Recognizing Critical Processes and Scales in Conceptual Site Models for Decision Support at Sites of Groundwater Contamination

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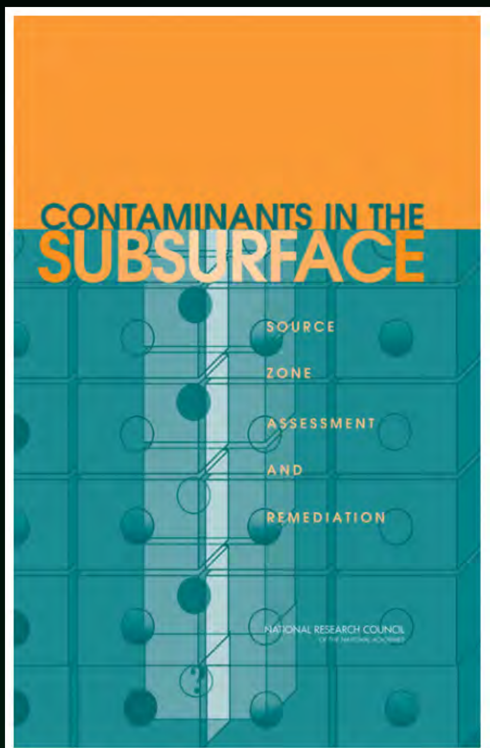
Management Decisions at Sites of Groundwater Contamination

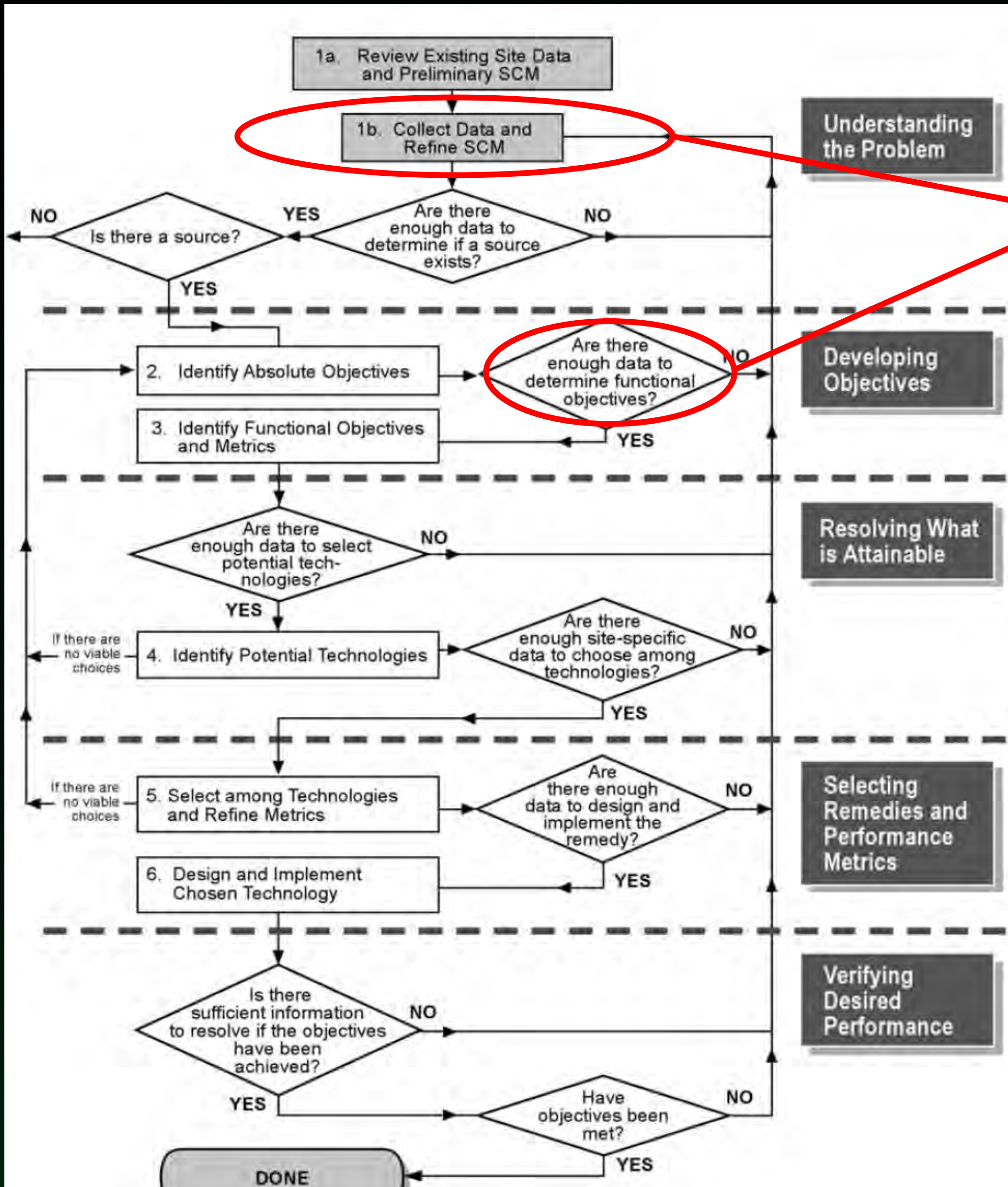
- What motivates the development of a Conceptual Site Model (*CSM*) ?



Absolute Objectives: Higher order community and societal (stakeholder) requirements (e.g., mitigate human and ecological adverse health effects, minimize disturbances to community, adherence to drinking water standards, etc.)

Functional Objectives: Operational goals that lead to successful achievement of absolute objectives (e.g., prevent off-site migration, source zone reduction/removal, reduction of concentrations to MCLs, etc.)

National Research Council, 2005, https://doi.org/10.17226/11146



SCM = Site Conceptual Model

Functional objectives are the driving force for establishing & refining a Conceptual Site Model (*CSM*) and data collection to implement functional objectives. . .

. . .data requirements and detail in the *CSM* will vary depending on the defintion of the *functional objectives*. . .

Six-Step Process for Source Remediation

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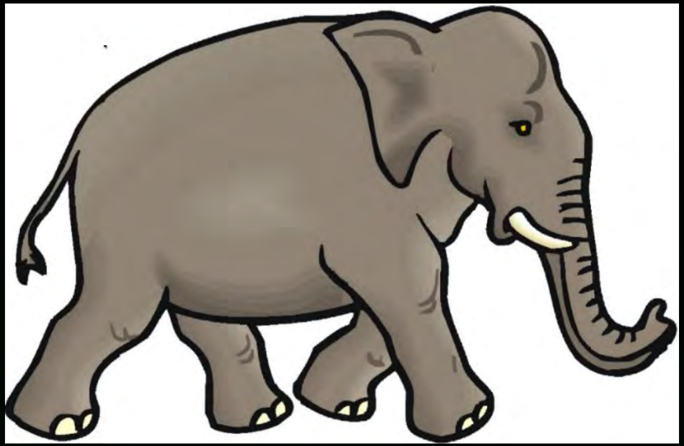
National Research Council, 2005

Functional objectives are like an elephant . . .
they can appear to be large and cumbersome. . .



. . . require conceptualizing operational, physical, hydrogeologic, and biogeochemical processes over multiple spatial and temporal scales. . .

For example: *Functional objective: Mitigating off-site contaminant migration*

- Source zone characterization. . .source zone architecture and fluxes, chemical phases, solid-phase reactions, biogeochemical process, etc. . . .

Former Naval Air Warfare Center (NAWC), West Trenton, NJ

- Local and regional groundwater flow and contaminant transport. . . local and regional geologic controls, hydrologic & topographic controls, surface water drainages, chemical attenuation processes, etc. . . .

