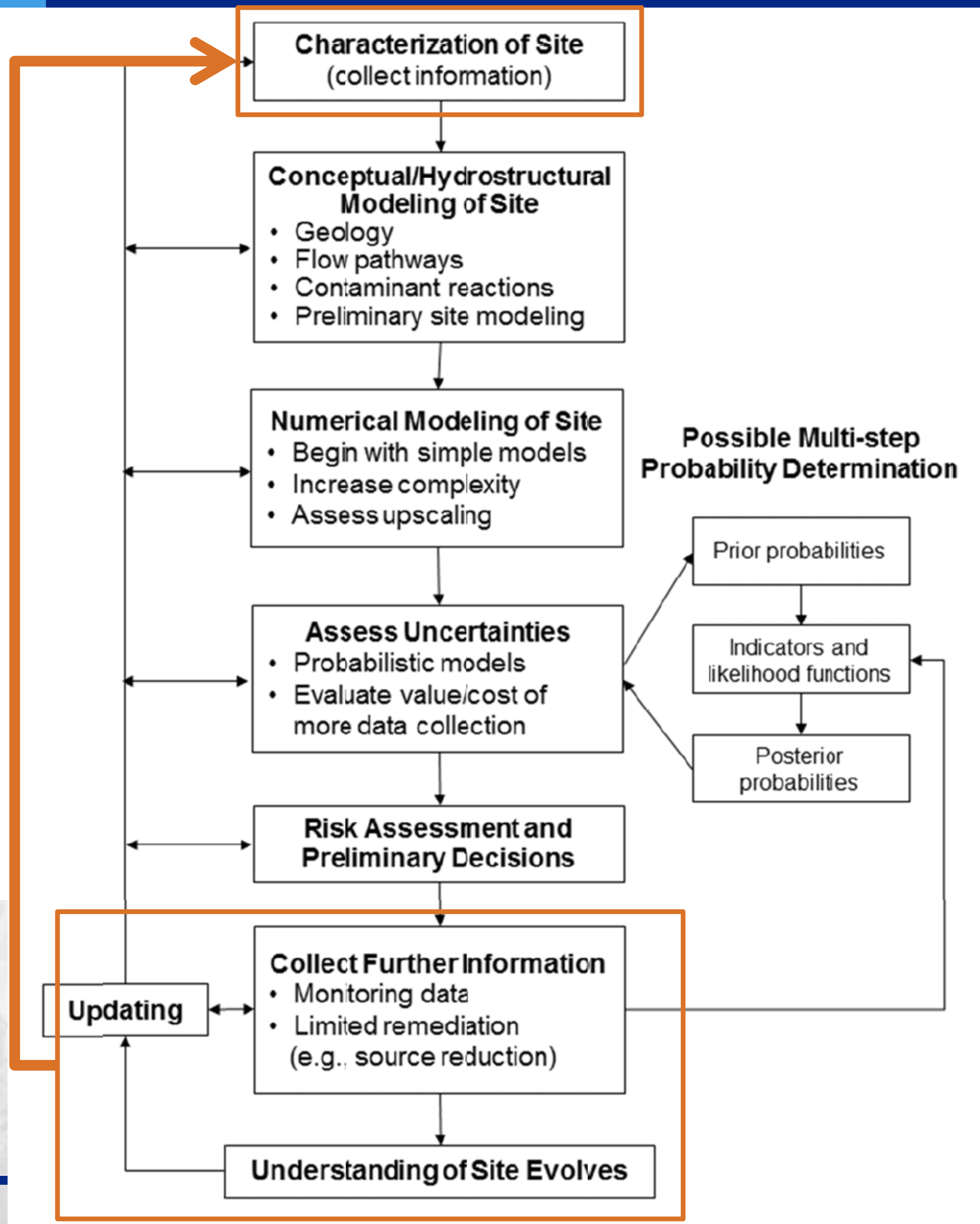


Figure 7.3 Adaptation of an observational approach to engineering at a fractured rock site.

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GW Technical Considerations during the Five-Year Review Process (EPA, 2015)

- “. . . analysis of the monitoring program may identify apparent monitoring gaps and indicate the need for a geospatial analysis of the monitoring well network.
- Some long-term monitoring optimization software packages include geospatial analysis modules for this purpose (EPA, 2005); however, such analyses do not take groundwater gradients into account and generally cannot identify when plumes are unbounded . . .”

GW Technical Considerations during the Five-Year Review Process (EPA, 2015)

Review Needs	Questions
Evaluate whether contaminant concentration data may indicate a need for remediation system evaluation (EPA, 2000) or LTMO*(EPA, 2005). *Long-Term Monitoring Optimization	• Is the groundwater remedy effective (and cost effective) • For a pump-and-treat remedy, has a capture zone analysis been conducted recently? • Do the data suggest that there may be a contaminant source that has not been controlled? • If contaminant levels have "tailed" and the plume is stable, could monitored natural attenuation (MNA) play a larger role in the groundwater remedy? • What are the life-cycle energy costs? • Could sampling frequencies be reduced without a significant loss in ability to track contaminant trends? • Are there any redundant monitoring wells?

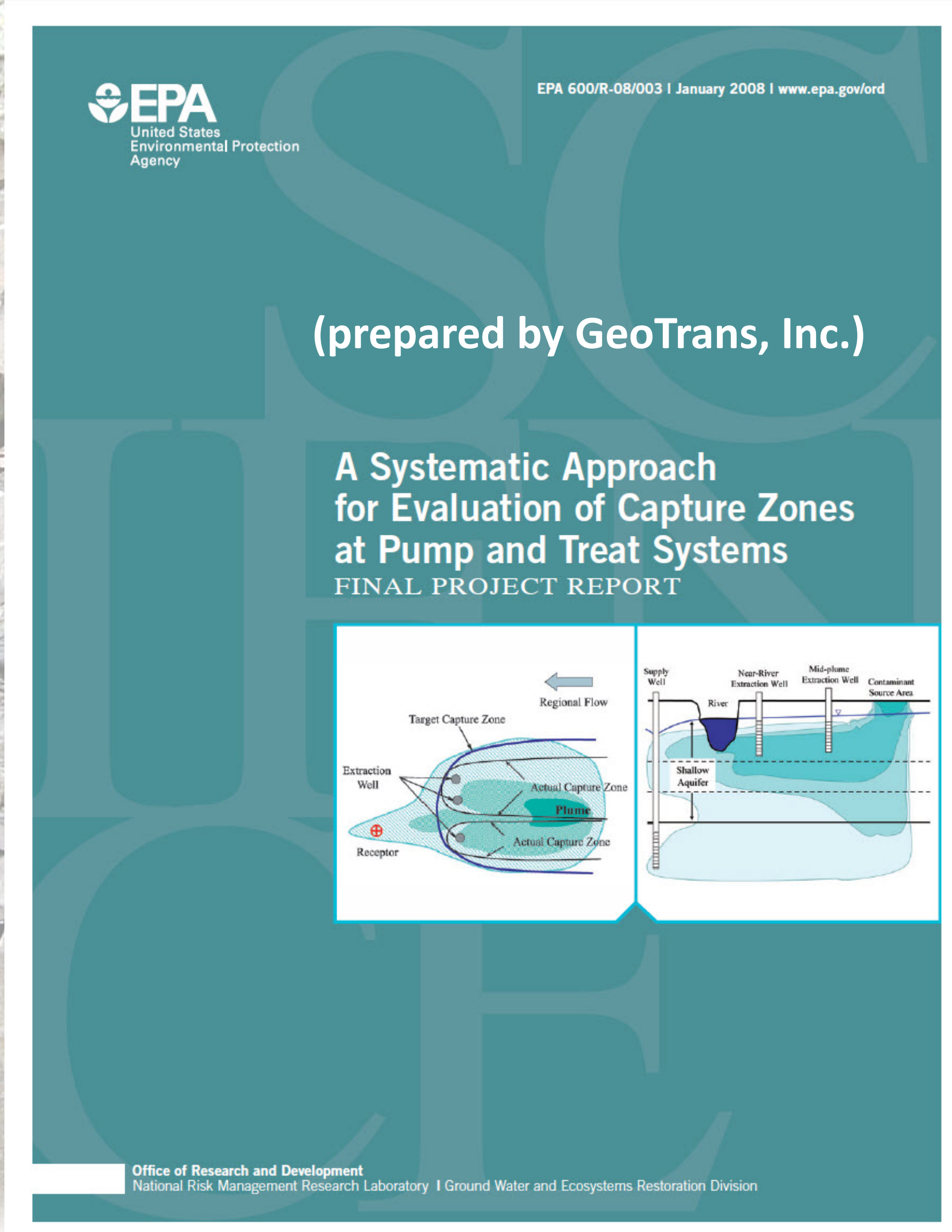
Capture Zone Guidance (EPA, 2008)

Explicitly limited to porous media:

"The scope . . . is limited to evaluating capture in porous media and not necessarily karst or fractured rock settings."

But (next sentence):

"The methods and techniques presented here may be used for such settings, but other more intensive techniques may also be required."



