SOURCE BARRIER TOOL

Contaminant Flux Reduction Barriers for Managing Difficult-to-Treat Source Zones in Unconsolidated Media

ESTCP Project ER-201328

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Charles Newell
GSI Environmental, Inc.

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Charles Newell, Poonam Kulkarni, Shahla Farhat, Ryan Newell, Phil deBlanc, Andrew Keat, Whitney Godwin, Beatrice Li, Zachary Esquivel, Dylan Hart, Marcela Interiano

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GSI Environmental, Inc.
2211 Norfolk Street, Suite 1000
Houston, TX 77098

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14. ABSTRACT
Source Barrier Tool and what is does: 1) The tool explains the potential benefits of a physical barrier around a chlorinated solvent source zone and 2) The tool helps you understand if a barrier would work at your site.
The overall objective of this project was to evaluate if inexpensive flow reduction agents delivered via permeation grouting technology could help manage difficult-to-treat chlorinated solvent source zones, or any other source zone comprised of contaminants that degrade primarily via anaerobic biodegradation processes that are inhibited by naturally-occurring competing electron acceptors such as oxygen and sulfate.

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Source Barrier Tool, chlorinated solvent source zone, permeation grouting technology, anaerobic biodegradation

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Source Barrier Tool

Version 1.0

Quick-Start Instructions

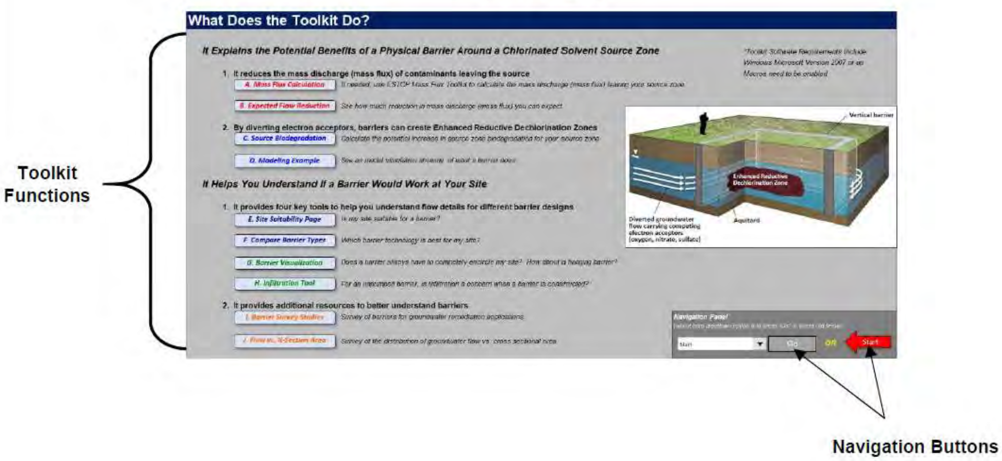
- **To Start:**
  - Double-click the file "ESTCP_SourceBarrier.xlsm"
  - When Microsoft Excel starts, select "Enable Macros"
  - Select the **Start** button on the splash screen

- **Toolkit Software Requirements:**
  - Windows Microsoft Version 2007 or higher
  - Macros need to be enabled

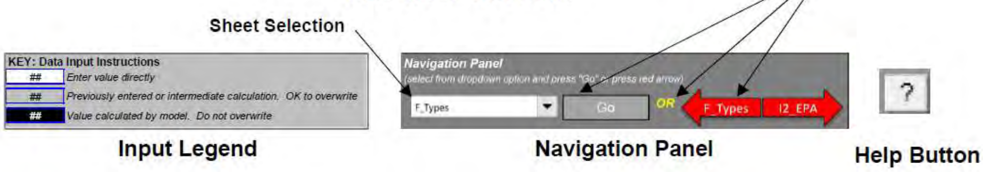
- **Toolkit Functions:**
  - The toolkit explains the potential benefits of a physical barrier around a chlorinated solvent source zone
  - The toolkit helps you understand if a barrier would work at your site

- **Using the Toolkit:**
  - Move between sheets using the Navigation Panel
  - Enter data in cells (white/gray cells) and retrieve results (black cells) based on the Input Legend
  - Click Help Buttons for more information

MAIN MENU



INPUT LEGEND, NAVIGATION PANEL, AND HELP BUTTONS



ABOUT THE SOURCE BARRIER TOOL

WHAT THIS TOOL DOES

- The tool explains the potential benefits of a physical barrier around a chlorinated solvent source zone
- The tool helps you understand if a barrier would work at your site

DISCLAIMER

AUTHORS

Poonam Kulkarni
Shahla Farhat
Ryan Newell
Phil deBlanc
Andrew Keat
Whitney Godwin
Beatrice Li
Zachary Esquivel
Dylan Hart
Marcela Interiano
Charles Newell

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Final Project Report:
Kulkarni, P.R., E.A. Higgins, B.A. Strastert, C.J. Newell, 2017. Final Report: Contaminant Flux Reduction Barriers for Managing Difficult-to-Treat Source Zones in Unconsolidated Media. ESTCP Project ER-201328. Environmental Security Technology Certification Program (ESTCP). June 2017. www.serdp-estcp.org

Technical Guidance Manual:
Kulkarni, P.R., E.A. Higgins, B.A. Strastert, C.J. Newell, 2017. Technical Guidance Manual: Contaminant Flux Reduction Barriers for Managing Difficult-to-Treat Source Zones in Unconsolidated Media. ESTCP Project ER-201328. Environmental Security Technology Certification Program (ESTCP). June 2017. www.serdp-estcp.org

CONTACT
Poonam Kulkarni, GSI Environmental, 713 522-6300, prk@gsi-net.com

EXECUTIVE SUMMARY

The overall objective of this project was to evaluate if inexpensive flow reduction agents delivered via permeation grouting technology could help manage difficult-to-treat chlorinated solvent source zones, or any other source zone comprised of contaminants that degrade primarily via anaerobic biodegradation processes that are inhibited by naturally-occurring competing electron acceptors such as oxygen and sulfate. Examples include brominated compounds, perchlorate, some metals, and potentially petroleum hydrocarbons. This approach aims to provide two benefits for improving groundwater quality at chlorinated volatile organic carbon (CVOC) sites by:

1. physically reducing the mass flux of contaminants leaving the source zone by using permeation grouting, thereby reducing risk and making the downgradient plume more amenable for management by natural attenuation processes; and
2. increasing the Natural Source Zone Depletion (NSZD) rate within the source by diverting competing electron acceptors (e.g., dissolved oxygen, nitrate, and sulfate) around the source zone to create an enhanced reductive dechlorination zone (ERDZ) that biodegrades CVOC source materials even though the source zone is isolated by the barrier.

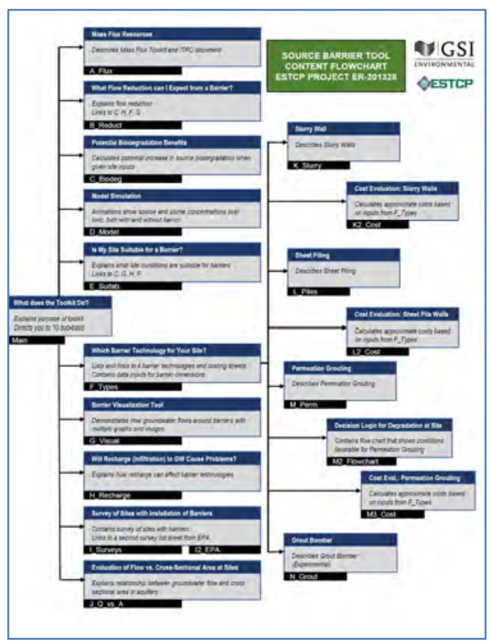
Download the ESTCP Project Report here describing a the background of the barrier concept and describing a field demonstration of a permeation grouting barrier:

https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-201328/ER-201328

The ESTCP Source Barrier Tool was created to:

1. explain the potential benefits of a physical barrier around a chlorinated solvent source zone; and
2. help practitioners understand if a barrier would work at their site.

This report summarizes the Source Barrier Tool and provides individual sheets in the tool as well as additional information pertaining to each calculation or informational module.



See larger version on next page

SOURCE BARRIER TOOL OVERVIEW

Figure 1 on the next page summarizes the contents of the tool, as well as a description of each sheet. Screenshots of the individual sheets and related technical material are provided in the following pages.