Lockatong Mudstone, Newark Basin West Trenton, NJ

Topographic map showing surface drainages near NAWC

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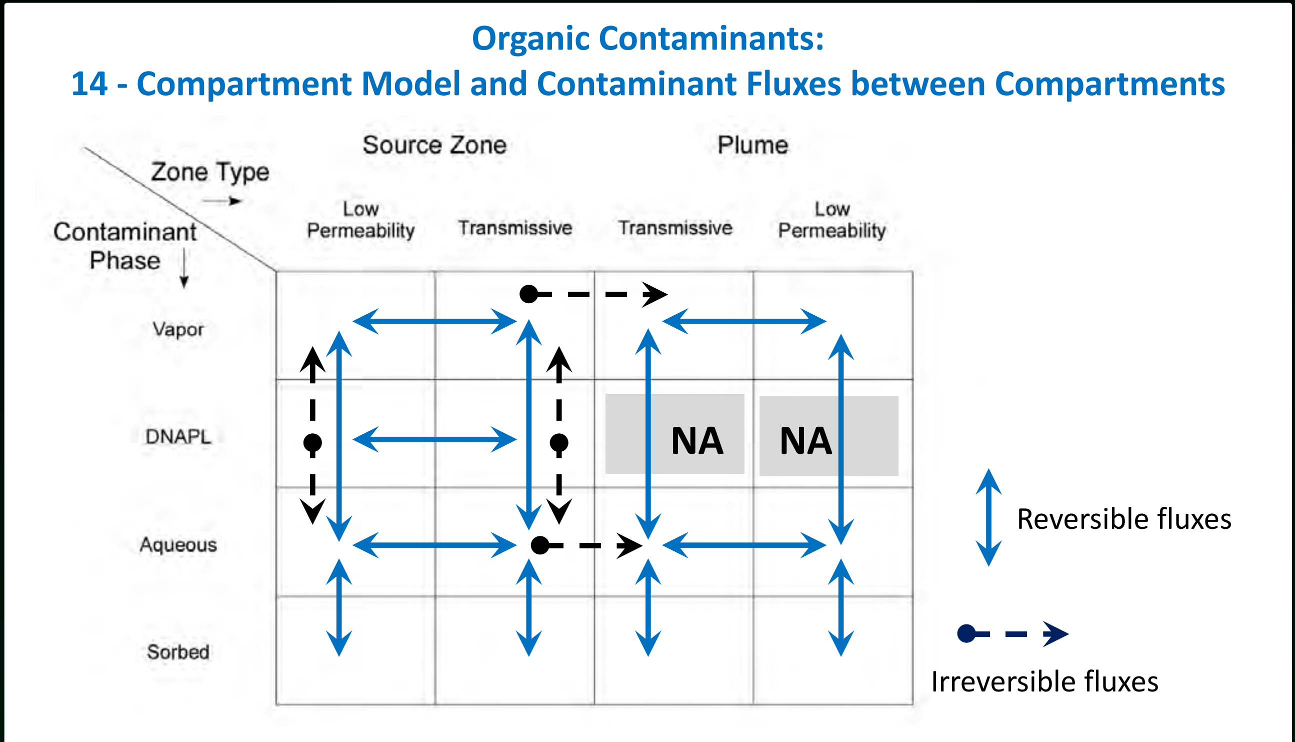
It helps to "compartmentalize" our thinking about Conceptual Site Models. . .



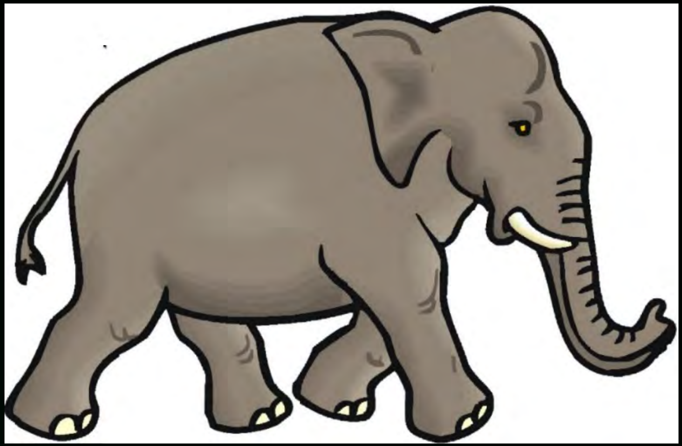
(modified from Sale et al., 2008; Sale and Newell, 2011; ITRC 2011)

- Conceptualize processes that affect contaminant "storage" and contaminant fluxes
- Define site characterization, monitoring, and modeling to quantify contaminant "reservoirs" and contaminant fluxes (relevant to *functional objectives*)

Functional objectives are like an elephant . . .
they can appear to be large and cumbersome. . .

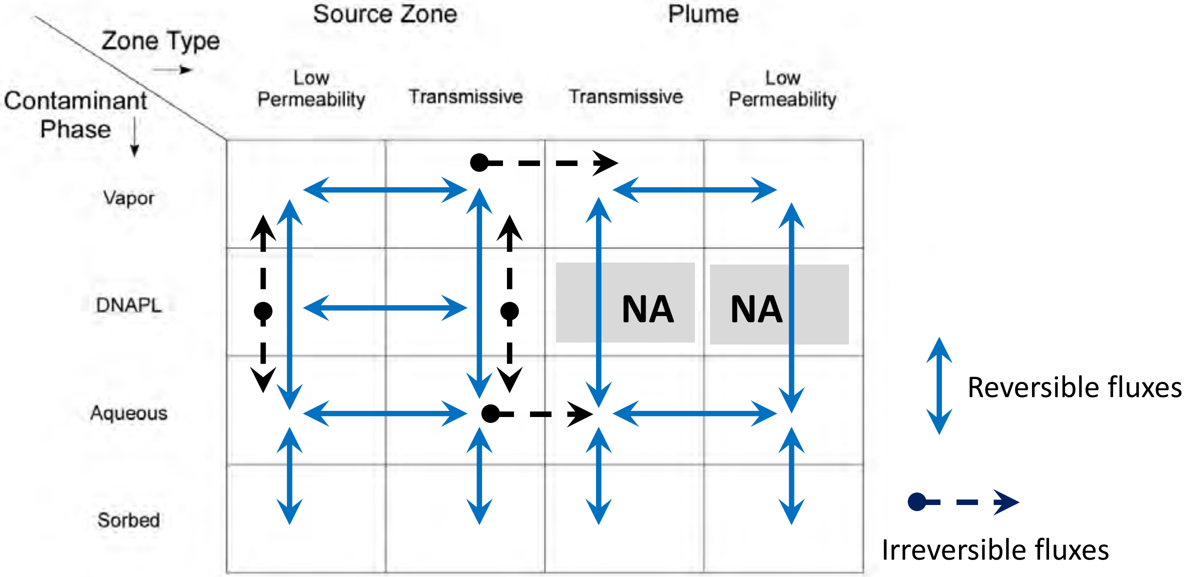
. . how do you eat an elephant?

. . . one bite at a time !



- Identify contaminant "reservoirs" and fluxes that dominate process outcomes. . .
- Identify spatial and temporal scales that dominate processes outcomes. . .