From: http://www.clu-in.org/conf/tio/capturezones_111308/prez/internet-seminar-draft-slide-091808ppt.ppt

Six Basic Steps for Capture Zone Analysis

- Step 1: Review site data, site conceptual model, and remedy objectives
- Step 2: Define site-specific Target Capture Zone(s)
- Step 3: Interpret water levels
  - Potentiometric surface maps (horizontal) and water level difference maps (vertical)
  - Water level pairs (gradient control points)
- Step 4: Perform calculations (as appropriate based on site complexity)
  - Estimated flow rate calculation
  - Capture zone width calculation (can include drawdown calculation)
  - Modeling (analytical and/or numerical) to simulate water levels, in conjunction with particle tracking and/or transport modeling
- Step 5: Evaluate concentration trends
- Step 6: Interpret actual capture based on steps 1-5, compare to Target Capture Zone(s), and assess uncertainties and data gaps

"Converging lines of evidence" increases confidence in the conclusions

Application to Fractured Rock

"The methods and techniques presented here may be used for such settings, but other more intensive techniques may also be required."

"Some of the simple techniques in this guidance are not adequate for hydrogeologically complex settings, such as fractured rock."

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Capture Zones in Fractured Rock Aquifers:

Evaluating Water Levels

Geology still matters . . . water levels interpreted in concert with site conceptual model . . .three-dimensional interpretations . . .

Monitoring devices filter aquifer responses . . . open holes as conduits between high-K fractures . . . large casing volume relative to fracture porosity . . .

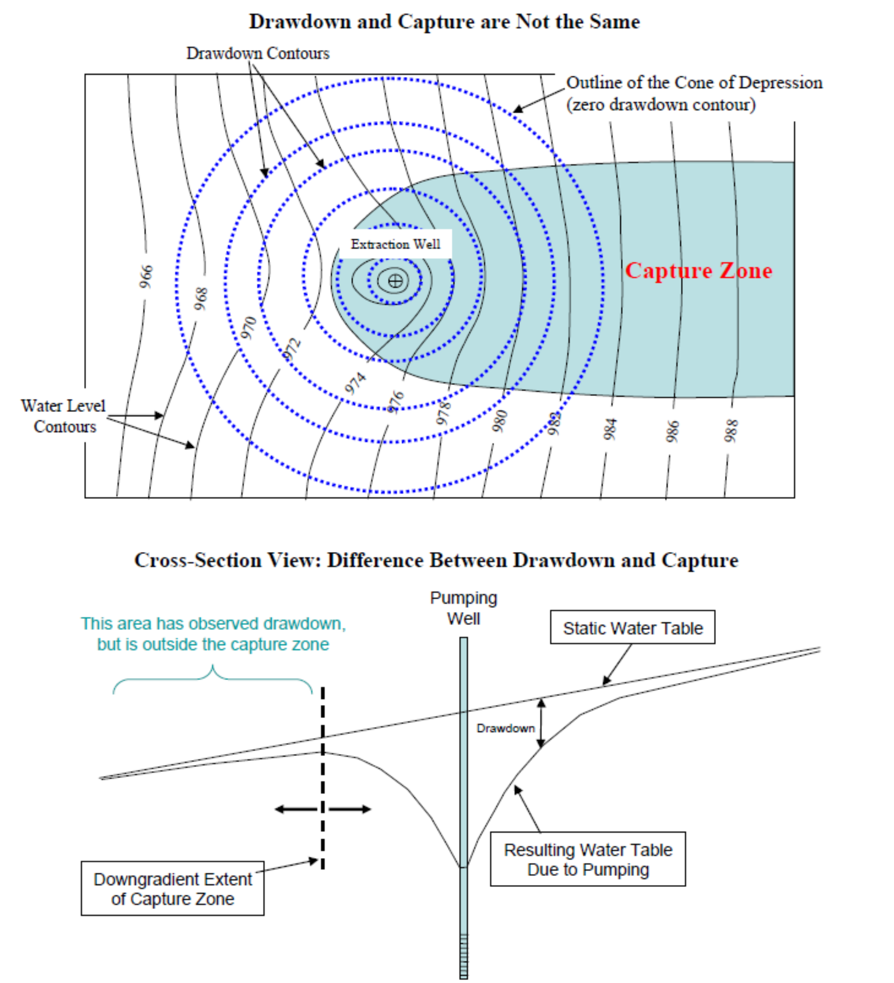
Transient responses . . . fractured rock aquifers have low storativity, respond rapidly to hydraulic and geochemical changes . . .

Fluxes . . . contouring water levels vs. modeling of water levels . . .

Water Levels – Filling the Space

Contours

- Software available
- Usually 2D only
- Steady state
- Interpolation using functions
- Vectors & fluxes assume isotropic homogeneous 2D "academic aquifer"
- Easy
- Hydrogeologist judgment by hand, or virtual points



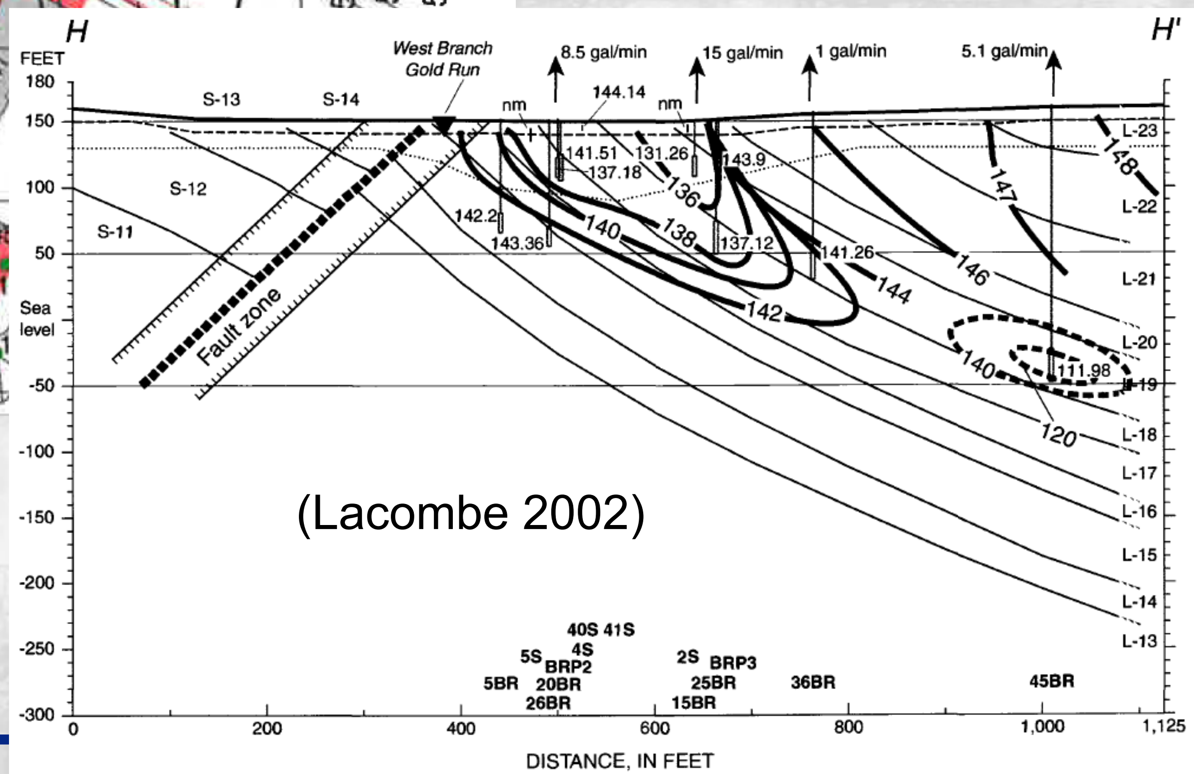
Drawdown is the change of water level due to pumping. It is calculated by subtracting water level under pumping conditions from the water level without pumping.

Cone of Depression is the region where drawdown due to pumping is observed.

Capture Zone is the region that contributes the ground water extracted by the extraction well(s). It is a function of the drawdown due to pumping and the background (i.e., without remedy pumping) hydraulic gradient. The capture zone will only coincide with the cone of depression if there is zero background hydraulic gradient.

Figure 6. Drawdown and capture are not the same.