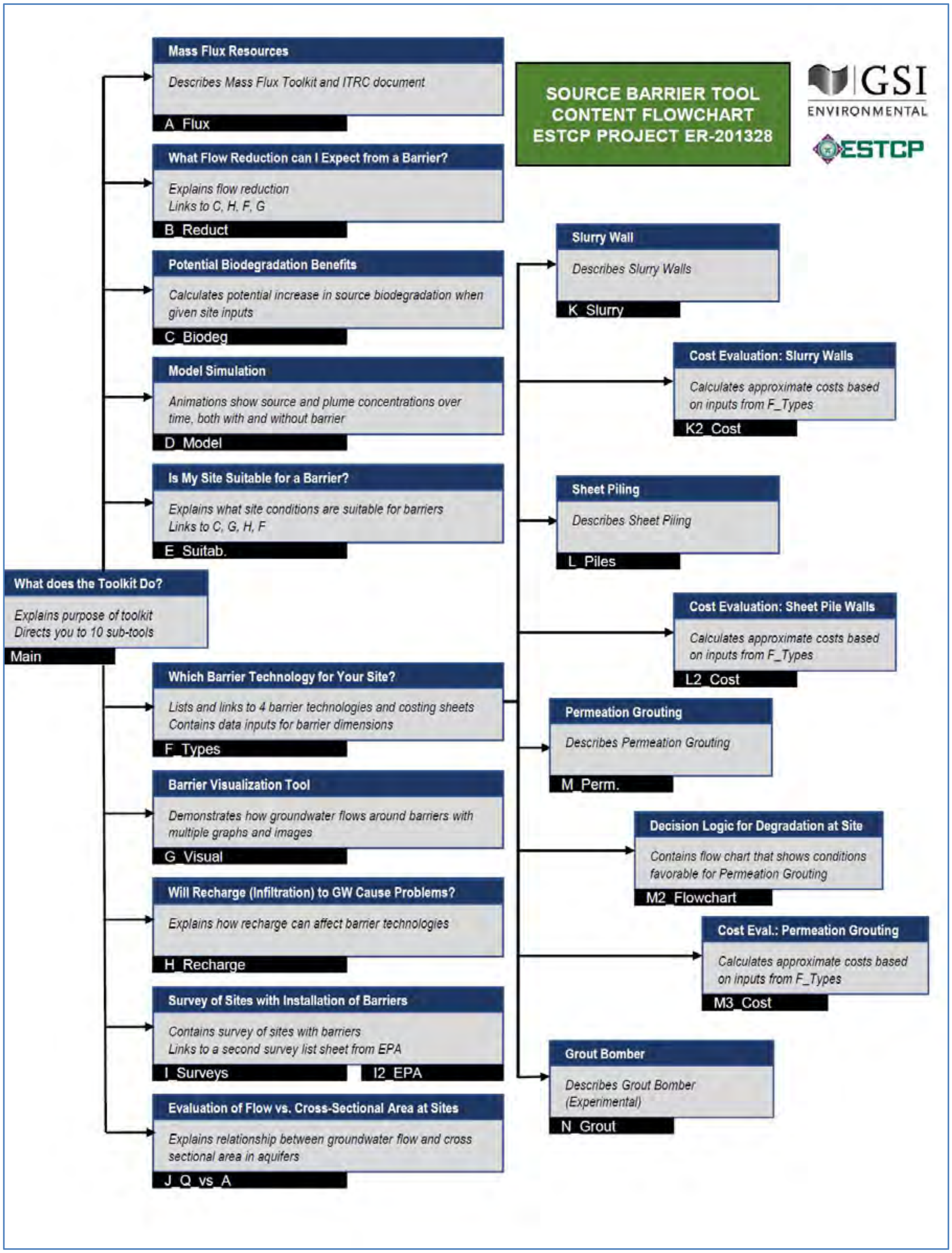
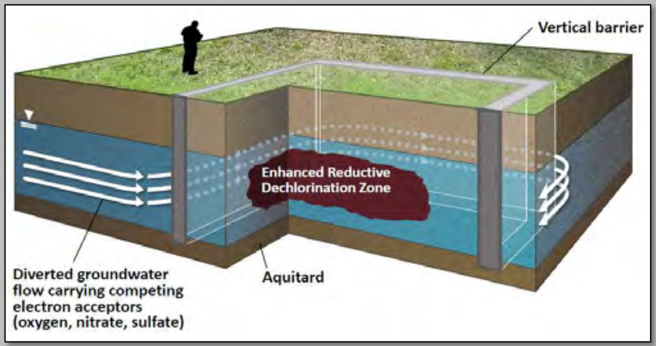


Figure 1: Source Barrier Tool Content Flowchart

SHEET MAIN:
What Does the Toolkit Do?

Source Barrier Tool

For understanding and evaluating subsurface barriers



START

About

System Info

Version 1.0

What Does the Toolkit Do?

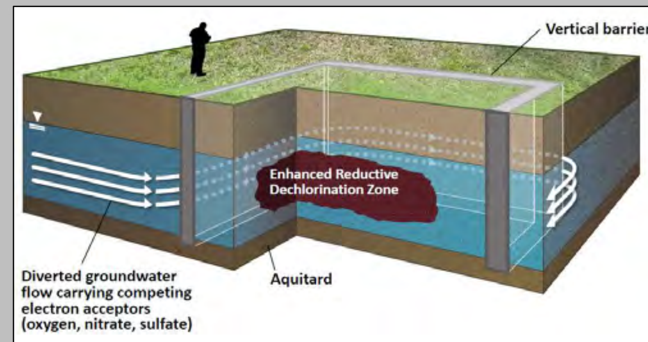
It Explains the Potential Benefits of a Physical Barrier Around a Chlorinated Solvent Source Zone

1. It reduces the mass discharge (mass flux) of contaminants leaving the source

- **A. Mass Flux Calculation** — *If needed, use the ESTCP Mass Flux Toolkit to calculate the mass discharge (mass flux) leaving your source zone.*
- **B. Expected Flow Reduction** — *See how much reduction in mass discharge (mass flux) you can expect.*

2. By diverting electron acceptors, barriers can create Enhanced Reductive Dechlorination Zones

- **C. Source Biodegradation** — *Calculate the potential increase in biodegradation for your source zone.*
- **D. Modeling Example** — *See a model simulation showing what a barrier does.*



It Helps You Understand If a Barrier Would Work at Your Site

1. It provides four key tools to help you understand flow details for different barrier designs

- **E. Site Suitability Page** — *Is my site suitable for a barrier?*
- **F. Compare Barrier Types** — *Which barrier technology is best for my site?*
- **G. Barrier Visualization Tool** — *Does a barrier always have to competely encircle my site? How about a hanging barrier?*
- **H. Recharge Tool** — *For an unpumped barrier, is recharge a concern when a barrier is constructed?*

See Tool Map

2. It provides additional resources to better understand barriers

- **I. Barrier Survey Studies** — *Survey of barriers for groundwater remediation applications.*
- **J. Flow vs. X-Sectional Area** — *Survey of the distribution of groundwater flow vs. cross-sectional area.*

Navigation Panel
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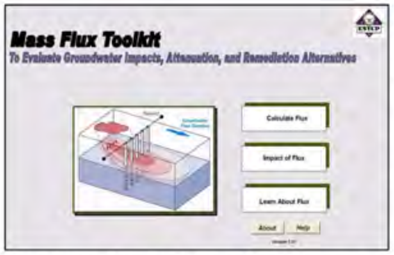
Start | Go | *OR* | Start

SHEET A_FLUX:
Mass Flux Resources

Mass Flux Resources

Mass Flux Toolkit



MASS FLUX TOOLKIT

The Mass Flux Toolkit gives site personnel the capability to compare different mass flux approaches, calculate mass flux from transect data, and apply mass flux to manage groundwater plumes. With this tool, site personnel will be able to perform mass flux calculations more quickly and cheaply, permitting their inclusion in more evaluations of groundwater plumes.

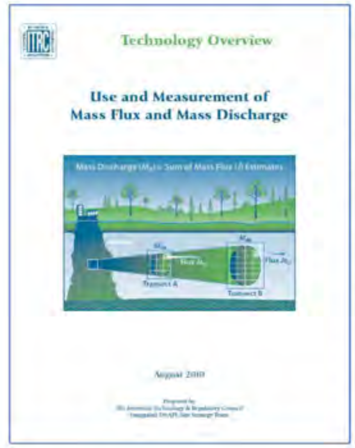
The Mass Flux Toolkit can be accessed and downloaded for free at:
https://www.gsi-net.com/en/software/free-software/mass-flux-toolkit.html

Reference:

Farhat, S.K., Newell, C.J., E.M. Nichols, "Mass Flux Toolkit to Evaluate Groundwater Impacts, Attenuation, and Remediation," in Proceedings of Battelle's Fifth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterrey, California, 2006.

https://www.gsi-net.com/en/software/free-software/mass-flux-toolkit.html

ITRC Mass Flux Guidance



ITRC MASS FLUX AND MASS DISCHARGE GUIDANCE DOCUMENT

The ITRC Guidance Document "Use and Measurement of Mass Flux and Mass Discharge" provides additional background information underlying mass flux and mass discharge concepts.

The ITRC document can be downloaded here for free at: https://www.itrcweb.org/GuidanceDocuments/MASSFLUX1.pdf

Reference:

ITRC, 2010. "Use and Measurement of Mass Flux and Mass Discharge", prepared by The Interstate Technology & Regulatory Council Integrated DNAPL Site Strategy Team, August 2010.

https://www.itrcweb.org/GuidanceDocuments/MASSFLUX1.pdf

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)
Start | Go | OR | Main

SHEET B_REDUCT:
What Flow Reduction Can I Expect from a Barrier?

What Flow Reduction Can I Expect from a Barrier?

It depends on if you pump from within the barrier:

In theory, pumping to maintain an inward gradient reduces outflow to zero.

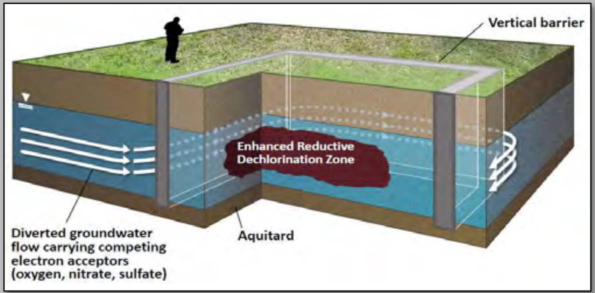
In practice, this can be expensive and more difficult than expected.