Organic Contaminants:
14 - Compartment Model and Contaminant Fluxes between Compartments



(modified from Sale et al., 2008; Sale and Newell, 2011; ITRC 2011)

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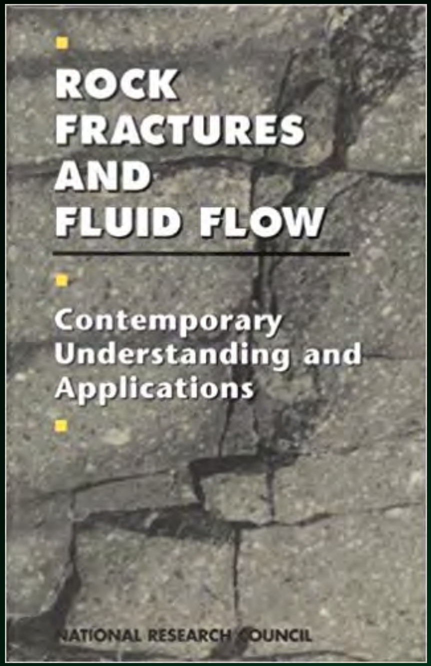
An Example of Applying Functional Objectives

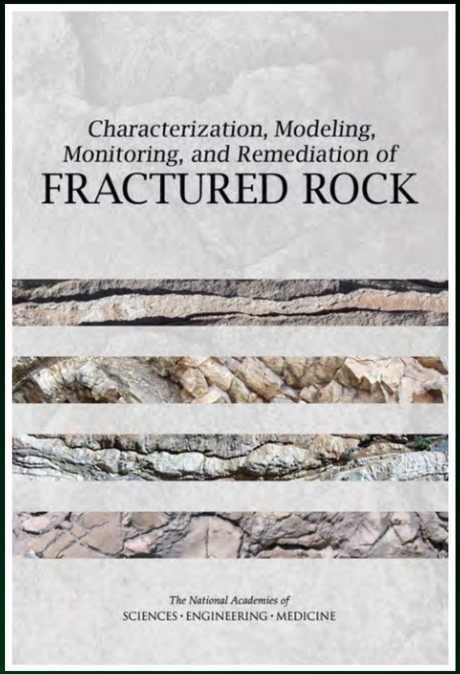
❑ *Mitigating off-site contaminant migration in fractured rock*

Discussions of the complexity of fractured rock aquifers (Site Characterization, Modeling, and Applications to Waste Isolation and Remediation)



National Research Council. 1996. https://doi.org/10.17226/2309.

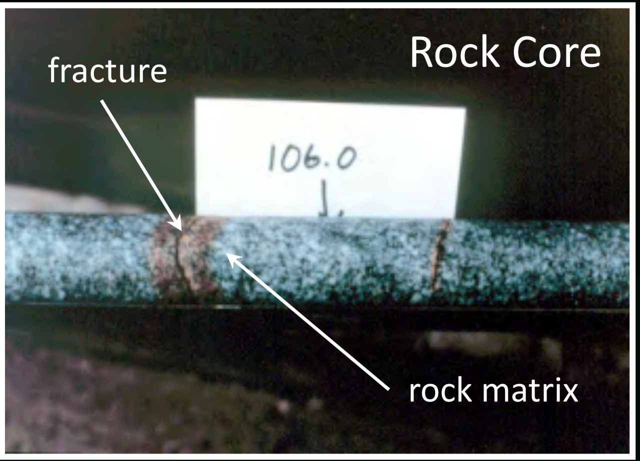
National Research Council. 2013. https://doi.org/10.17226/14668.



National Academies of Sciences, Engineering, and Medicine. 2015. https://doi.org/10.17226/21742.

An Example of Applying Functional Objectives

- ***Mitigating off-site contaminant migration in fractured rock***



Hierarchy of void space

Fault Zone

Fractures control groundwater flow. . .

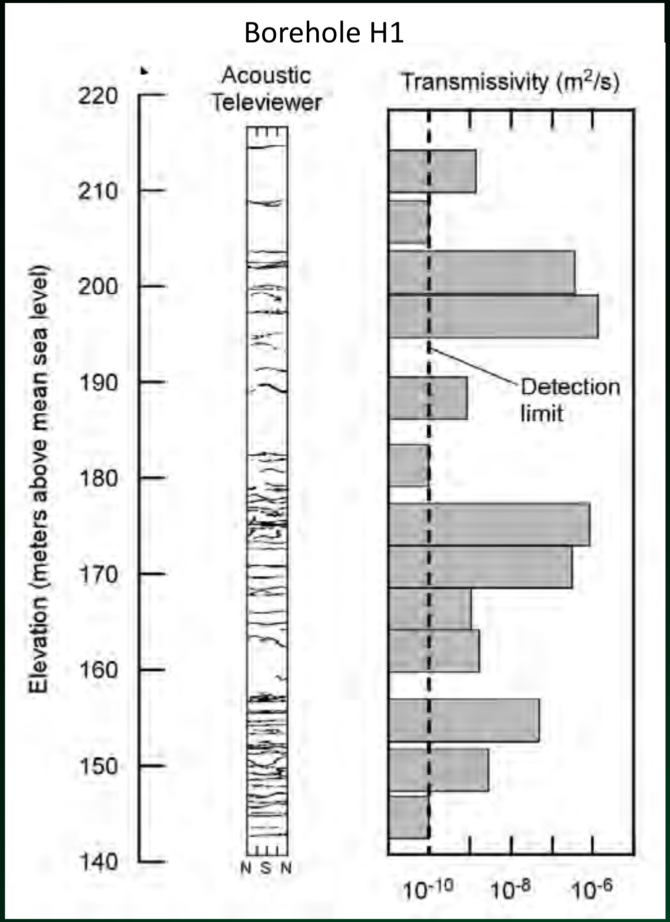
. . .but, there are numerous fractures. . .

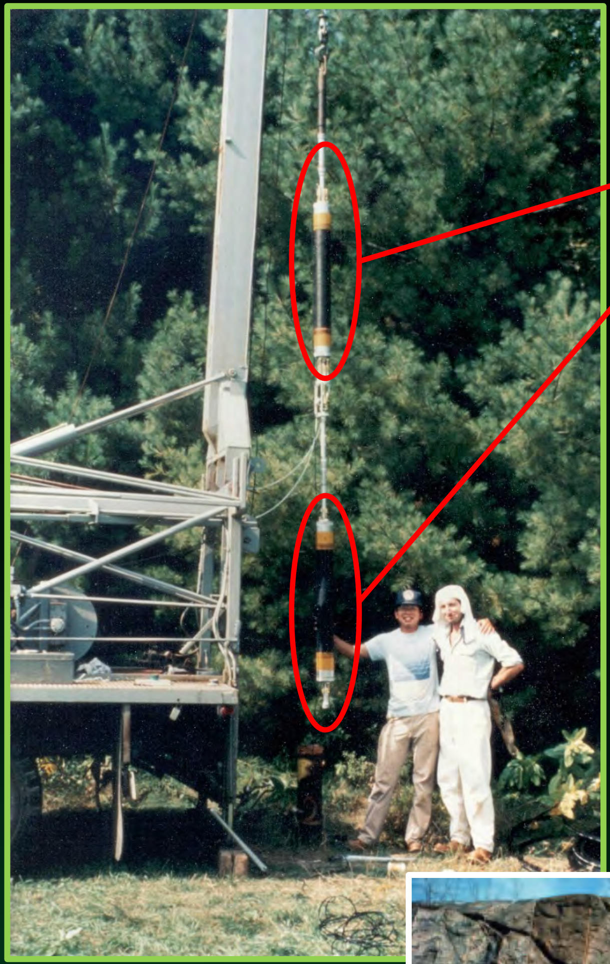
. . .over dimensions from centimeters to kilometers. .

Do we need to characterize "all" fractures to achieve the objective of mitigating off-site contaminant migration ?

What do we know about fractures and their capacity to transmit groundwater?