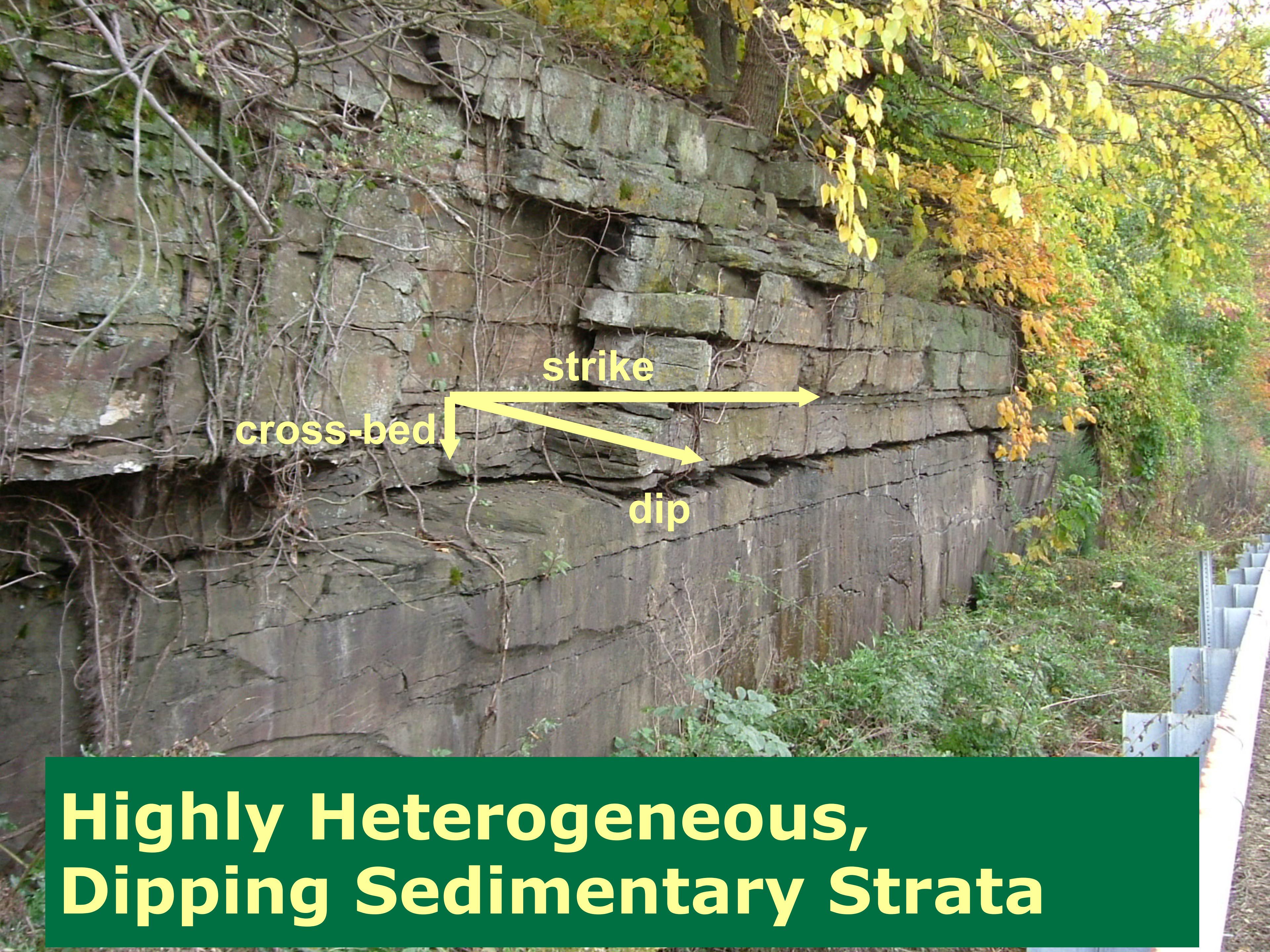
Figure 4. The stressed potentiometric surface at an altitude of + 150 feet (approximately land surface), May 18, 2000, Naval Air Warfare Center, West Trenton, N.J.



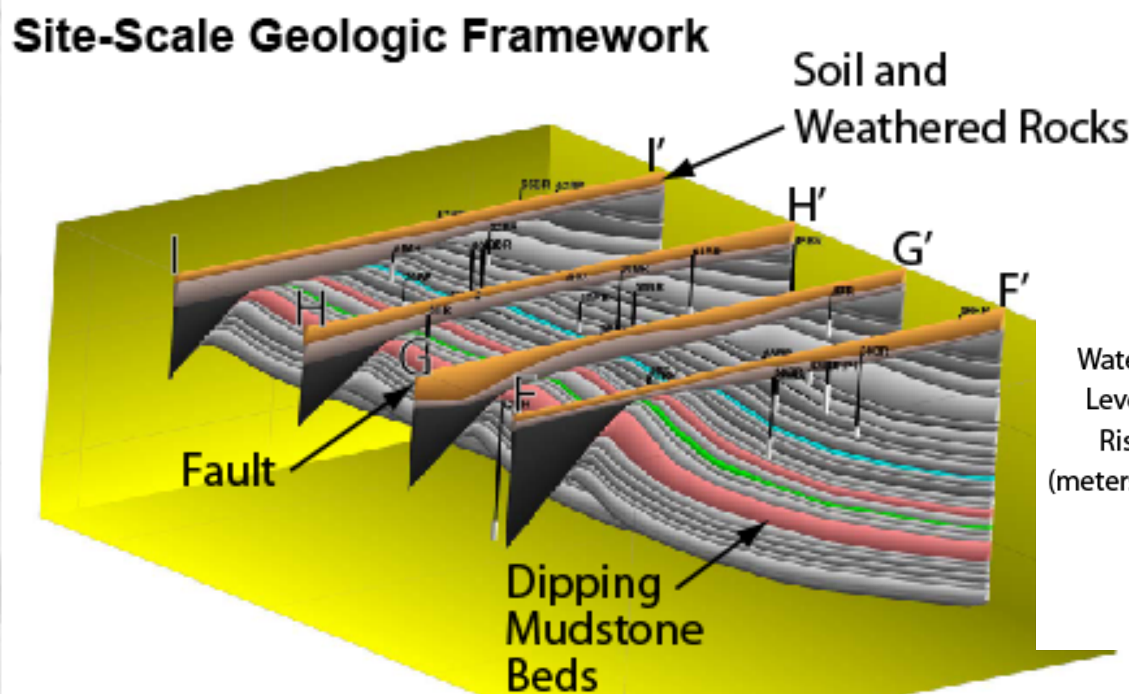
(Lacombe 2002)

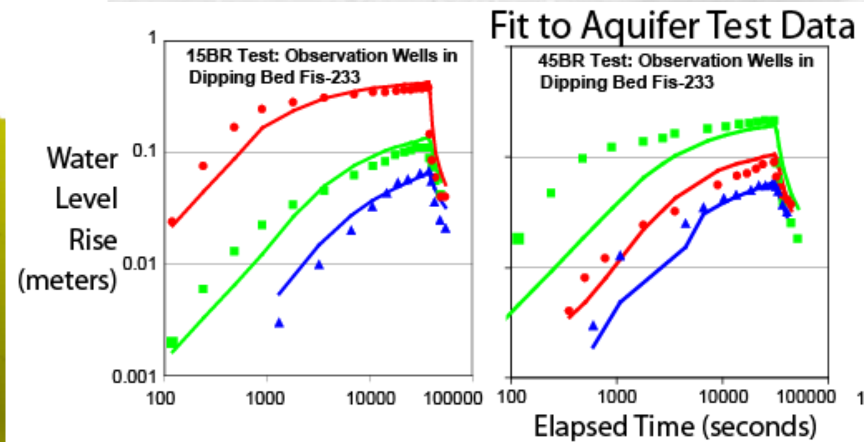
Figure 6h. Stressed water-level altitudes and potentiometric surface along section *H-H'*, May 18, 2000, Naval Air Warfare Center, West Trenton, N.J.