At some low-risk sites, we feel that unpumped barriers can provide significant benefits compared to source treatment projects that are faced with diminishing returns.

At these sites, the reduction in mass flux leaving the source zone may be enough for MNA to control the plume.

At chlorinated solvent sites, enhanced reductive dechlorination is also enhanced that will slowly treat the source within the barrier.

C. Source Biodegradation



It depends on recharge:

If the barrier is unpumped, then recharge will increase flow through the wall and increase groundwater levels inside the wall.

Having clay soils or an engineered cap will reduce recharge.

Evaluate recharge using the recharge tool:

H. Recharge Tool

It depends on the wall:

Sheet piling and slurry walls provide very low permeability barriers, grout barriers provide less flow reduction.

Typical bentonite slurry walls and sheet pile walls have hydraulic conductivities of 10^{-7} cm/sec or lower.

Permeation grouting can create barriers with hydraulic conductivity as low as 10^{-5} cm/sec and can reduce groundwater flow in sandy aquifers by 90% to 99%.

F. Barrier Comparison

It depends on the design:

Completely enclosed barriers are much more efficient.

Three sides barriers are less efficient.

Single walls don't work well at all.

Efficiency drops if you can't key into a low permeability "floor" and have to use a "hanging wall".

G. Barrier Visualization Tool

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

Start | Go | OR | Main

SHEET C_BIODEG:
Potential Biodegradation Benefits

Potential Biodegradation Benefits

This calculator provides an estimate of the increase in biodegradation rate in a source zone enclosed by a barrier

KEY: Data Input Instructions

##	*Enter value directly*
##	*Previously entered or intermediate calculation. OK to overwrite*
##	*Value calculated by model. Do not overwrite*

Step 1: Enter Site Information

Select Chlorinated Volatile Organic Chemical (CVOC): TCE

b = Saturated Aquifer Thickness	40.0	ft
i = Regional Hydraulic Gradient	0.007	ft/ft
K = Hydraulic Conductivity	14.00	ft/day
Width of Barrier / Treatment Zone Perpend. to Flow	500	ft
Porosity	0.3	
Groundwater (GW) Darcy Velocity	35.8	ft/yr
% Reduction in Flowrate After Barrier Construction	90%	%
Volumetric Groundwater Flowrate	5,351,192	gal/yr
Volumetric Groundwater Flow Rate After Barrier	535,119	gal/yr

Step 2: Calculate Potential Increase in Biodegradation

Assumed Efficiency (% of Hydrogen Going to Dechlorination): 10%

lbs of CVOC Degraded to Ethene per lb of H_2: 21.9

	Conc. in Upgradient Groundwater (mg/L)	Current Conc. in Source Zone (mg/L)	Diff. in Electron Acceptor Mass Discharge (lb/year)	H_2 Equiv. Consumed Per lb Analyte* (lb/lb)	H_2 Equivalents (lb/yr)	Increase in Biodegradation Rate for CVOC (lb/yr)
O_2	8.9	0.2	351.2	8.0	43.9	96.1
NO_3^-	5.5	0.1	218.7	12.4	17.6	38.6
SO_4^{2-}	76.7	0.1	3076.3	12.0	256.4	561.4
					Total	696 lb/yr CVOC

*Source: BIOBALANCE Tool (www.gsi-net.com)

RESULT SUMMARY

Potential Increase in Biodegradation **696** lb/yr CVOC

C. Learn More About This Topic

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

Start | Go | *OR* | Main

GSI ENVIRONMENTAL

ENHANCED REDUCTIVE DECHLORINATION ZONES (ERDZ) USING BARRIERS

OVERVIEW

Hydrogen is the key electron donor required for the biologically- mediated dechlorination of chlorinated compounds (see Wiedemeier et al., 1999 for a discussion and literature review). In this process, hydrogen acts as an ***electron donor*** and halogenated compounds such as chlorinated solvents act as ***electron acceptors***, becoming reduced in the reductive dechlorination process. At sites where natural dechlorination is occurring, organic substrates such as aromatic hydrocarbons (BTEX), landfill leachate, or other non-chlorinated organics are fermented by indigenous bacteria to provide a source of dissolved hydrogen. The hydrogen is then rapidly utilized as an electron donor by naturally-occurring dechlorinating bacteria to achieve reductive dechlorination of chlorinated compounds.

The dechlorinating reaction only occurs in the appropriate geochemical environment, i.e., deeply anaerobic conditions where concentrations of competing electron acceptors are low. Conditions must be anaerobic to allow both the fermentation process and the reductive dechlorination process to proceed. In addition, there must be very low concentrations of dissolved oxygen or nitrate, as many bacteria will preferentially use these compounds over chlorinated solvents as electron acceptors. These competing electron acceptors **must be consumed** through reaction with source-zone electron donors (non-chlorinated organic substrates and/or hydrogen) before the appropriate geochemical environment is produced.

To accelerate the natural dechlorination process for the purpose of bioremediation, numerous research groups have focused on methods to **increase the supply** of electron donors to the dechlorinating bacteria. Most researchers and technology developers have focused on adding an indirect electron donor (such as lactate, molasses, mulch, etc.) that ferments to produce hydrogen. A second method involves the delivery of dissolved hydrogen directly to the subsurface. However, there is a third way to increase the supply of electron donors to dechlorinating bacteria (described below).

One can permanently interrupt the transport of competing electron acceptors (oxygen, nitrate, and sulfate) to chlorinated solvent plumes so that more electron donor (i.e., non-chlorinated organic substrates and/or dissolved hydrogen) is preserved for the desired reductive dechlorination processes. The method involves constructing a low-cost, low-permeability barrier upgradient of a chlorinated solvent source zone to reduce the transport of competing electron acceptors to a chlorinated solvent source zone (Newell et al., 2001a; Newell et al. 2001b; Newell et al. 2003) (see Figure 1). The calculations (below) show that ERDZ can be inexpensive, reliable, and have the potential to increase the rate of natural biological attenuation processes in a chlorinated solvent source zone once the source zone is isolated. The innovative aspect to this approach is that it will make physical containment much more desirable because it demonstrates that physical barriers will increase mass destruction at many chlorinated solvent sites.

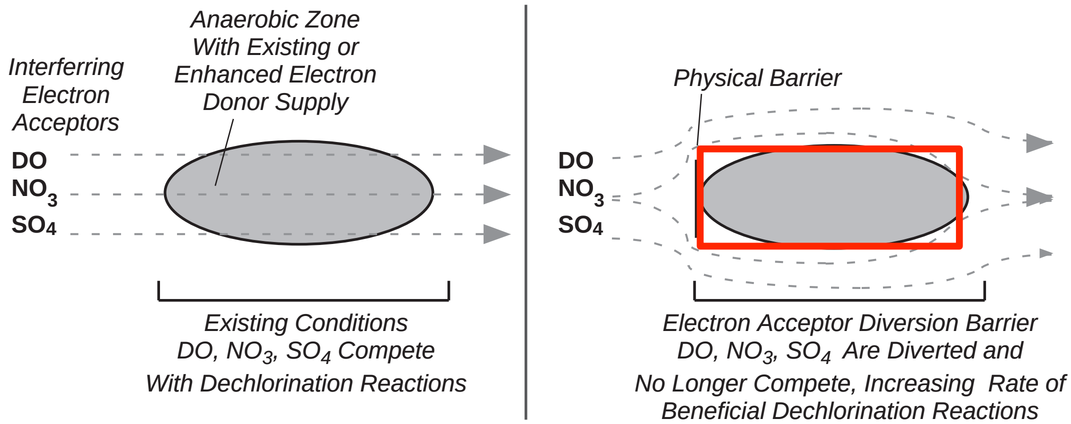


Figure 1. Conceptual Model of Enhanced Reductive Dechlorination Zone (ERDZ) Barrier

BACKGROUND

The presence of competing electron acceptors (primarily dissolved oxygen, nitrate, and sulfate) in a source zone will result in biodegradation reactions that compete with beneficial dechlorination reactions for electron donor. This competition occurs in cases where the electron donor is present in the source zone prior to remediation (a Type I or Type II chlorinated solvent site; Wiedemeier et al., 1999) or if the electron donor supply is enhanced by adding fermentation substrates or hydrogen directly.

MASS DESTRUCTION PERFORMANCE

By diverting the transport of competing electron acceptors (oxygen, nitrate, and sulfate) around a contaminated groundwater zone, the electron donor supply to the beneficial reductive dechlorination reactions is effectively increased, in some cases significantly. For example, a 14-site chlorinated site database in Wiedemeier et al. (1999) show the following characteristics (Table 1).

TABLE 1. Selected hydrogeologic, plume, and background groundwater characteristics from 14 chlorinated solvent sites.

Median plume/source width: 400 ft	Median Background D.O.: 8.0 mg/L
Median seepage velocity: 110 ft/yr	Median Background NO3: 5.8 mg/L
Median saturated thickness: 40 ft	Median Total Chlor. Solvents in Source: 1.5 mg/L

Assuming a porosity of 0.3, a representative specific discharge through a chlorinated solvent source zone is equivalent to 15 x 10^6 L/yr of flow. Approximately 258 pounds of dissolved oxygen and 189 pounds of nitrate flow into a representative source zone per year, where they compete for electron donor. One method to account for the potential amount of lost reductive dechlorination to competing electron acceptors is to assume that every 16 pounds of dissolved oxygen can consume the equivalent of 2 pounds of dissolved hydrogen (based on the stoichiometry of water formation), and that every 50 pounds of nitrate can consume the equivalent of about 4 pounds of dissolved hydrogen (based on the stoichiometry of nitrate reduction; see BIOBALANCE Toolkit, Kamath et al., 2006).