Fractures and Fracture Transmissivity in a Single Borehole





Straddle packers isolate a section of borehole to conduct hydraulic tests

Granite and schist
Mirror Lake, NH

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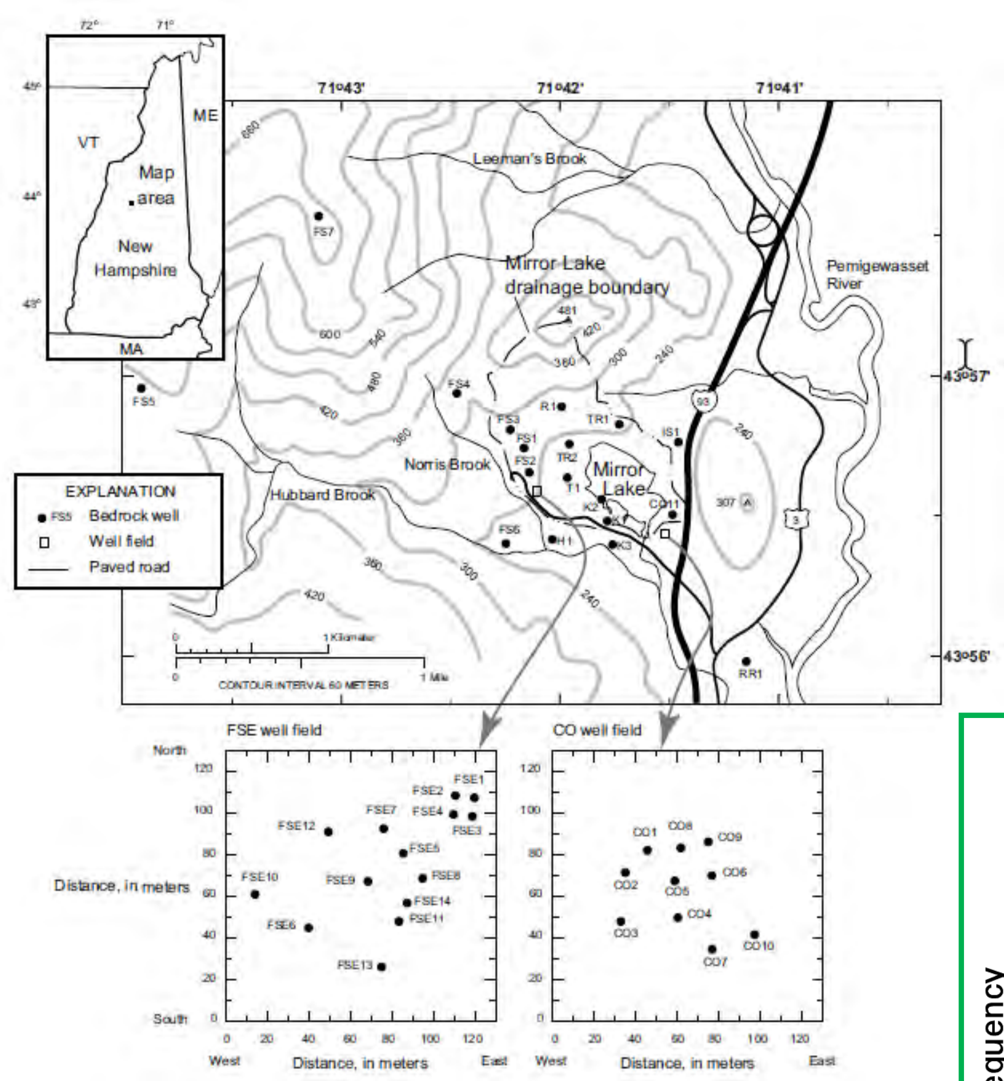
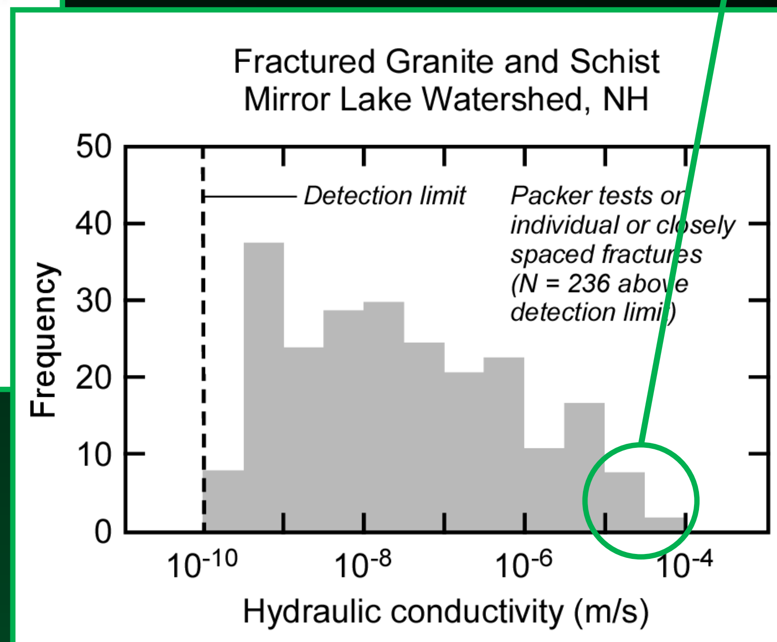


Mirror Lake, NH (courtesy of W. Burton)

Few fractures control majority of groundwater flow



Results of hydraulic tests conducted in boreholes over the Mirror Lake watershed, New Hampshire

An Example of Applying Functional Objectives

- ***<u>Mitigating off-site contaminant migration in fractured rock</u>***

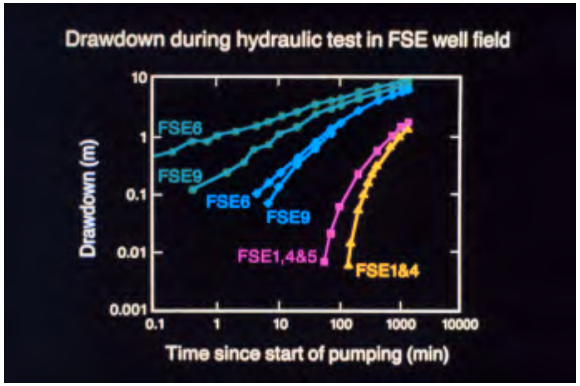
Critical Process and Scales:

- Narrowed from looking at all fractures. . .to only the most transmissive fractures & their connectivity
- Narrowed data collection and monitoring efforts
- Information critical to design of mitigation (e.g., hydraulic containment, constructed barriers, etc.)

Identifying Transmissive Fractures and Their Connectivity

Advances over 25+ years

- Local and regional tectonic and lithologic controls on fracturing
- Surface and borehole geophysical methods
- Multilevel monitoring equipment
- Design and interpretation of hydraulic and tracer tests
- Modeling groundwater flow and parameter estimation methods