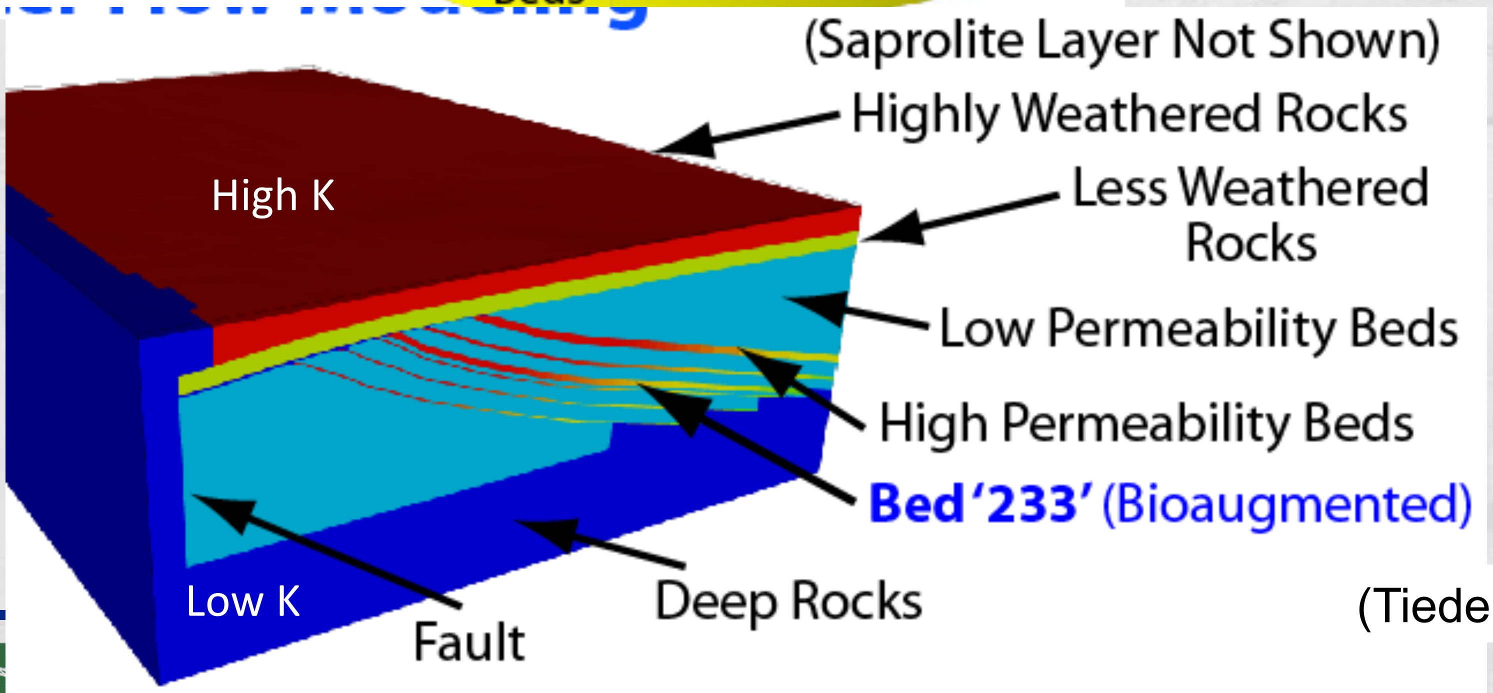
USGS

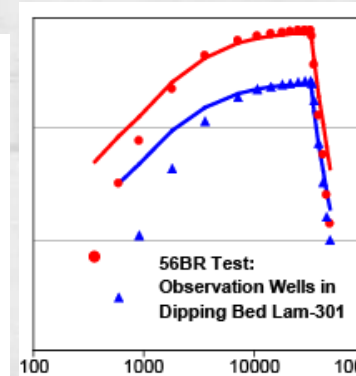

strike
cross-bed
dip
Highly Heterogeneous,
Dipping Sedimentary Strata

2018 Field Conference of Pennsylvania Geologists

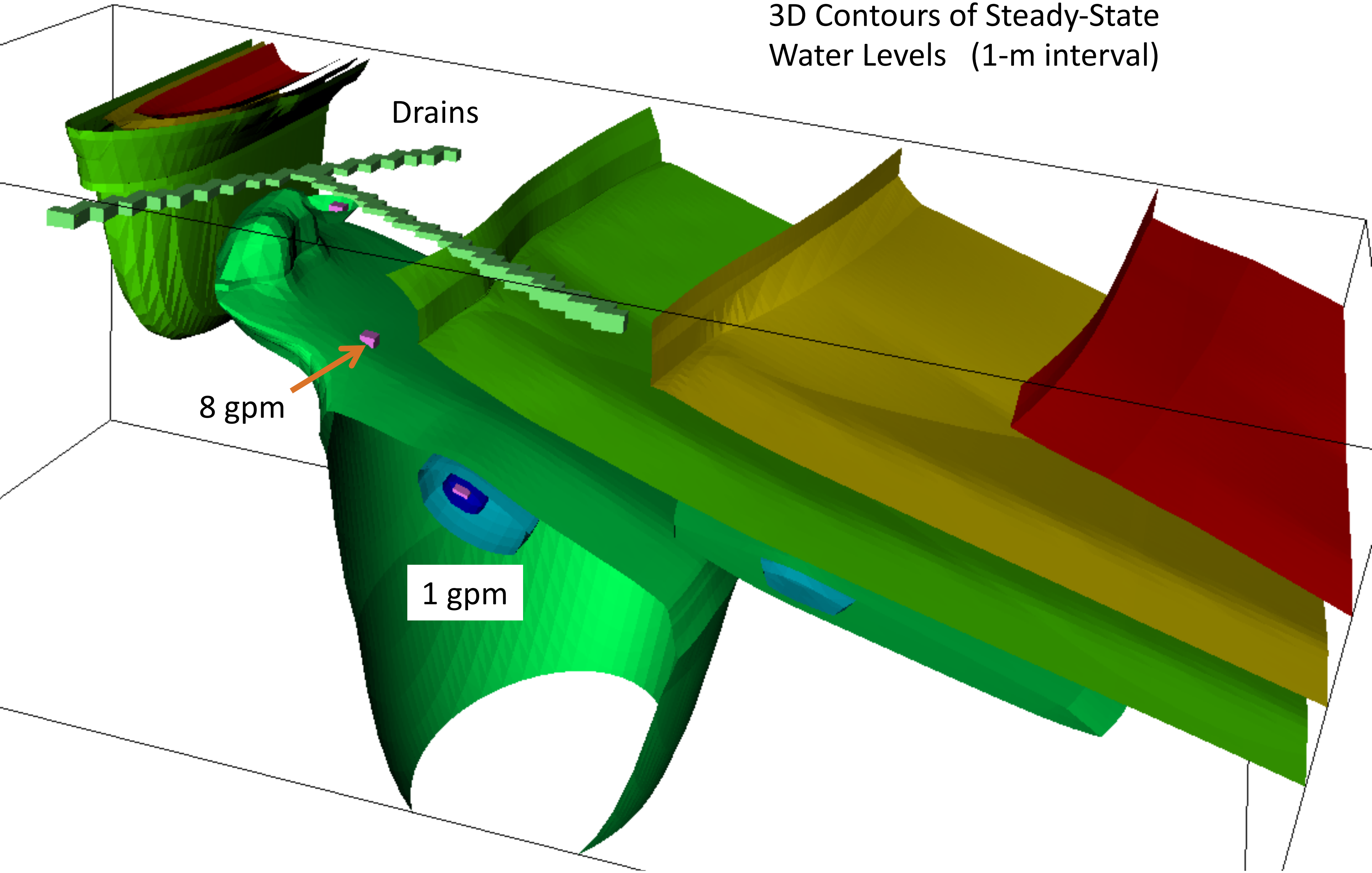




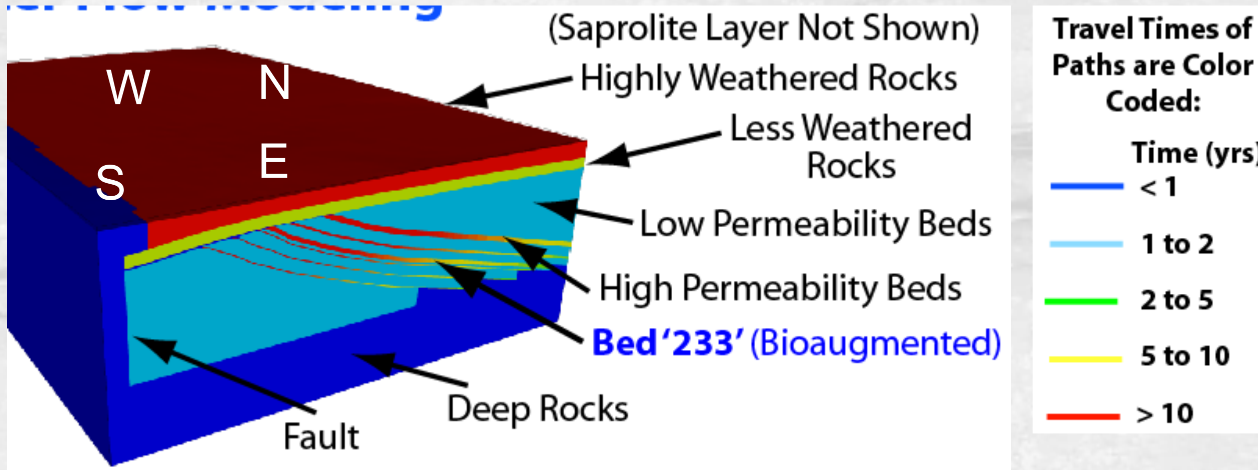


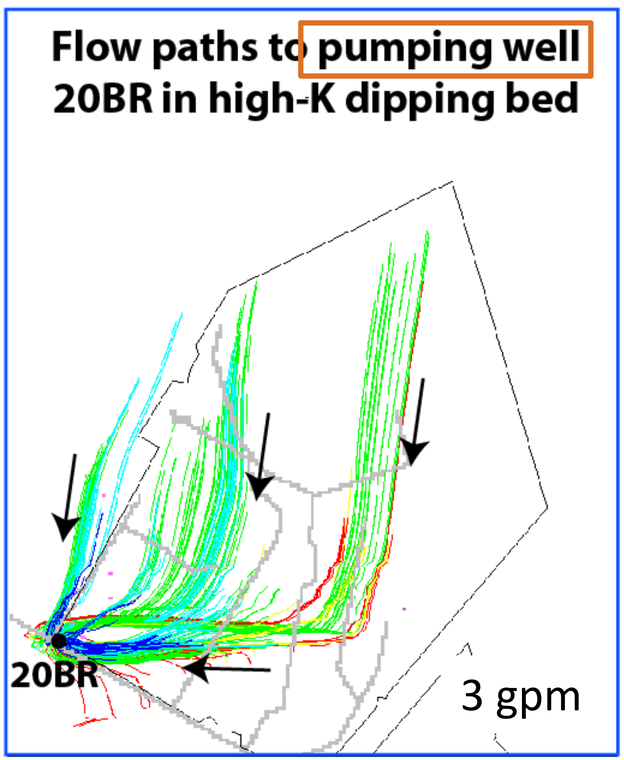


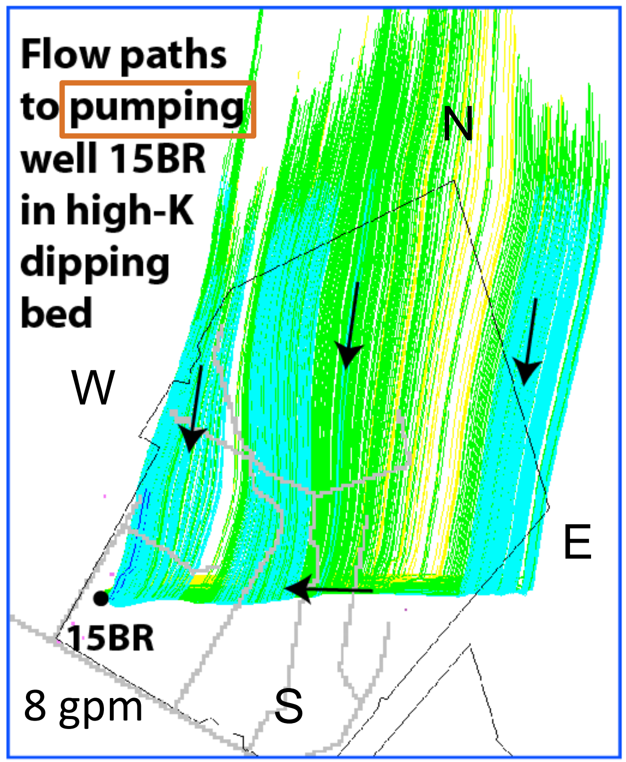
(Tiedeman and others 20

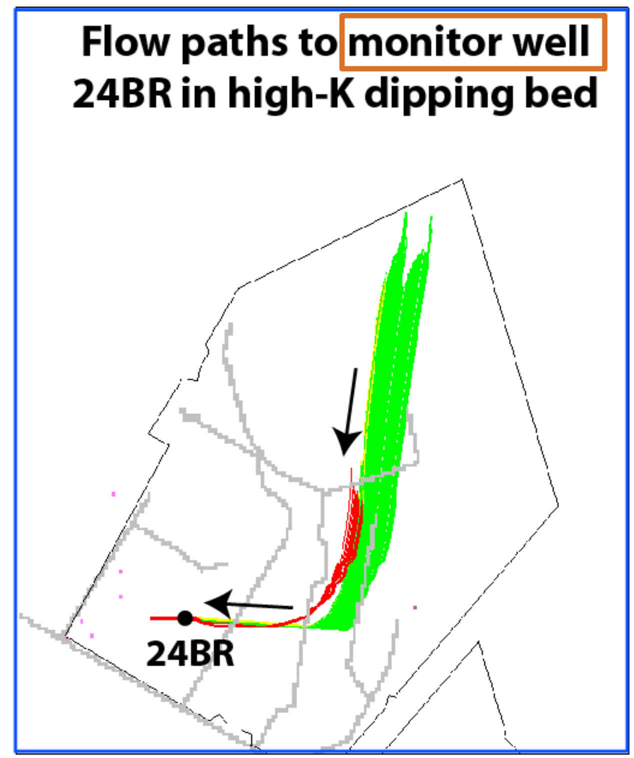

3D Contours of Steady-State
Water Levels (1-m interval)
Drains
8 gpm
1 gpm

Recharge Flow Paths to Pumping and Monitoring Wells









Water Levels – Filling the Space

Contours

- Software available
- Usually 2D only
- Steady state
- Interpolation using functions
- Vectors & fluxes assume isotropic homogeneous 2D "academic aquifer"
- Easy
- Hydrogeologist judgment by hand, or virtual points

Groundwater-Flow Model

- Software available
- 2 or 3D
- Steady or Transient
- Solve groundwater flow equation
- Vectors & fluxes based on properties, recharge, sinks / sources, mass conservation
- Effort depends on complexity of model, simple model is easy
- Explicit Hydrogeologist judgment