Therefore the introduction of the 258 pounds of dissolved oxygen and 189 pounds of nitrate into the source zone per year is equivalent to the consumption of 48 pounds of dissolved hydrogen per year (i.e., 120*2/16+87*4/50). Finally, if one uses the accepted stoichiometry where 1 pound of hydrogen has the potential to completely dechlorinate 21 pounds of PCE, then as a theoretical upper limit an additional 1040 pounds of PCE could be completely dechlorinated to ethene per year. (Note as a simplifying factor the calculation above does not account for sulfate as a competing electron acceptor, which at many sites would provide more benefit than diverting oxygen and nitrate combined).

In practice only a fraction of the hydrogen mass that is conserved by diverting electron acceptors around the source zone is likely to go directly to dechlorination, so an efficiency factor should be added (based on lab studies, typical efficiency values may in the 10% range with the rest of the hydrogen going to methanogenesis, but there is considerable uncertainty about this amount) (Wiedemeier et al, 1999, Chapter 6). If a value of 10% is used, then about an additional 100 pounds per year of PCE could be degraded every year in the source zone for the barrier ERDZ case compared to the non-barrier, non-ERDZ case.

By comparison, naturally-occurring reductive dechlorination processes in a source zone at a typical chlorinated solvent site may be on the order of tens of pounds per year. Using the BIOCHLOR natural attenuation model (Aziz et al., 2000a) with the representative site data above and a typical biodegradation rate coefficient for chlorinated solvents from the BIOCHLOR database (Aziz et al, 2000b), it is estimated that less than 100 pounds per year of chlorinated solvents are biodegraded naturally per year in a 400 ft by 400 source zone.

Therefore merely diverting the competing electron acceptors away from the source zone has the potential to significantly increase the biodegradation of chlorinated solvents in the source zone of a representative chlorinated solvent site (in the examples above the increase would be from 40 pounds per year to 40+100 pounds per year). Note that these calculations are estimates only and should be confirmed with detailed field measurements. The diversion of competing electron acceptors can be performed in a number of ways as shown in Sheet F_Types.

BIODEGRADATION CALCULATOR INPUT DATA

% Reduction in Flowrate After Barrier Construction:
This is your best estimate of the reduction in groundwater flow through the barrier, typically ranges from 90 to 99%.

Assumed Efficiency (% of Hydrogen Going to Dechlorination):
10% is a best estimate based on laboratory studies (see Wiedemeier et al., 1999, Chapter 6)

lb of COC Degraded to Ethene per lb of H_2: (see Wiedemeier et al., 1999, Chapter 6)
1 pound H2 will dechlorinate 21 pound of PCE to ethene
1 pound H2 will dechlorinate 22 pound of TCE to ethene
1 pound H2 will dechlorinate 24 pound of DCE to ethene
1 pound H2 will dechlorinate 31 pound of VC to ethane

REFERENCES

Aziz, C.E., C.J. Newell, and J.R. Gonzales, 2000. *BIOCHLOR Chlorinated Solvent Plume Database Report*, Air Force Center for Environmental Excellence, Brooks AFB, Texas.

Kamath, R.K., C.J. Newell, B.B. Looney, K.M. Vangelas, and D.T. Adamson. 2006. BioBalance - A Mass Balance Toolkit, User's Manual, May 2006. www.gsi-net.com

Newell, C.J., C.E. Aziz, and G.A. Cox, 2001a. "Novel Method to Enhance Chlorinated Solvent Biodegradation by the Use of Barriers," 2001 Int. Containment & Rem. Technology Conf., June 10-13, 2001, Orlando, Florida.

Newell, C.J., C.E. Aziz, P.E. Haas, J. B. Hughes, and T.A. Khan, 2001b. "Two Novel Methods for Enhancing Source Zone Bioremediation: Direct Hydrogen Addition and Electron Acceptor Diversion", Proceedings of the Battelle Sixth International In Situ and On-Site. Bioremediation Symposium, June 4-7, 2001. San Diego, CA, Battelle Press, Columbus, Ohio.

Newell, C.J., C.A. Aziz, and G.A. Cox, 2003. "Enhanced Anaerobic Treatment Zones in Groundwater", U.S. Patent No. 6562235, 5/13/03.

Wiedemeier, T.H., H.S. Rifai, C.J. Newell, and J.T. Wilson, 1999. Natural Attenuation of Fuel Hydrocarbons and Chlorinated Solvents, John Wiley and Sons, New York, New York.

SHEET D_MODEL:
Model Simulation

Model Simulation

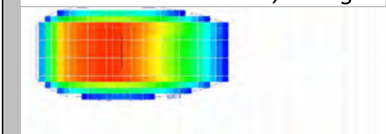
These modeling runs show the biodegradation and mass flux benefits of a barrier. Simulations for the Base Case (No Barrier) and With Square Barrier are shown below for PCE, VC, and EA concentrations over a 30 year period.

Base Case (No Barrier) | **With Square Barrier**

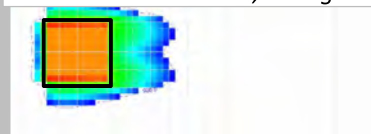
Year: 30

PCE

Dissolved Mass = 20,400 kg



Dissolved Mass = 8,900 kg

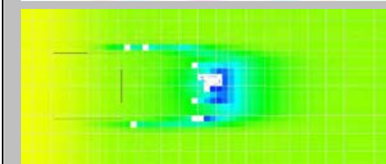


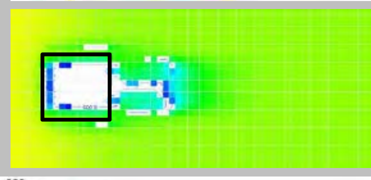
VC

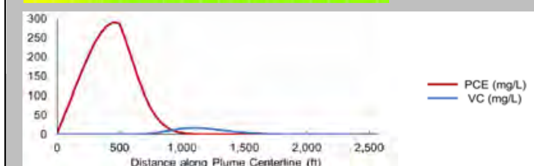
Dissolved Mass = 1,200 kg

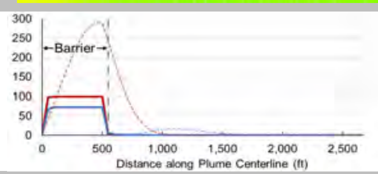
Dissolved Mass = 4,700 kg

EA







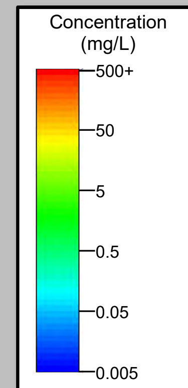


Start/Restart Model Animations

Press "Esc" once to speed up animations.

Press "Esc" again to jump to end of animations.

Additional Details



Notes:

1. PCE = Tetrachloroethylene, VC = Vinyl chloride, EA = Electron Acceptors (e.g. oxygen, sulfate, nitrate).
2. Flow models for degradation products (i.e. TCE and DCE) are not shown.

Navigation Panel

(select from dropdown option and press "Go" or press red arrow)

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A MODELING INVESTIGATION OF THE EFFICACY OF BARRIER WALL CONTAINMENT AS A METHOD TO PROMOTE AND SUSTAIN REDUCTIVE DECHLORINATION OF DISSOLVED CHLORINATED VOLATILE ORGANIC COMPOUNDS IN GROUNDWATER

BACKGROUND AND OBJECTIVES

Chlorinated solvents are ubiquitous contaminants of groundwater. Compared to petroleum hydrocarbons, chlorinated volatile organic compounds (CVOCs) form larger and more persistent groundwater plumes. The larger plumes are the result of higher source concentrations, greater water solubility, and slower biodegradation in the natural groundwater environment.

Although comparatively resistant to biodegradation, most CVOCs do biodegrade in groundwater under anaerobic conditions in the presence of an electron donor (Wiedemeier et al., 1999). The donor at many chlorinated solvent source zones are non-chlorinated hydrocarbons that were co-released with the CVOCs. Anaerobic bacteria will ferment these hydrocarbons and form dissolved hydrogen and acetate as byproducts.

Under these conditions, CVOCs are utilized as the electron acceptor in the oxidation-reduction biodegradation reactions and the hydrogen/acetate serves as the electron donor. This process is called reductive dichlorination. In reductive dichlorination reactions, a chlorine atom is removed from the chlorinated compound and is replaced by a hydrogen atom. This process can continue until all of the chlorine atoms are removed from the original compounds, producing hydrocarbon compounds that biodegrade under both aerobic and anaerobic conditions. Unfortunately existing electron acceptors in groundwater and soil (i.e., dissolved oxygen, nitrate, sulfate in groundwater, and ferric iron on soil) compete for the electron donor, as do methanogenic bacteria that use the hydrogen/acetate to generate methane.