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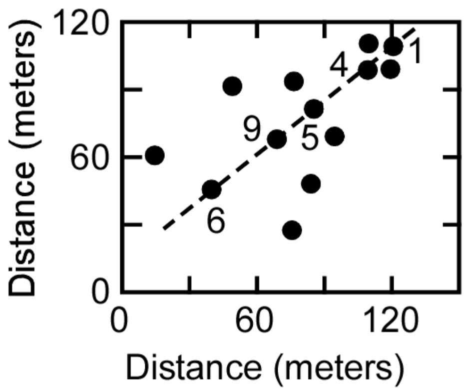
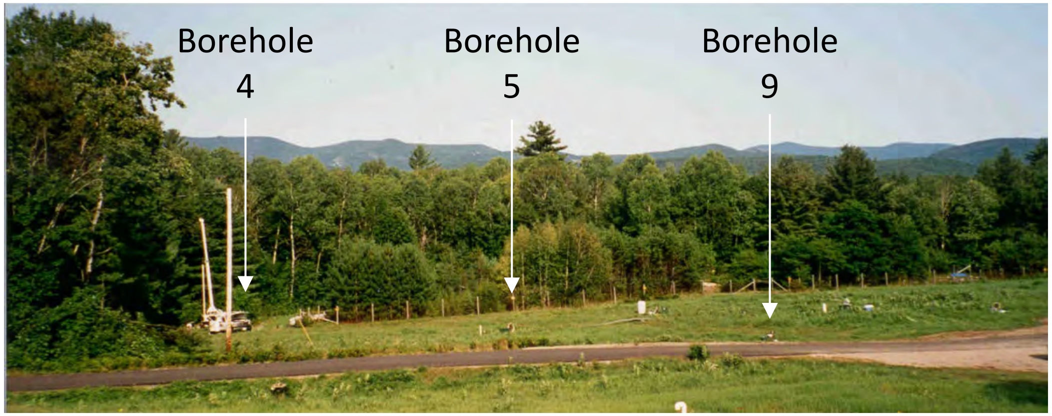
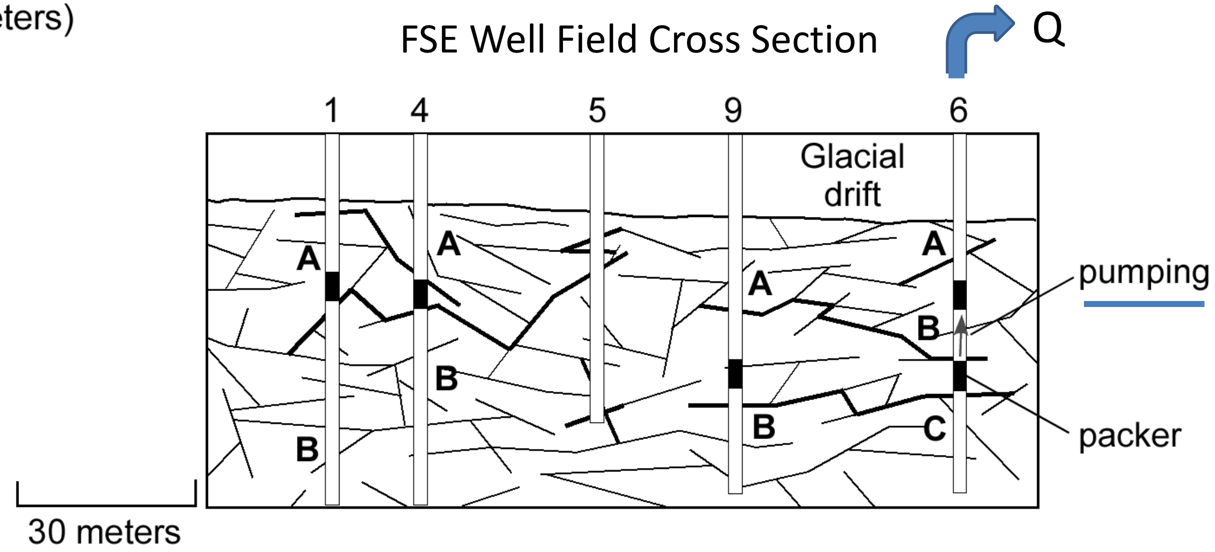
Identifying Transmissive Fractures and Their Connectivity

FSE Well Field
Plan View



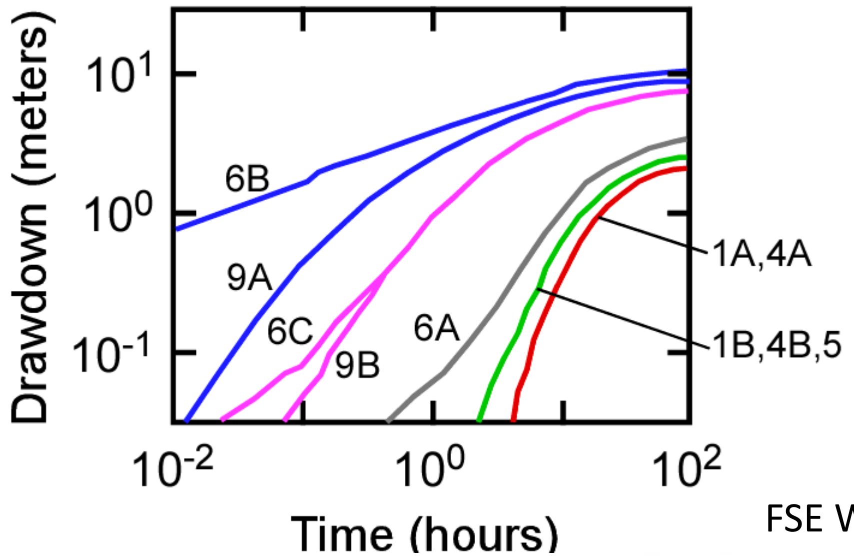


FSE Well Field Cross Section



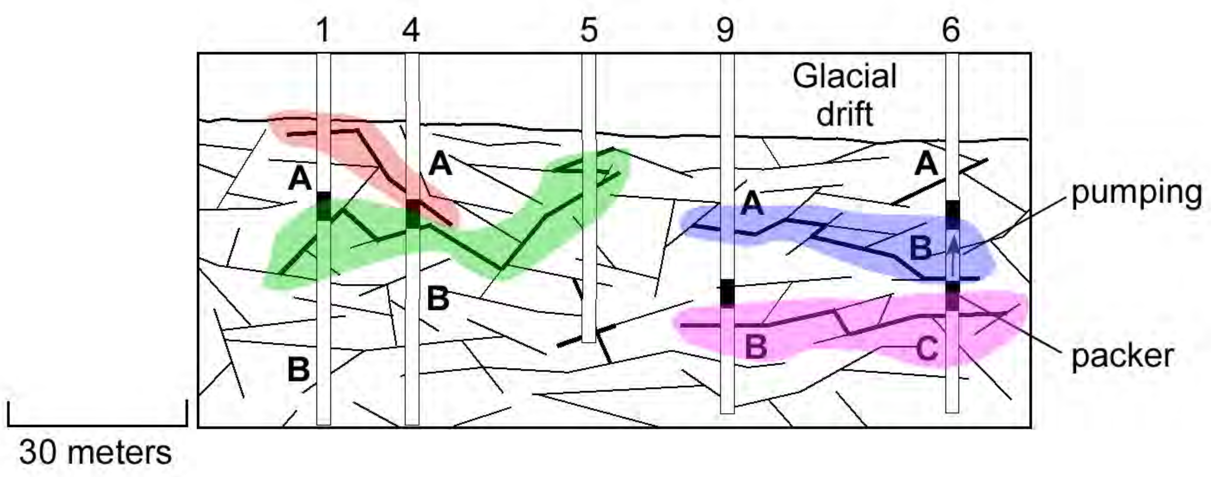
Granite and Schist,
Mirror Lake Waters
New Hampshire

Identifying Transmissive Fractures and Their Connectivity



Clustering of drawdown records from different monitoring intervals during hydraulic tests provides evidence of transmissive fractures & fracture connectivity. . .