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EPA Region 3, Superfund

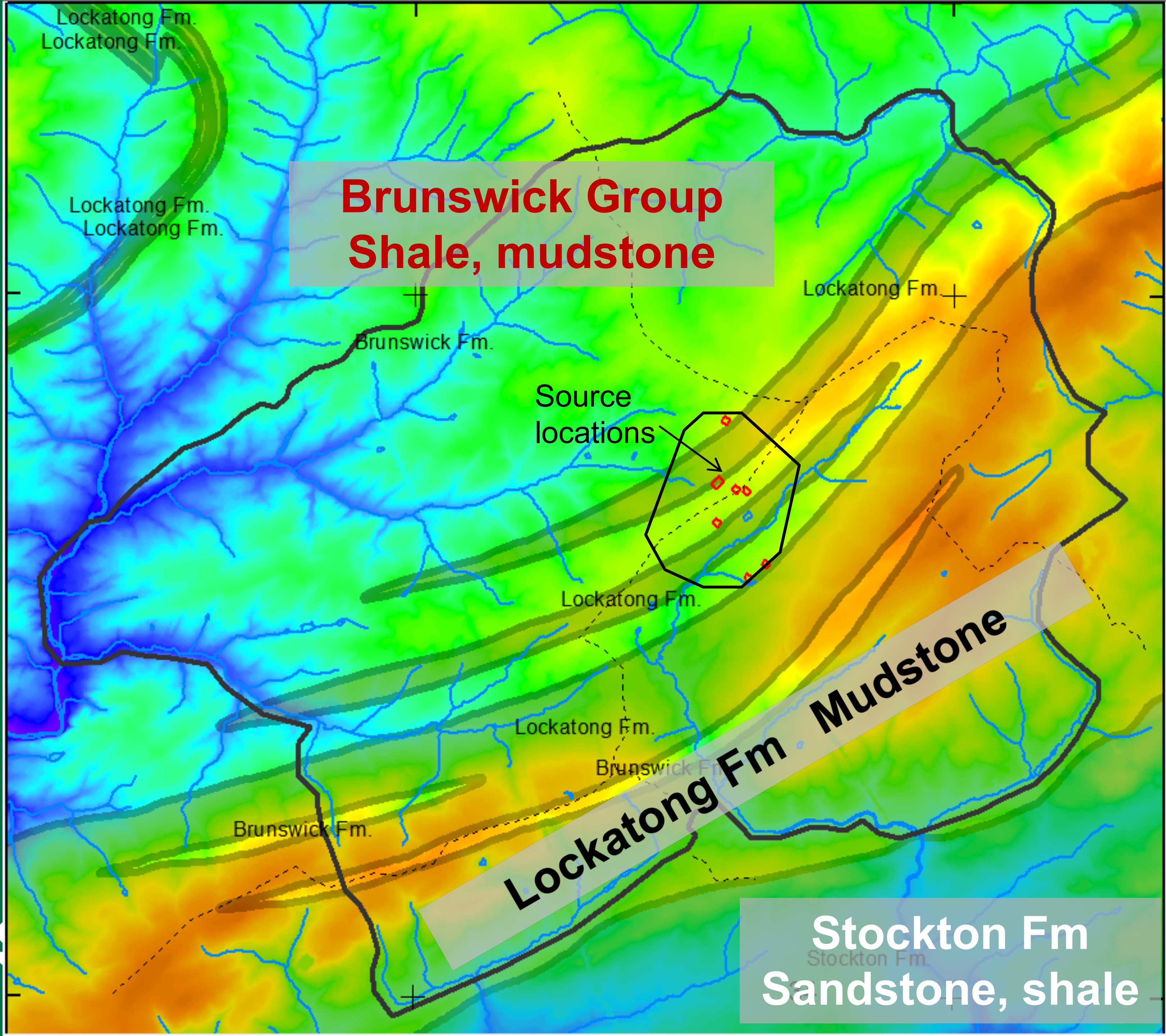
North Penn 7
Groundwater Model Update

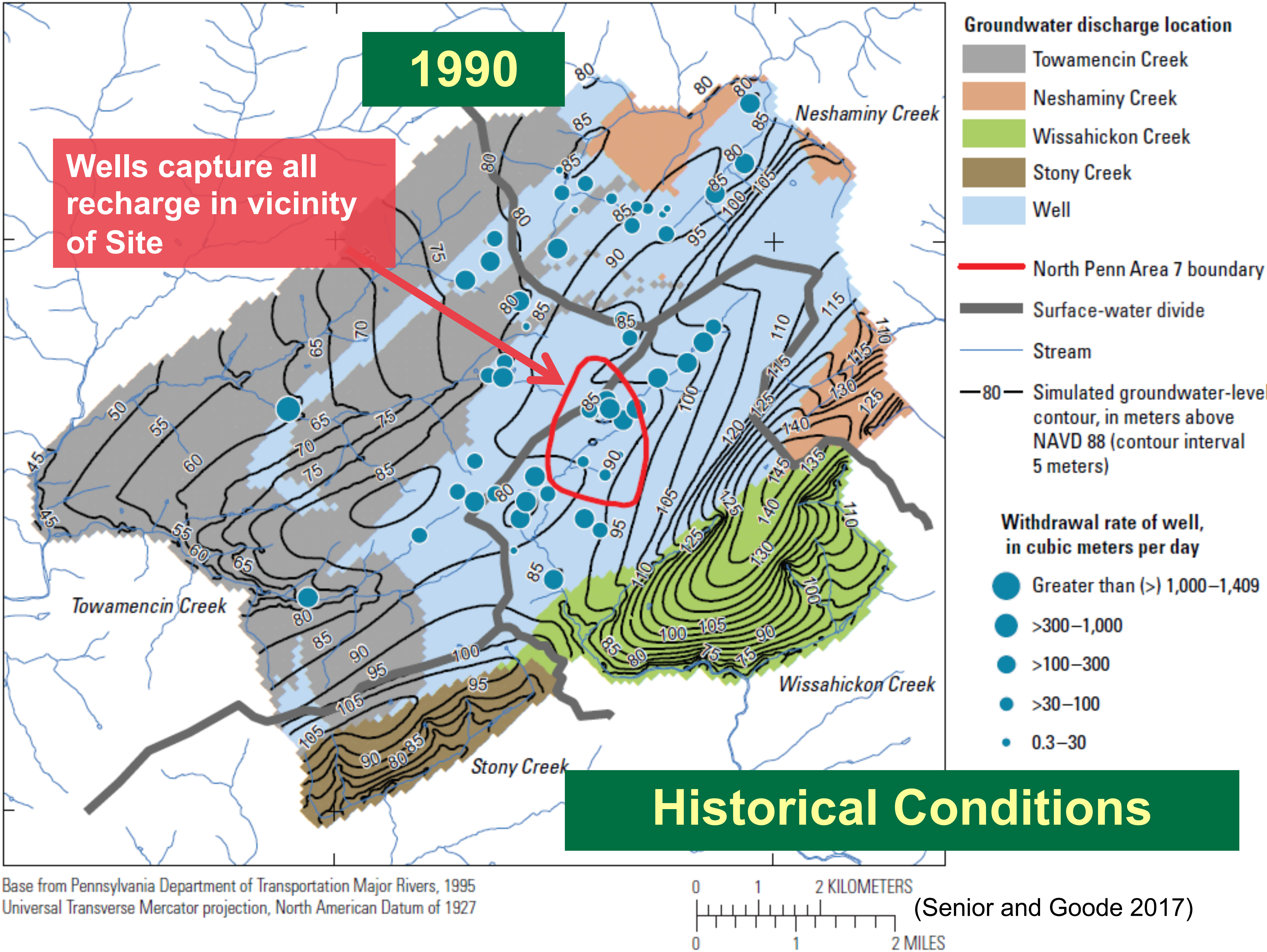
Lisa A. Senior
Daniel J. Goode

Philadelphia
7 March 2014

U.S. Department of the Interior
U.S. Geological Survey

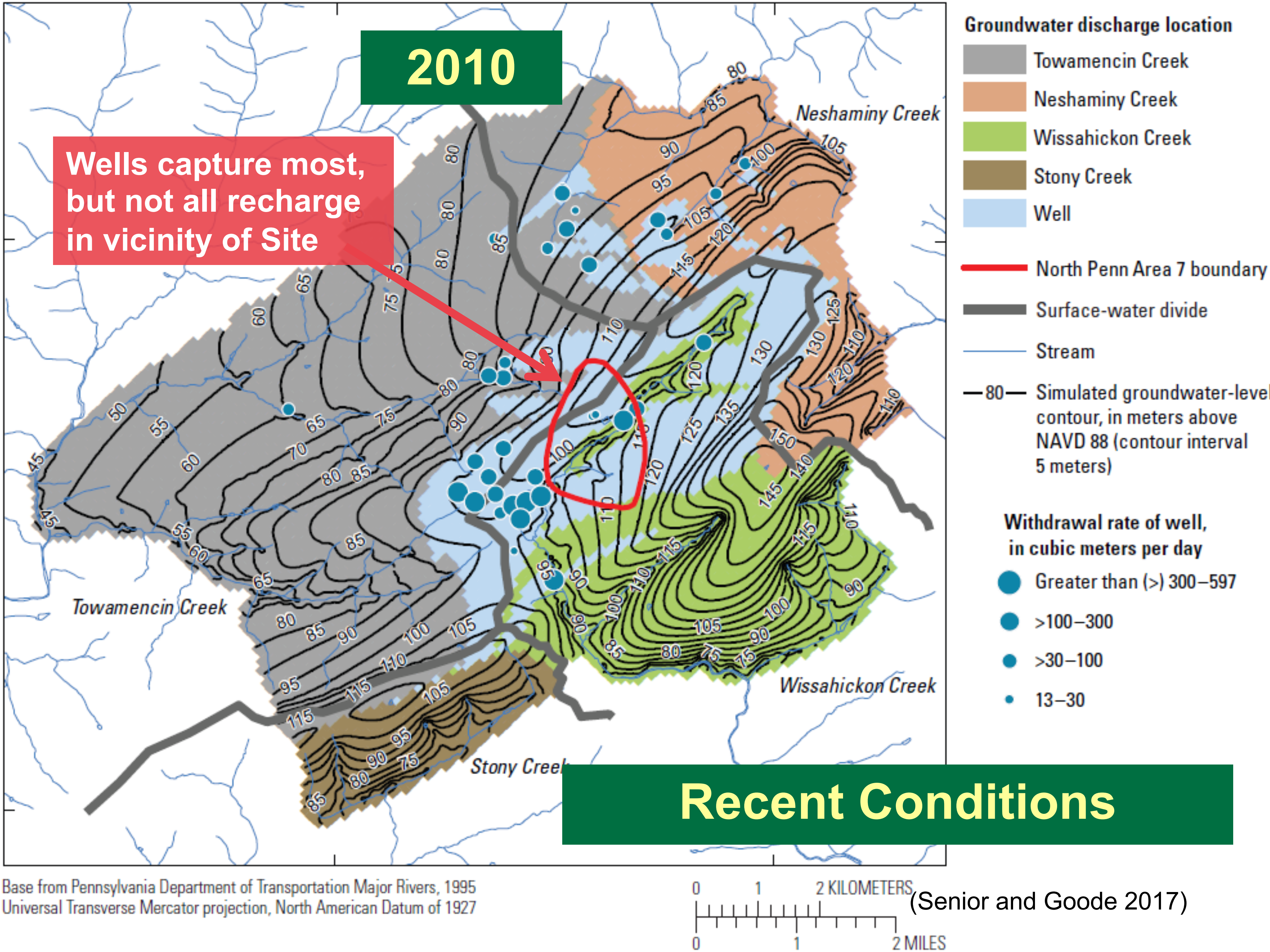
(Senior and Goode 2013, 2017)


Brunswick Group
Shale, mudstone
Source
locations
Lockatong Fm Mudstone
Stockton Fm
Sandstone, shale
Lockatong Fm.
Lockatong Fm.
Lockatong Fm.
Lockatong Fm.
Lockatong Fm.
Brunswick Fm.
Lockatong Fm.
Lockatong Fm.
Brunswick Fm.
Stockton Fm.