One method to improve the efficiency of CVOC biodegradation reactions in the source zone is to use a subsurface vertical barrier wall around the source that diverts groundwater around the CVOC-impacted groundwater (Kulkarni et al., 2017). The subsurface barrier wall performs two functions. First, it isolates the source of CVOC impacts to the groundwater, significantly limiting further groundwater contamination. Second, by isolating the CVOC source area, the source zone is deprived of oxygen and other electron acceptors (EAs) that would normally flow into the area in groundwater or flow downward from above as precipitation infiltration. The resulting lower EA concentrations in the source zone create the methanogenic conditions needed for reductive dichlorination, so that CVOCs in the source zone are not only isolated, but also biodegraded through reductive dichlorination reactions.

As part of the ESTCP project to determine the effectiveness of a subsurface barrier wall on the degradation of CVOCs, simulations of an isolated region of groundwater containing dissolved tetrachloroethene (PCE) were performed using a numerical groundwater flow and contaminant transport model. The objective of the simulations was to determine the effect of the barrier wall on both plume length and mass reduction over a fixed period of time.

TECHNICAL APPROACH

Conceptual Model and Assumptions

A source zone assumed to contain PCE is presumed to exist in a 10-ft thick confined aquifer. The PCE undergoes reductive dichlorination to trichloroethene (TCE), then to cis-1,2-dichloroethene (DCE), and finally to vinyl chloride (VC). It is assumed that all of the PCE is located within the aquifer, so that there is no PCE contribution to the groundwater from above.

PCE is assumed to be present in dissolved form at a concentration of 100 mg/L over a 500 x 500 ft area. A steady DNAPL source maintains the concentration of PCE inside the wall at the initial concentration. This CVOC "treatment zone" is surrounded by a low-permeability vertical barrier wall that limits the amount of water that can flow through the area. The barrier wall is presumed to be sealed perfectly against the bottom and tops of the aquifer. It is assumed that the treatment zone is covered by a low-permeability cap that prevents infiltration of precipitation that contains dissolved oxygen and other EAs into the area.

A non-specific electron donor (NSED) representing dissolved hydrogen and acetate is assumed to be present within the treatment zone at an initial concentration of 5,000 mg/L. At this concentration, there is an unlimited supply of electron donor. The NSED contributes hydrogen required for reductive dichlorination of the CVOCs. The NSED can also biodegrade using other electron acceptors, including oxygen, nitrate, sulfate, and ferric iron, which are lumped together and designated as a generic EA. The degradation of NSED causes these other EAs within the treatment zone to be depleted, thus creating the necessary highly reducing methanogenic environment for reductive dichlorination to occur.

A control source zone is also simulated for comparison to the treatment zone. In the control zone, initial conditions and the PCE source are identical to the CVOC source zone. However, the control zone is not surrounded by a barrier wall.

Numerical Model

Simulations were performed using a custom reaction module ("GSIM" for general substrate interaction module) for the MODFLOW/RT3D models (McDonald and Harbaugh, 1983; Clement, 1997) run through the Groundwater Vistas Version 6 graphical user interface (ESI, 2017). The custom module allows custom reaction kinetics to be simulated in the MODFLOW/RT3D environment.

Reductive dichlorination was simulated in GSIM by using the NSED as an electron donor with the generic EA as the electron acceptor for aerobic and anaerobic but non-methanogenic reactions, and NSED as the donor with the CVOCs as electron acceptors under methanogenic conditions. Monod kinetic parameters were manipulated so that the reactions utilizing CVOCs closely follow first-order kinetics. Degradation of each CVOC generates a daughter product in the order PCE to TCE to DCE to VC.

Two biological species are assumed to be present. The first biological species, X_F, are a mixed population of facultative organisms capable of utilizing the NSED and generic EAs in respiration reactions. This population of microorganisms is allowed to grow. The second biological species, X_M, utilize NSED as the electron donor and CVOCs as the electron acceptors under methanogenic conditions. Growth of X_M is assumed to be negligible.

An example illustrating the functioning of the reaction model is shown in Figure 1. The concentrations of the CVOCs, NSED, EAs, and the aerobic biological species degrading the NSED is plotted against time in a batch system. At early times, the NSED is degraded aerobically and anaerobically, and EA is consumed. When EAs reach very low levels in the methanogenic range, reductive dichlorination reactions begin.

The numerical model grid consists of 150 rows, 75 columns, and 5 layers. All grid cells measure 50 ft square horizontally, and each layer is 2 ft thick. The grid contains two source areas, one surrounded by a barrier wall and the other not surrounded by a wall for comparison. The locations of the sources in the model grid are shown in Figure 2. Constant head boundaries on the left and right side of the model domain maintain a constant hydraulic gradient of 0.007 to the right.

Reductive dechlorination of PCE occurs when EA levels are low. A switching function increasingly inhibits reductive dichlorination when EA is present. For example, reductive dichlorination is limited to 1% of the potential maximum rate at an EA concentration of 0.6 mg/L, 60% of the maximum rate at an EA concentration of 0.2 mg/L, and 90% of the maximum rate at an EA concentration of 0.09 mg/L.

Simulation Parameters

Three simulations were performed using three different amounts of flow reduction within the CVOC zone: 75%, 90%, and 99%. Trial and error was used to determine the barrier wall hydraulic conductivity that results in these amounts of flow reduction. The results of the trial and error tests indicated that the following barrier wall hydraulic conductivities lead to the desired flow reductions through the CVOC zone:

Flow Reduction	Barrier Wall K (cm/s)
99%	5.6×10^{-8}
90%	6.1×10^{-7}
75%	1.8×10^{-6}

Other key parameters for all simulations are provided in Table 1.

RESULTS

The concentrations of CVOCs and EA from the simulation with a 99% flow reduction are shown in Figure 2 after 30 years. PCE in the control area has migrated with the groundwater, and the simultaneous migration and reductive dechlorination within the moving NSED plume creates a zone of depleted EA. However, because the initial PCE source is not isolated, the CVOC plumes extend a substantial distance from the control area.

By contrast, the CVOC plumes emanating from the treatment zone are much shorter than those from the control area. The EA has become depleted from within the treatment zone because of its isolation from the surrounding aquifer. This isolation has allowed methanogenic conditions to develop within the treatment zone, causing the reductive dechlorination of PCE and its daughter products.

After 30 years, the simulated mass of PCE remaining in the aquifer is 20,400 kg without the barrier wall and 8,900 kg with the barrier wall. VC concentrations greater than 0.005 mg/L extend approximately 1,950 ft downgradient of the control area, and approximately 1,750 feet downgradient of the treatment zone. The peak VC concentration in the control plume is 17 mg/L, while the peak concentration in the treatment zone plume is 2.8 mg/L.

CONCLUSION

The simulations indicate that isolation of a CVOC source to promote reductive dechlorination appears to be a viable method of increasing the destruction of CVOCs while substantially reducing plume migration. In the numerical simulations, the barrier wall decreases PCE mass by 50%, a significant reduction. Outside of the barrier wall, the VC maximum concentration is six times lower, and the VC plume length is also reduced.

REFERENCES

Clement, 1997. RT3D, A modular computer code for simulating reactive multispecies transport in 3 dimensional groundwater systems, R.T. Clement, Pacific Northwest National Laboratory, PNNL11720, 1997.

ESI, 2017. Groundwater Vistas, http://www.groundwatermodels.com.

Kulkarni, P.R., Higgins, E.A., Starters, B.A., Newell, C.J., 2017. Final Report: Contaminant Flux Reduction Barriers for Managing Difficult-to-Treat Source Zones in Unconsolidated Media. ESTCP Project ER-201328. Environmental Security Technology Certification Program (ESTCP). June 2017.

McDonald and Harbaugh, 1983, A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Michael G. McDonald and Arlen W. Harbaugh, USGS Open-File Report 83-875, 1983.