FSE Well Field Cross Section



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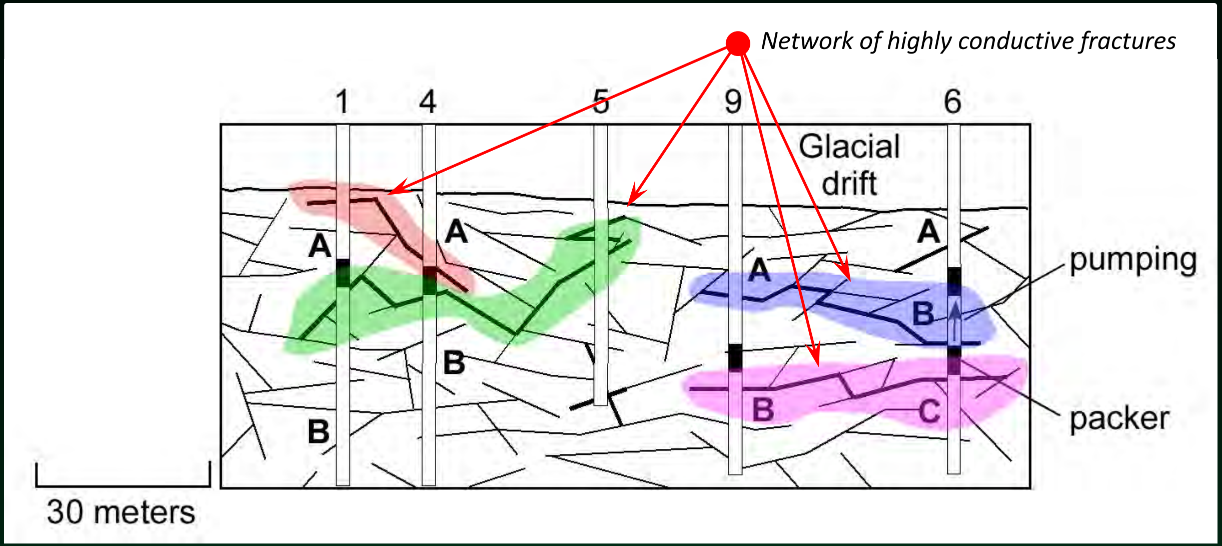
An Example of Applying Functional Objectives

- ***Mitigating off-site contaminant migration in fractured rock***
  - Identify the most transmissive fractures & their connectivity

. . .identify pathways of contaminated groundwater from source zone to compliance boundaries. . .



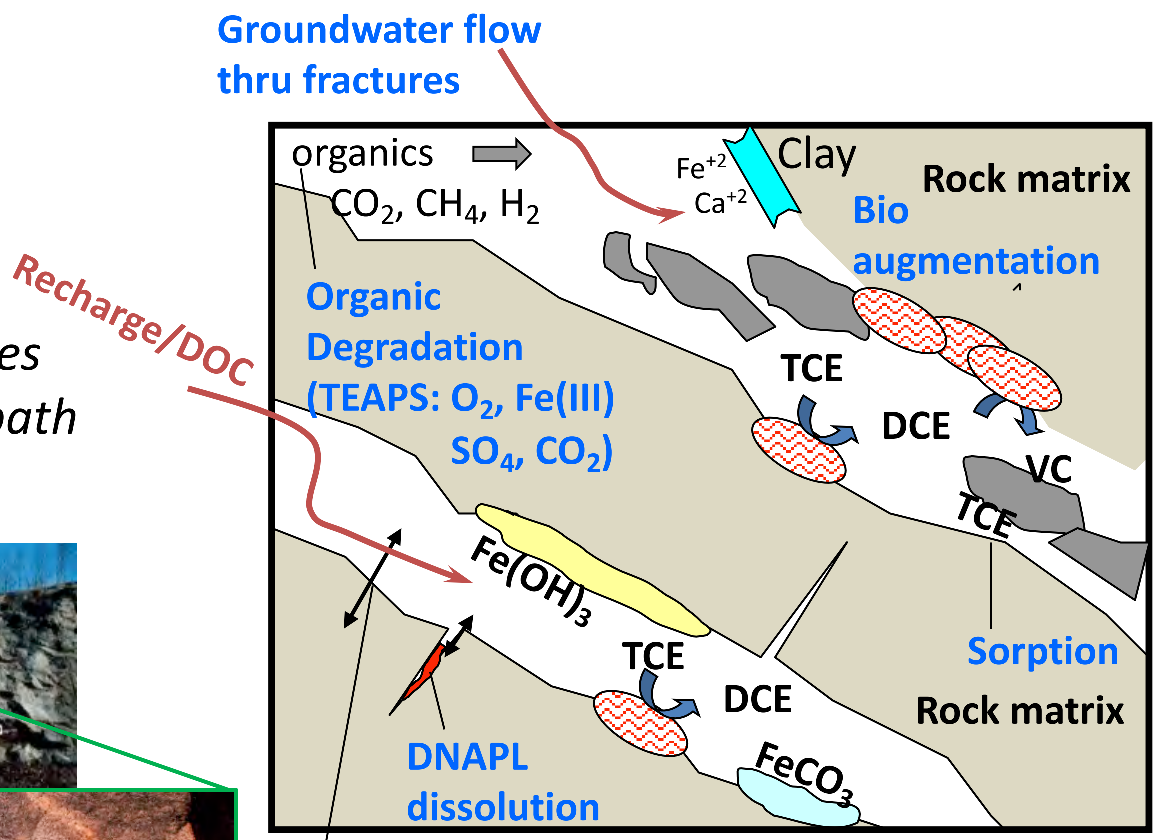
. . .<u>additional information needed</u> to characterize the potential for off-site migration. . .e.g., source zone inputs, attenuation processes, sources/sinks from rock matrix, etc. . . .

An Example of Applying Functional Objectives

❑ *<u>Mitigating off-site contaminant migration in fractured rock</u>*

- Identify contaminant fate and transport along groundwater flow paths. . .

<u>One approach</u> -> incorporating biogeochemical processes into groundwater flow path models. . .



TCE, DCE, VC are electron acceptors which compete with other electron accepting processes

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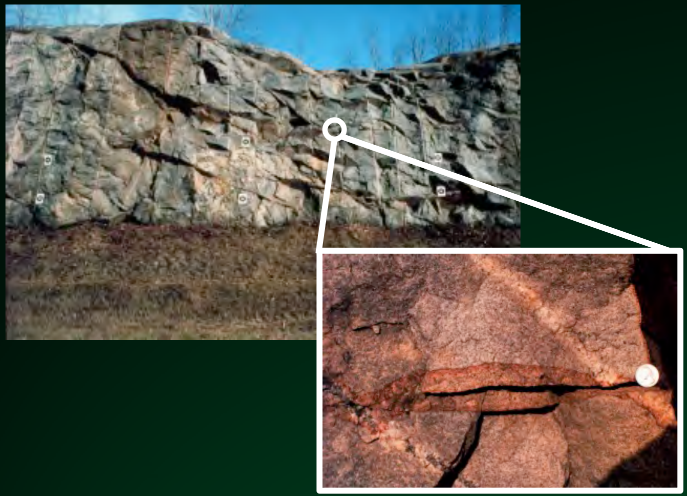
An Example of Applying Functional Objectives

❑ ***Mitigating off-site contaminant migration in fractured rock***

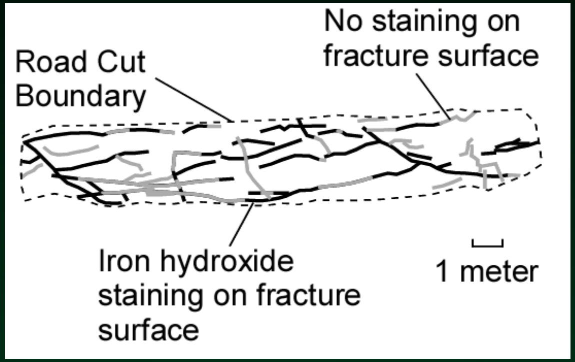
- Identify contaminant fate and transport along groundwater flow paths. . .

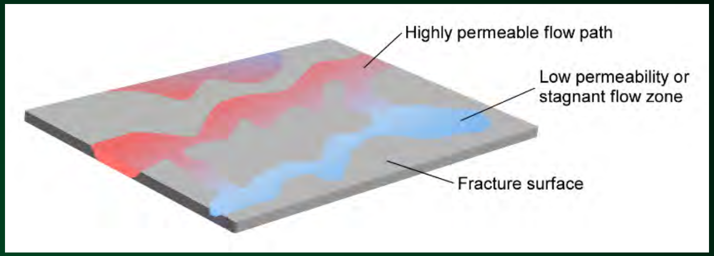
Modeling chemical transport in fracture networks is conceptually complex & computationally intensive to account for mobile and immobile groundwater. . . parameterization is highly uncertain. . .