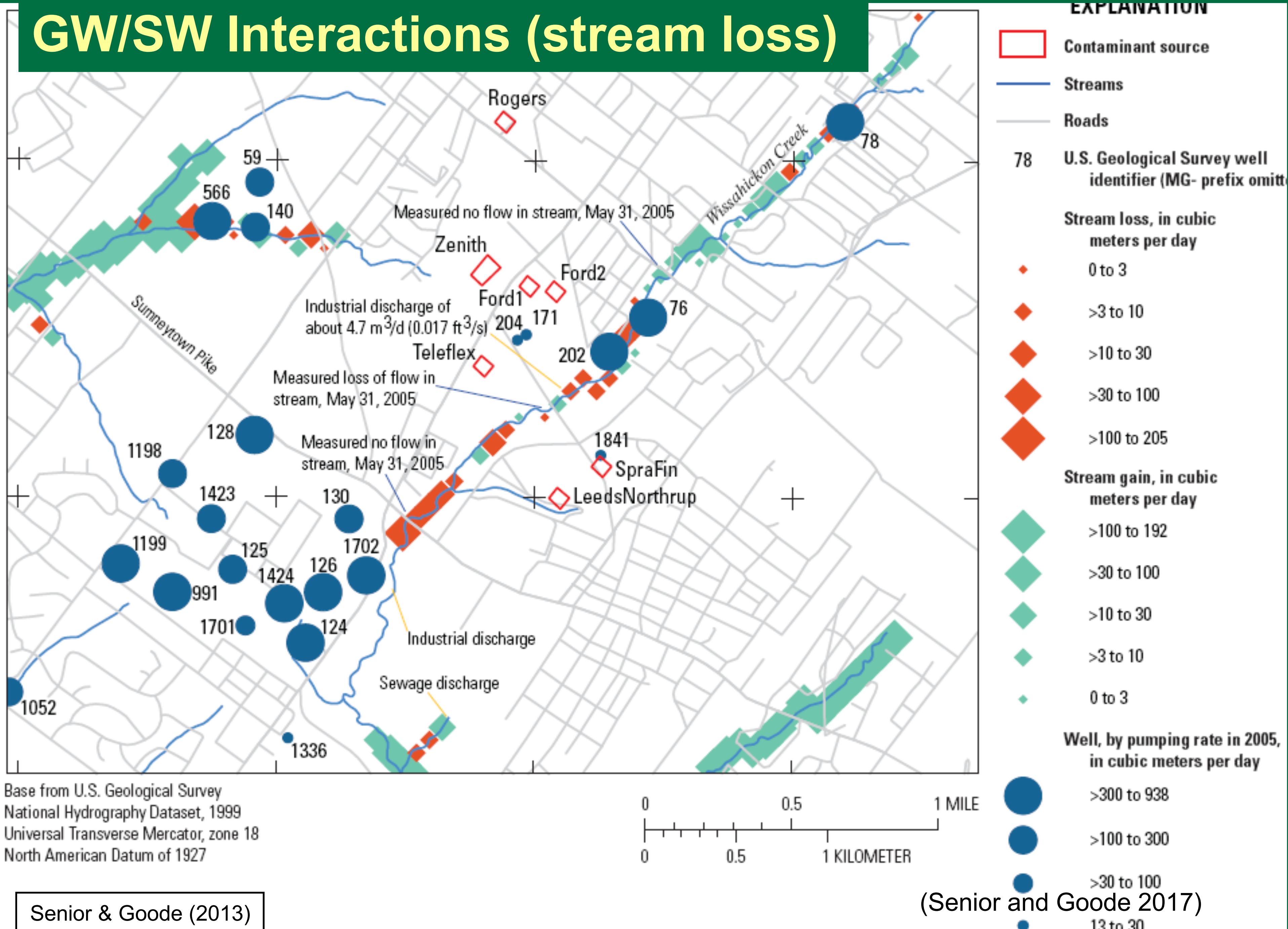


Base from Pennsylvania Department of Transportation Major Rivers, 1995
Universal Transverse Mercator projection, North American Datum of 1927

(Senior and Goode 2017)

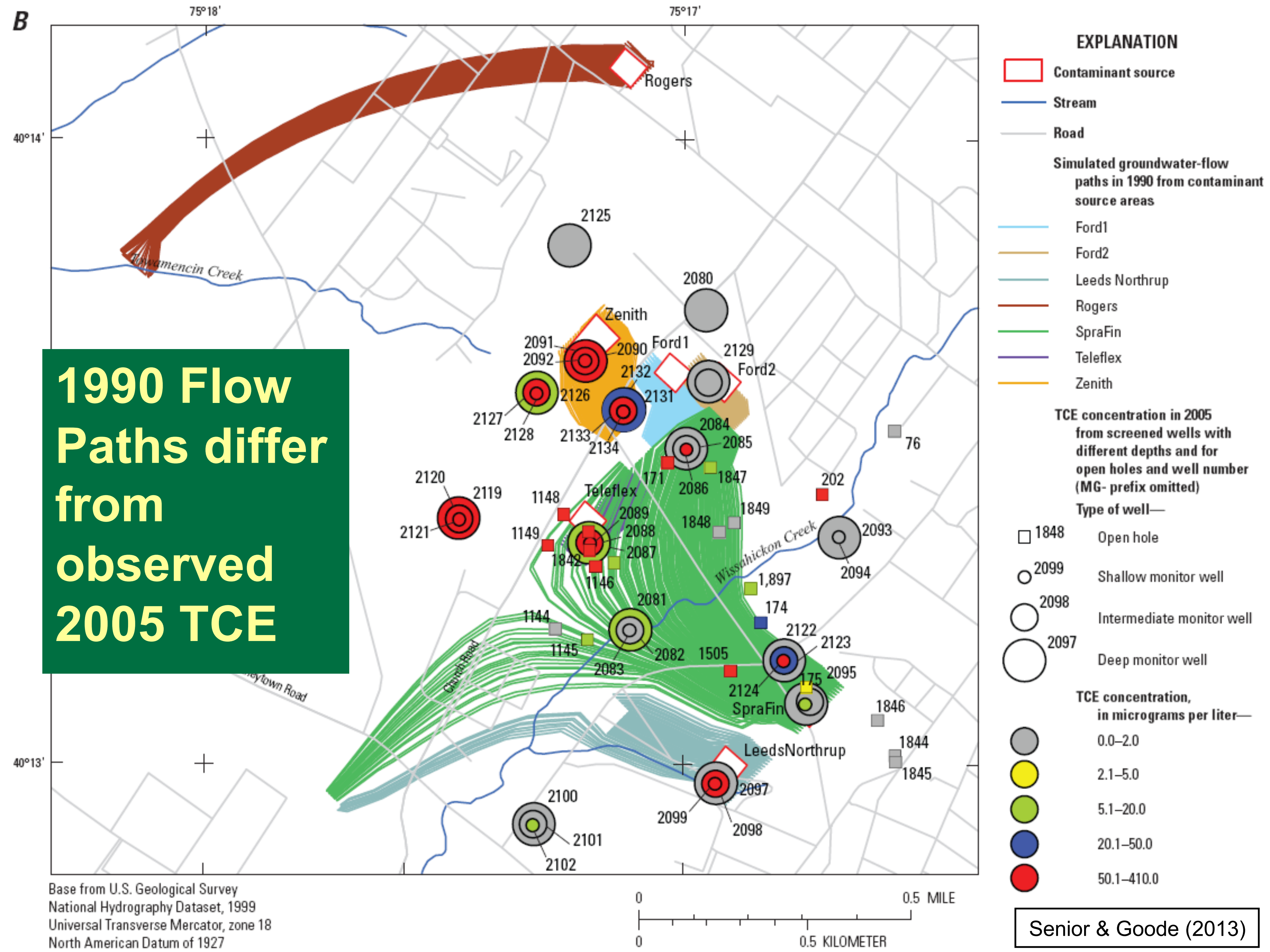

2010
Wells capture most, but not all recharge in vicinity of Site
Neshaminy Creek
Towamencin Creek
Stony Creek
Wissahickon Creek
Recent Conditions
Groundwater discharge location
Towamencin Creek
Neshaminy Creek
Wissahickon Creek
Stony Creek
Well
North Penn Area 7 boundary
Surface-water divide
Stream
—80— Simulated groundwater-level contour, in meters above NAVD 88 (contour interval 5 meters)
Withdrawal rate of well, in cubic meters per day
Greater than (>) 300–597
>100–300
>30–100
13–30
Base from Pennsylvania Department of Transportation Major Rivers, 1995
Universal Transverse Mercator projection, North American Datum of 1927
0 1 2 KILOMETERS
0 1 2 MILES
(Senior and Goode 2017)

GW/SW Interactions (stream loss)