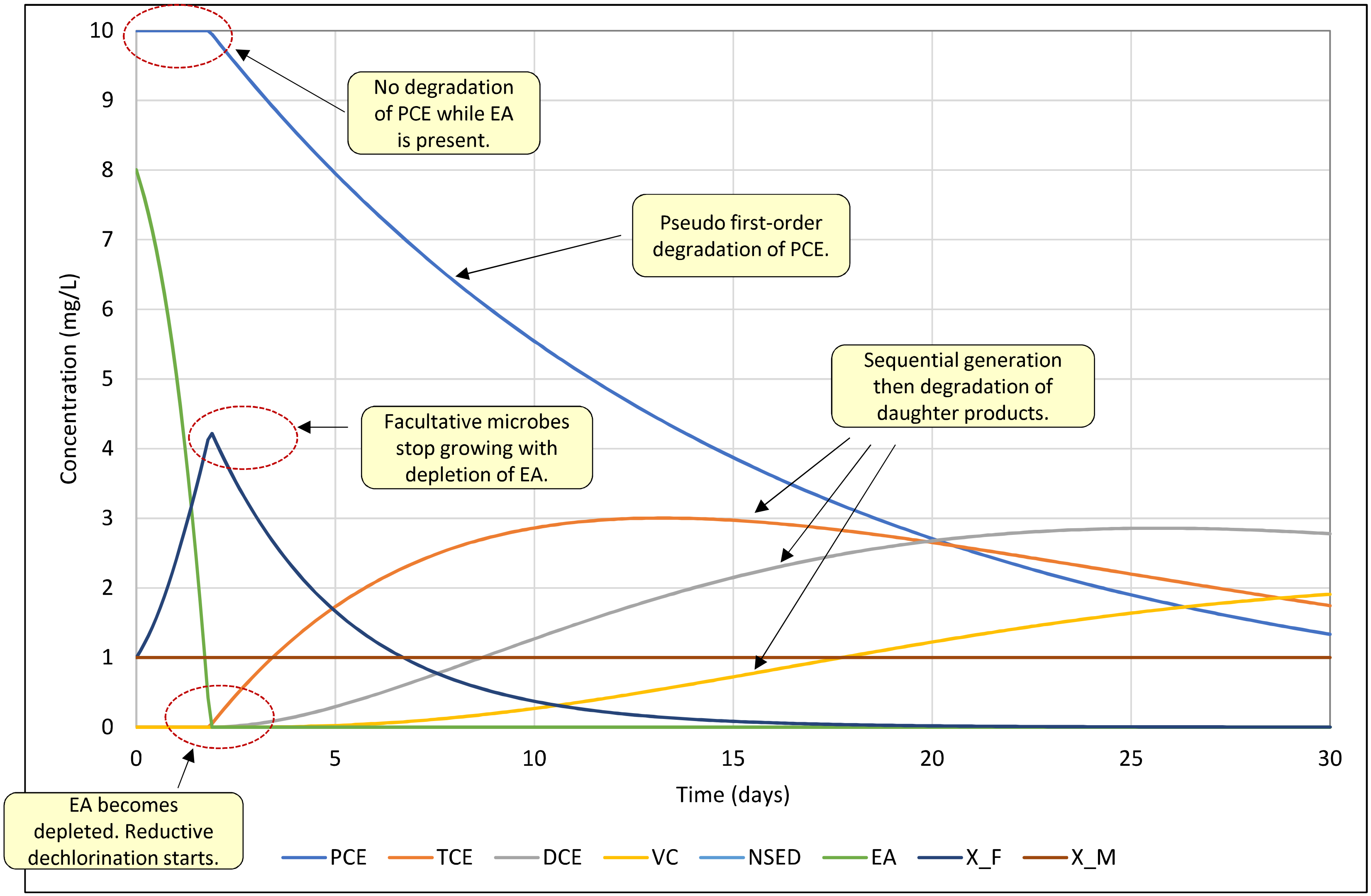
Wiedemeier et al., 1999. Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface, Todd H. Wiedemeier, Hanadi S. Rifai, Charles J. Newell, and John T. Wilson, John Wiley and Sons, New York

GSI ENVIRONMENTAL

Table 1
Simulation Parameters for All Simulations

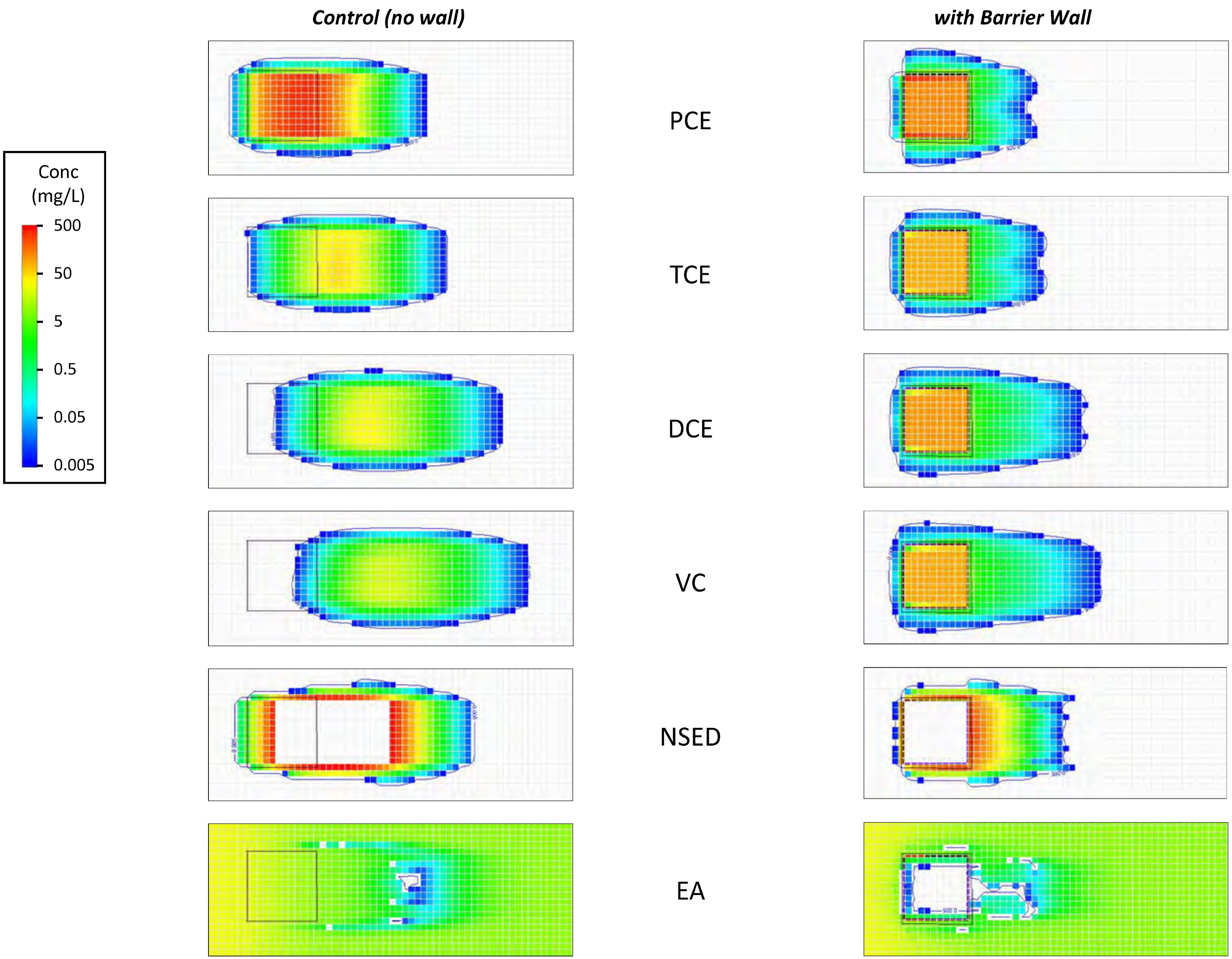
Parameter	Units	Value	Basis
Hydraulic gradient	ft/ft	0.007	Project data
Horizontal hydraulic conductivity (Kh)	cm/s	0.001	Project data
Ratio Kh/Kv		10	Engineering judgment
Longitudinal dispersivity	ft	5	Engineering judgment
Transverse dispersivity	ft	0.5	Engineering judgment
Vertical dispersivity	ft	0.05	Engineering judgment
Effective and total porosity		0.2	Engineering judgment
Barrier wall thickness	ft	4	Project data
NSED initial concentration	mg/L	5,000	Engineering judgment – sufficient to create unlimited supply
PCE initial concentration	mg/L	100	Approximately 10% of PCE solubility
EA initial concentration	25	25	Oxygen concentration at 55 deg C and 5,000 mg/L TDS
Soil bulk density	g/cm3	1.7	Engineering judgment
Organic carbon fraction		0.002	Engineering judgment
PCE retardation factor		3.64	Large R to simulate presence of DNAPL
TCE retardation factor		2.59	Koc of TCE = 93.3
DCE retardation factor		1.49	Koc of DCE = 29.0
VC retardation factor		1.19	Koc of VC = 11.0
NSED retardation factor		2.7	Koc of NSED = 100
EA retardation factor		1	Assumed negligible or inorganic species
PCE half-life	days	950	Average of field observed rates in Table 6.6 of Wiedemeier et al., 1999.
TCE half-life	days	650	Average of field observed rates in Table 6.6 of Wiedemeier et al., 1999.
DCE half-life	days	870	Average of field observed rates in Table 6.6 of Wiedemeier et al., 1999.
VC half-life	days	730	Average of field observed rates in Table 6.6 of Wiedemeier et al., 1999.
EA utilization factor	mass EA/mass NSED	1.0	Engineering judgment
Maximum specific growth rate of X_F	d	1.0	Engineering judgment
Yield coefficient of X_F on growth of NSED	mass X_F/mass NSED	0.5	Engineering judgment
Half-saturation coefficient for substrate (Ks)	mg/L	10.0	Engineering judgment
Half-saturation coefficient for EA (Ka)	mg/L	0.01	Engineering judgment

Figure 1
CVOC Reductive Dechlorination in a Batch System as Simulated by Numerical Model



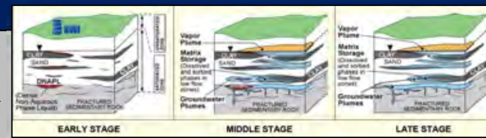
GSI Job No. G3938
Issued: 31 August 2018

Figure 2
Results of Simulations after 30 Years



SHEET E_SUITAB:
Is My Site Suitable for a Barrier?

Is My Site Suitable for a Barrier?



Does my site have a low "remediation potential"?

Late stage chlorinated solvent sites are dominated by matrix diffusion and are very difficult to remediate.

(See ESTCP Project ER-0530 (google "ESTCP FAQ Chlorinated").)

(See SERDP Project ER-1740 for more information on matrix diffusion (google "SERDP ER-1740").)

The ITRC's "Remediation Management of Complex Sites" document provides an 8 question tool to evaluate remediation potential (see table to right), https://rmcs-1.itrcweb.org/3-remediation-potential-assessment/

If the remediation potential is low, then a barrier is one option for managing the hard-to-remediate contaminant.