Road cut near Mirror Lake, NH



Mapping iron hydroxide staining on fractures





Flow paths in fractures are highly convoluted

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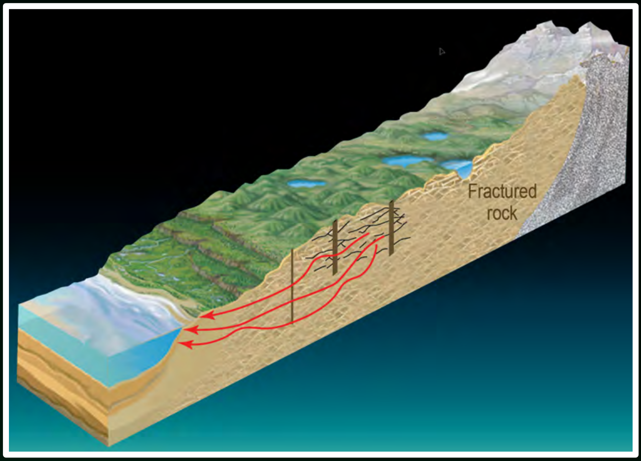
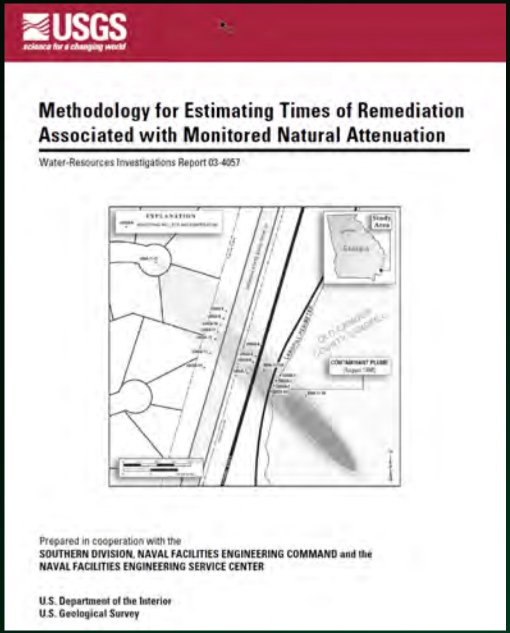
An Example of Applying Functional Objectives

- Mitigating off-site contaminant migration in fractured rock
  - Identify contaminant fate and transport along groundwater flow paths



. . .alternatively -> conceptualize biogeochemical processes along <u>representative flow paths</u> and identify conditions that <u>bound process responses</u>. . .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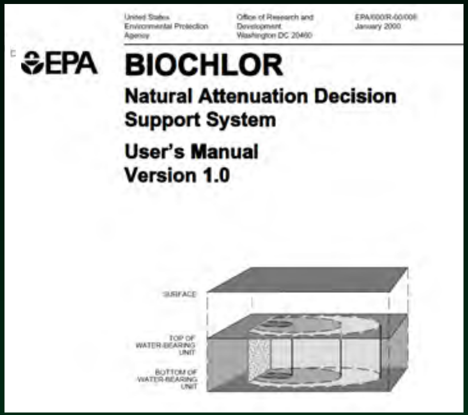
Methodology for Estimating Times of Remediation Associated with Monitored Natural Attenuation

Water-Resources Investigations Report 03-4057

Prepared in cooperation with the
SOUTHERN DIVISION, NAVAL FACILITIES ENGINEERING COMMAND and the
NAVAL FACILITIES ENGINEERING SERVICE CENTER

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


United States Environmental Protection Agency | Office of Research and Development Washington DC 20460 | EPA/600/R-00/008 January 2000

EPA

BIOCHLOR

Natural Attenuation Decision Support System

User's Manual
Version 1.0

Natural Attenuation Software

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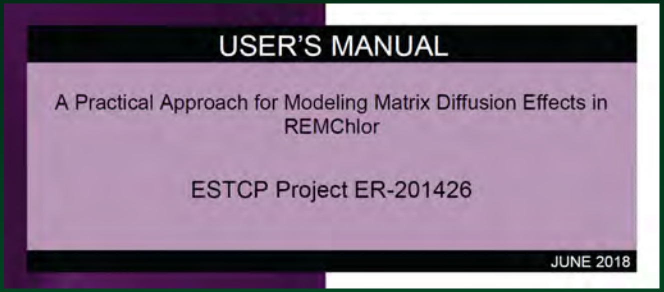
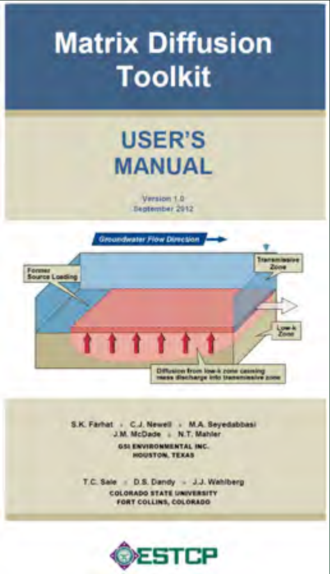
REMChlor


USER'S MANUAL

A Practical Approach for Modeling Matrix Diffusion Effects in REMChlor

ESTCP Project ER-201426

JUNE 2018


Matrix Diffusion Toolkit

USER'S MANUAL

Version 1.0
September 2012

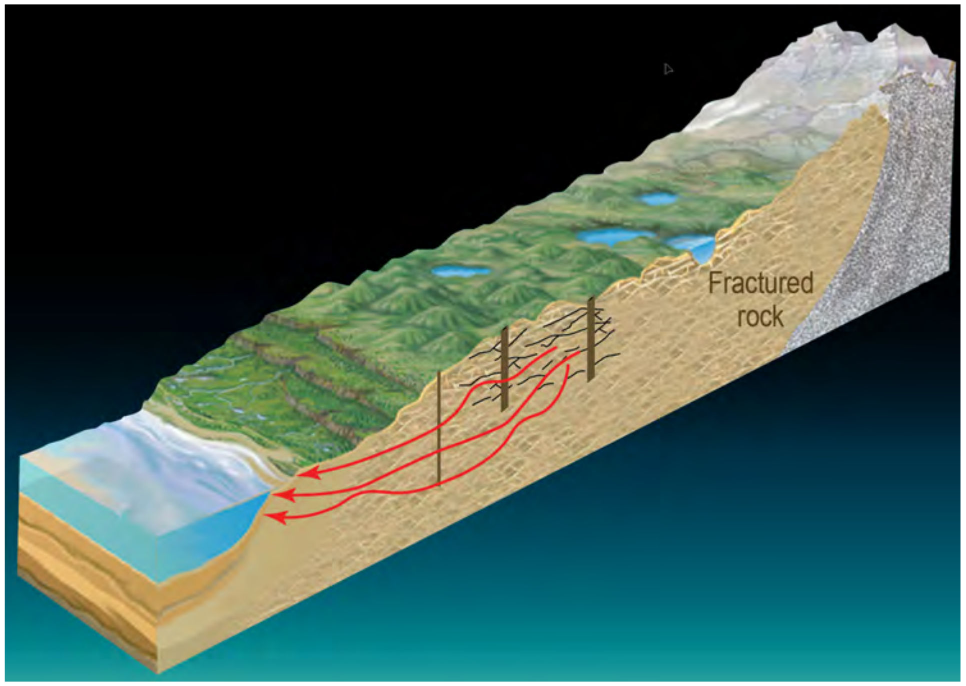
S.K. Farhat · C.J. Newell · M.A. Seyedabbasi
J.M. McDade · N.T. Mahler
GSI ENVIRONMENTAL INC.
HOUSTON, TEXAS