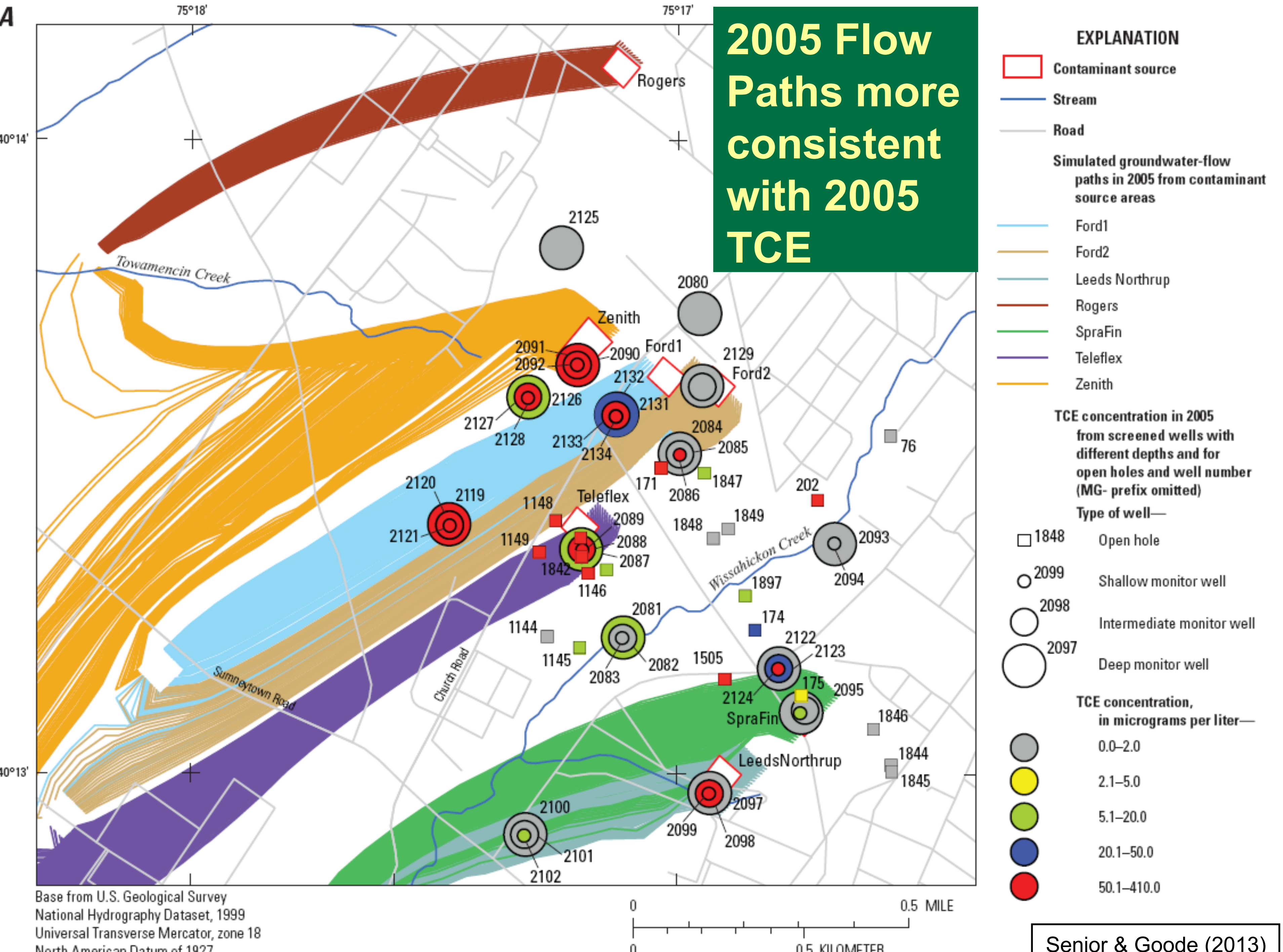
(Senior and Goode 2017)

Senior & Goode (2013)

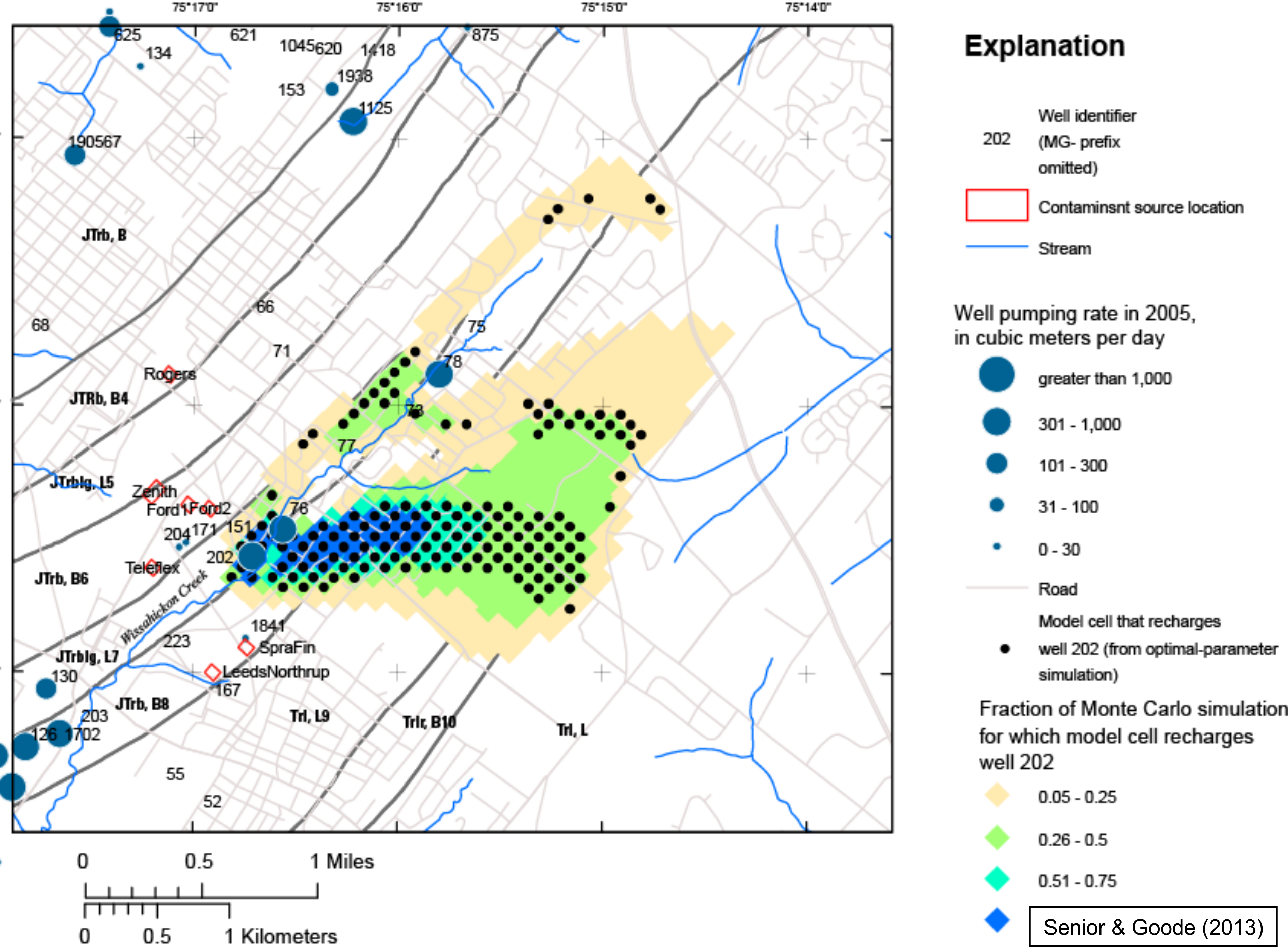


1990 Flow Paths differ from observed 2005 TCE
B
75°18′
75°17′
40°14′
40°13′
Rogers
Towamencin Creek
2125
2080
Zenith
2091
2092
2090
Ford1
2129
Ford2
2132
2126
2131
2127
2128
2133
2134
2084
2085
2120
2119
2121
1148
Teleflex
171
2086
1847
202
2089
2088
2087
1149
1842
1146
1848
1849
2093
2094
Wissahickon Creek
1,897
174
76
2081
1144
1145
2082
2083
1505
2122
2123
2124
175
2095
SpraFin
1846
Church Road
Sumneytown Road
LeedsNorthrup
1844
1845
2097
2099
2098
2100
2101
2102
Base from U.S. Geological Survey
National Hydrography Dataset, 1999
Universal Transverse Mercator, zone 18
North American Datum of 1927
0
0.5 MILE
0
0.5 KILOMETER
EXPLANATION
Contaminant source
Stream
Road
Simulated groundwater-flow paths in 1990 from contaminant source areas
Ford1
Ford2
Leeds Northrup
Rogers
SpraFin
Teleflex
Zenith
TCE concentration in 2005 from screened wells with different depths and for open holes and well number (MG- prefix omitted)
Type of well—
1848 Open hole
2099 Shallow monitor well
2098 Intermediate monitor well
2097 Deep monitor well
TCE concentration, in micrograms per liter—
0.0–2.0
2.1–5.0
5.1–20.0
20.1–50.0
50.1–410.0
Senior & Goode (2013)

2005 Flow Paths more consistent with 2005 TCE



Senior & Goode (2013)



Senior & Goode (2013)

Modeling Wrap Up

- A Systematic Process to Extract and Organize Information from Data – Models are Tools
- Modeling Complexity (Cost) Depends on Site (SCM) Complexity, and Decision-Making Needs (including Risk)
- Flow Paths in Fractured Rock are Complex!
  - Water-Level Data Interpreted via SCM
  - Physics-Based, Account for Heterogeneity, Regional Flow, Nearby Wells, Transients, etc.
- Explicit, Transparent, Evolving

Practical Modeling Discussion (as time allows)

- Reviewing models
  - "Guidelines for Evaluating Ground-Water Flow Models" (Reilly and Harbaugh, 2004)
  - Are the important features of the SCM included?
  - Particular software less important (MODFLOW vs. SUTRA vs. FracMan)
  - Focus on assumptions, structure and parameters used, and how model is tested versus data (calibration)
  - Boundary conditions! Common sense! Use your Hydro's!
- Limitations
- Costs

Stop here.

Following slides included in handouts

Toxic Substances Hydrology Program
New Jersey Water Science Center
Hydrologic Research & Development Program
Office of Ground Water

Naval Facilities Engineering Command

Office of Superfund Remediation and Technology Innovation

Region 3 Superfund

References

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