Table 4. Key criteria for preremedy remediation potential assessment

Assessment Metric	Summary Discussion
1. How difficult is it to work at the surface of the site?	How much of the potential site treatment zone is accessible (such as for drilling or excavating)? Are structures, active process units, sensitive environments, or other restrictions present?
2. How difficult is it to drill at the site?	Is drilling difficult, slow, and resource-intensive in the site? For example, in uncomplicated conditions where contamination is shallow, direct push technologies can be used to install multiple wells.
3. What is the scale of the source zone or plume?	What is the extent of source and plume contamination? Remediation potential may be significantly less if source volume or plume area is extensive.
4. What contaminant concentration reduction is needed?	What is the reduction needed throughout the site to achieve interim objectives? If several orders of magnitude reduction in contaminant concentration is required to reach groundwater remediation goals, then a long remedial time frame is more likely.
5. Do the key site constituents readily attenuate relative to the travel time to receptors?	What is the estimated rate of biotic and abiotic attenuation in the site? If contaminants and geochemical environment are amenable to natural attenuation processes, a site is likely to be remediated in a reasonable time frame.
6. Does difficult-to-remove mass exist at the site?	How much contaminant mass is nonaqueous phase liquid (NAPL) or is present in the low hydraulic conductivity (low-K) zones in the site? If significant contaminant mass is in low-K zones (or in fractured or karst bedrock), the plume will likely persist for a long time without remediation of the mass. If contaminants are present as NAPL, contamination may also persist.
7. What is the predicted remediation performance for available remedial technologies?	Are proven applicable technologies available to address the contamination at the site? Do direct observations at similar sites indicate significant uncertainty and long remedial time frames?
8. What is the predicted time frame for achieving interim or site objectives?	Given available remediation approaches, how long would remediation of the site take? Calculation tools can be used to predict if any approach or combination of approaches could achieve interim objectives for the site in a reasonable time frame.

https://rmcs-1.itrcweb.org/3-remediation-potential-assessment/

Is my site a chlorinated solvent site with on-going biodegradation in the source zone?

If there is biodegradation occurring in the source zone, then building a barrier will divert competing electron acceptors and can increase the source biodegradation rate.

The source biodegradation tool will help you evaluate this potential benefit:

C. Source Biodegradation

What is the best hydrogeology for a barrier?

Relatively shallow or moderately deep sites: 40 feet or shallower.

Sand/silt/clay type sites (gravel, cobbles, and fractured rock media make it much more difficult to construct barriers).

Some type of bottom barrier (such as a low permeability lower clay layer) is usually needed; hanging barriers are less efficient than barriers keyed into clay.

G. Barrier Visualization Tool

Sites with low recharge or some type of cap make recharge less of a concern.

H. Recharge Tool

How much access do I need?

In most cases, a complete enclosure is needed. Three sided barriers are less efficient.

G. Barrier Visualization Tool

Slurry walls require the most working room for construction; the other technologies require less room.

F. Compare Barrier Types

Navigation Panel

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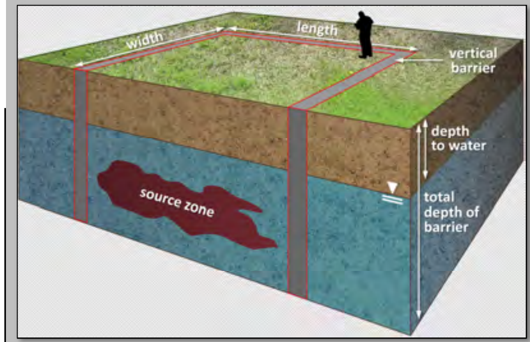
SHEET F_TYPES:
Which Barrier Technology for Your Site?

Which Vertical Barrier Technology Is Right For Your Site?



KEY: Data Input Instructions

##	*Enter value directly*
##	*Previously entered or intermediate calculation. OK to overwrite*
##	*Value calculated by model. Do not overwrite*

In General

- Typically, it must be a sand/silt/clay type site, not fractured rock.
- Likely will need to build a complete enclosure around the site *(see Sheet "G_Visual" for performance of 3-sided and 1-sided barriers).*
- At most sites, need low permeability floor to key barrier into *(see Sheet "G_Visual" for performance of hanging barriers).*
- To get source biodegradation benefit, must be a chlorinated solvent site with electron donor in the source zone (Type 1 chlorinated solvent site) *(see Sheet C_Biodeg for more information).*

Slurry Wall

- Proven, commonly used technology.
- Can extend down to 70 feet or more.
- Typical wall hydraulic conductivity: 10^{-7} cm/sec.
- Specialty contractors also available.
- Need ~15-foot wide working area around wall.

K. Learn More | **K2. Costing Tool**

Sheet Pile Wall

- Proven, commonly used technology.
- For remediation purposes, uses special interlocking pilings.
- Can extend down to ~90 feet.
- Typical wall hydraulic conductivity: 10^{-8} cm/sec.
- Specialty contractors also available.

L. Learn More | **L2. Costing Tool**

Permeation Grouting

- Less commonly used technology.
- Can be implemented with injection-based remediation technologies *(ESTCP Project ER-201328 describes how to do this).*
- Better for sites with a small working area for the barrier.
- Better for high permeability sites.
- Lowest expected wall hydraulic conductivity: 10^{-5} cm/sec; can reduce the hydraulic conductivity of sandy aquifers by 90 - 99%.
- Depth limit is 40 ft.

M. Learn More | **M2. Flowchart** | **M3. Costing Tool**

Grout Bomber

- Experimental technology for building barriers around source zones.
- Has some theoretical advantages, but unproven for barriers.

N. Learn More

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

Start | Go | OR | Main

SHEET G_VISUAL:
Barrier Visualization Tool

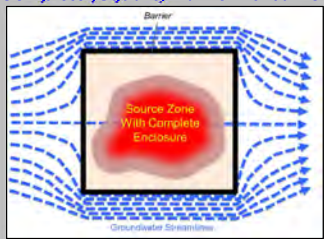
Barrier Visualization Tool

This tool helps you visualize how groundwater streamlines flow around different types of barriers and under different groundwater flow conditions.

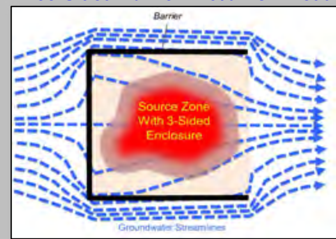
For example, the Base Case streamlines for a **complete (square) barrier**, a **three-side barrie**r, and a **single wall** perpendicular to groundwater are shown below. The corresponding groundwater flow reduction is also shown.

Base Case:

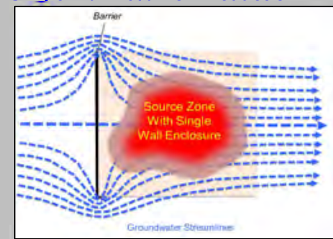
Complete (Square) Barrier: 97% Flow Reduction



Three-Sided Barrier: 79% Flow Reduction



Single Wall: 9% Flow Reduction



Click one of the buttons below to see a detailed groundwater modeling analysis of streamlines and reduction in groundwater flow for each of these three generic shapes for different variables:

- ◉ **Base Case for Three Barrier Configurations**
- ○ **Effect of Groundwater Flow Angle**
- ○ **Effect of Natural Hydaulic Gradient of Groundwater Flowing Around the Barrier**
- ○ **Effect of Barrier Size: Large, Medium, or Small**
- ○ **Effect of Aquifer Effective Porosity**
- ○ **Effect of Barrier Wall Thickness**
- ○ **Effect of Barrier Wall Hydraulic Conductivity/Aquifer Hydraulic Conductivity Ratio: High, Medium, or Low**
- ○ **Effect of Hanging Barrier Wall Configurations**
- ○ **Effect of Hanging Barrier Wall Configuration AND Hydraulic Conductivity of the Barrier**

Navigation Panel

(select from dropdown option and press "Go" or press red arrow)