T.C. Sale · D.S. Dandy · J.J. Wahlberg
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

ESTCP

An Example of Applying Functional Objectives

❑ Mitigating off-site contaminant migration in fractured rock



Conceptual Site Model:

- Critical process:
  Chemical advection by most transmissive fractures

- Bounding process outcomes:
  - Source zone and attenuation processes along representative groundwater flow paths
  - Account for uncertainty in groundwater flow paths

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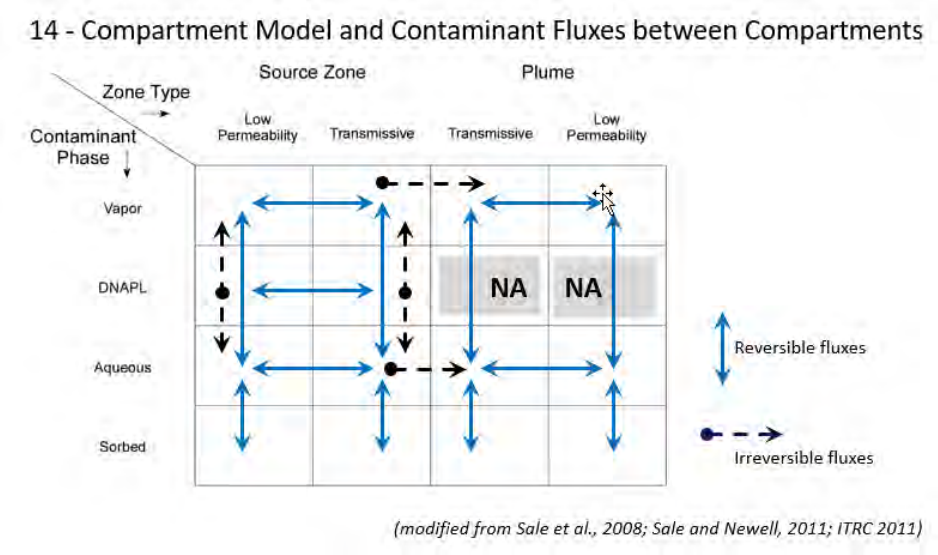
Recognizing Critical Processes and Scales in Conceptual Site Models for Decision Support at Sites of Groundwater Contamination

Summarizing. . .

- Beneficial to have understanding of all processes and scales that affect contaminant fate and transport. . .

- To address specific functional objectives. . .all processes and scales do not need to translate into a decision support tool. . .



- Recognize critical processes and fluxes – constrains and focuses data collection efforts. . .couple less complex models to bound process outcomes. . .

- Recognize critical processes and fluxes – address spatial and temporal scales consistent with limitations of complexity and data availability. . .

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Selected References

Aziz, C. E., Newell, C. J., Gonzales, J. R., Haas, P., Clement, T. P. and Sun, Y. 2000. BIOCHLOR: Natural attenuation decision support system user's manual Version 1.0. U.S. Environmental Protection Agency, Office of Research and Development EPA/600/R-00/008.

Chapelle, F. H., Widdowson, M. A., Brauner, J. S., III, E. M. and Casey, C. C. 2003. Methodology for Estimating Times of Remediation Associated with Monitored Natural Attenuation. U.S. Geological Survey Water-Resources Investigations Report 03-4057. 51p. https://pubs.usgs.gov/wri/wri034057/pdf/wrir03-4057.pdf.

Farhat, S. K., Newell, C. J., Seyedabbasi, M. A., McDade, J. M., Mahler, N. T., Sale, T. C., Dandy, D. S. and Wahlberg, J. J. 2012. Matrix diffusion toolkit: User's Manual. ESTCP Project ER-201126. https://www.serdp-estcp.org/Tools-and-Training/Environmental-Restoration/Groundwater-Plume-Treatment/Matrix-Diffusion-Tool-Kit.

Farhat, S. K., Newell, C. J., Falta, R. W. and Lynch, K. 2018. A Practical Approach for Modeling Matrix Diffusion Effects in REMChlor. ESTCP Project ER-201426. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-201426.

Feenstra, S., Cherry, J. A. and Parker, B. L. 1996. Conceptual models for the behavior of Dense Non-Aqueous Phase Liquids (DNAPLs) in the subsurface, *in* Dense Chlorinated Solvents and other DNAPLs in Groundwater. eds., J. F. Pankow and J. A. Cherry. Waterloo Press, Portland, OR. p. 53-88.

Golder Associates. 2010. Fractured bedrock field methods and analytical tools, Vol. 1. Science Advisory Board for Contaminated Sites in British Columbia, http://www.sabcs.chem.uvic.ca/fracturedbedrock.html. 87p.

Interstate Technology and Regulatory Council (ITRC). 2011. Integrated DNAPL site strategy. Interstate Technology and Regulatory Council, Integrated DNAPL Site Strategy Team. Washington, DC. Retrieved July 17, 2016, from http://www.itrcweb.org/guidancedocuments/integrateddnaplstrategy_idssdoc/idss-1.pdf.

National Academies of Sciences (NAS), Engineering, and Medicine. 2015. Characterization, Modeling, Monitoring, and Remediation of Fractured Rock. National Academy Press, Washington, DC. doi.org/10.17226/21742.

National Research Council (NRC). 1996. Rock Fractures and Fluid Flow: Contemporary Understanding and Applications. National Academies Press, Washington, DC. 551p.

National Research Council (NRC). 2005. Contaminants in the Subsurface: Source Zone Assessment and Remediation. National Academies Press, Washington, DC. 358p. https://doi.org/10.17226/11146.

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Selected References

National Research Council (NRC). 2013. Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites. National Academies Press, Washington, DC. 320p. doi.org/10.17226/14668.

Shapiro, A.M. 2002. Cautions and suggestions for geochemical sampling in fractured rock. Ground Water Monitoring and Remediation 22(3): 151–164.

Shapiro, A. M., Ladderud, J. A. and Yager, R. M. 2015. Interpretation of hydraulic conductivity in a fractured-rock aquifer over increasingly larger length dimensions. **Hydrogeology Journal** 23: 1319-1339. doi:10.1007/s10040-015-1285-7.

Shapiro, A. M., Hsieh, P. A., Burton, W. C., and Walsh, G. J. 2007. Integrated Multi-Scale Characterization of Ground-Water Flow and Chemical Transport in Fractured Crystalline Rock a the Mirror Lake Site, New Hampshire, *in* Subsurface Hydrology: Data Integration for Properties and Processes. eds., D. W. Hyndman, F. D. Day-Lewis and K. Singha. American Geophysical Union, Washington, DC. p. 201-226.

Shapiro, A. M., Tiedeman, C. R., Imbrigiotta, T. E., Goode, D. J., Hsieh, P. A., Lacombe, P. J., DeFlaun, M. F., Drew, S. R. and Curtis, G. P. 2018. Bioremediation in Fractured Rock: 2. Mobilization of Chloroethene Compounds from the Rock Matrix. **Groundwater** 56(2): 317-336. 10.1111/gwat.12586.

Tiedeman, C. R., Shapiro, A. M., Hsieh, P. A., Imbrigiotta, T. E., Goode, D. J., Lacombe, P. J., DeFlaun, M. F., Drew, S. R., Johnson, C. D., Williams, J. H. and Curtis, G. P. 2018. Bioremediation in Fractured Rock: 1. Modeling to Inform Design, Monitoring, and Expectations. Groundwater 56(2): 300-316. 10.1111/gwat.12585.

Wellman, T. P., Shapiro, A. M. and Hill, M. C. 2009. Effects of simplifying fracture network representation on inert chemical migration in fracture-controlled aquifers. Water Resources Research 45(1): 10.1029/2008WR007025.