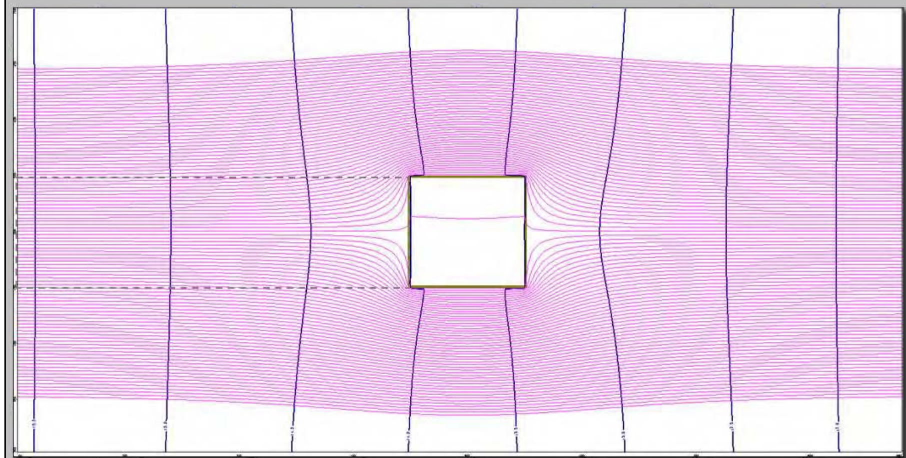
Start | Go | ***OR*** | Main

Results - Effects of Base Case

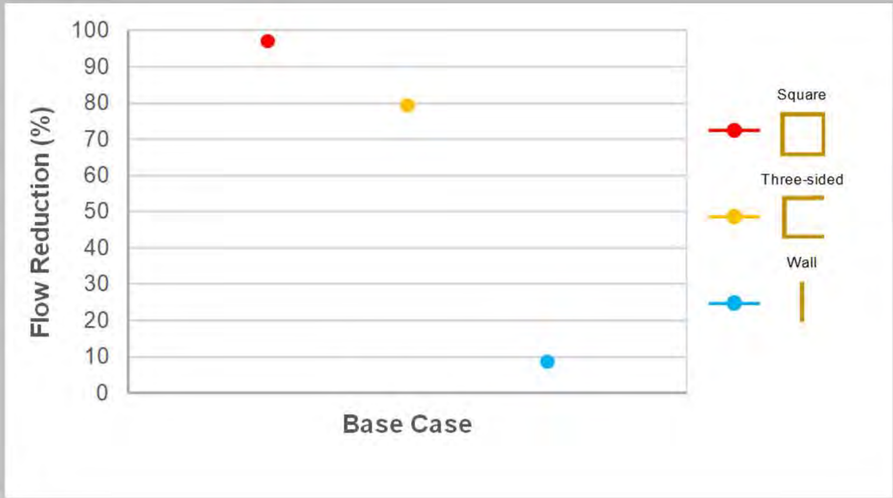
Groundwater streamlines from MODFLOW modeling runs with a barrier in place are shown below. A detailed description of the model is provided at the bottom.

Select option to see modeled flow lines: Base Case - Square

(The barrier (thick black line), equipotential lines (blue), and streamlines (magenta) are shown below in plan view for the different barrier configurations. The flow reduction percentage was determined by evaluating the number of flowlines that were diverted away from the source zone by the barrier. Areas used for the evaluation of the flow reduction are shown by the dashed gray lines.)



Flow Reduction for Barrier Design 97 **(%)**



Key Point
The Square barrier has a higher efficiency than the Three-sided or Wall barriers. The Wall barrier has the lowest efficiency.

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

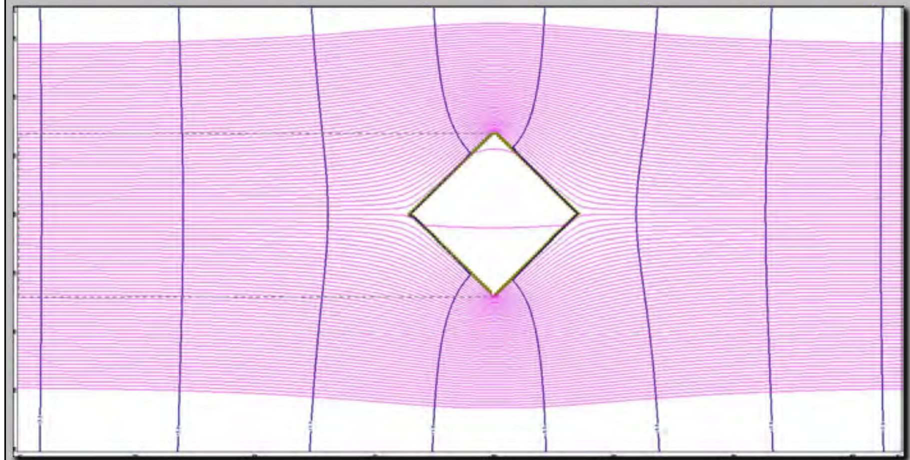
Start | Go | *OR* | G_Visual

Results - Effects of Barrier Angle

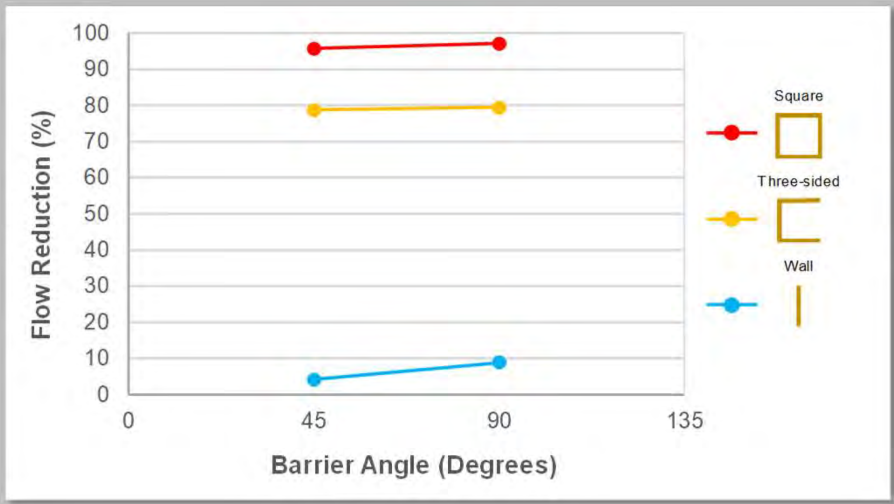
Groundwater streamlines from MODFLOW modeling runs with a barrier in place are shown below. A detailed description of the model is provided at the bottom.

Select option to see modeled flow lines: Square - 45 Degree Angle

(The barrier (thick black line), equipotential lines (blue), and streamlines (magenta) are shown below in plan view for the different barrier configurations. The flow reduction percentage was determined by evaluating the number of flowlines that were diverted away from the source zone by the barrier. Areas used for the evaluation of the flow reduction are shown by the dashed gray lines.)



Flow Reduction for Barrier Design 96 (%)



Key Point
Barrier angle has very small effect on the efficiency of Square, Three-sided and Wall barriers.

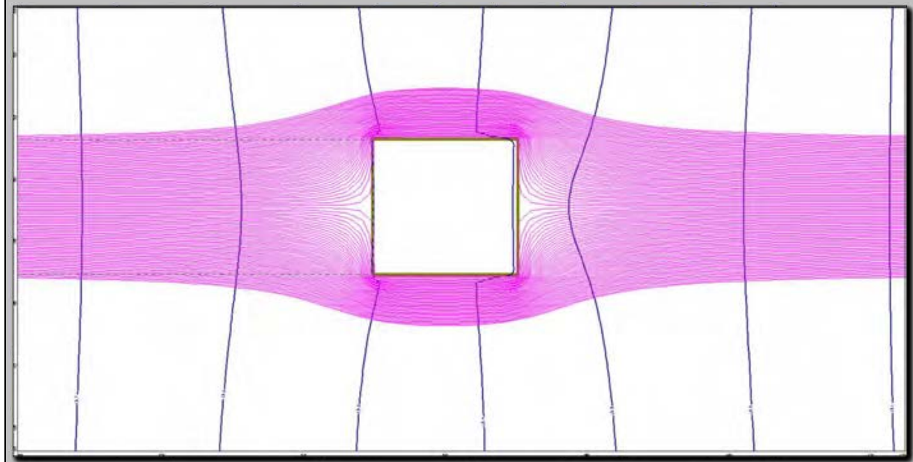
Navigation Panel
(select from dropdown option and press "Go" or press red arrow)
Start | Go | OR | G_Visual

Results - Effects of Barrier Size

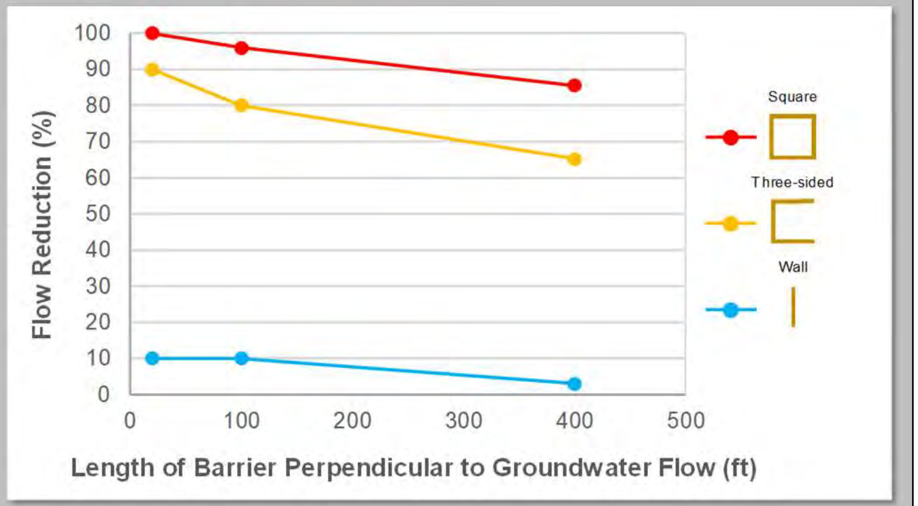
Groundwater streamlines from MODFLOW modeling runs with a barrier in place are shown below. A detailed description of the model is provided at the bottom.

Select option to see modeled flow lines: Square - 20 ft parallel to GW flow

((The barrier (thick black line), equipotential lines (blue), and streamlines (magenta) are shown below in plan view for the different barrier configurations. The flow reduction percentage was determined by evaluating the number of flowlines that were diverted away from the source zone by the barrier. Areas used for the evaluation of the flow reduction are shown by the dashed gray lines.)



Flow Reduction for Barrier Design 100 **(%)**



Key Point
Barrier size has a moderate inverse relationship with efficiency for Square and Three-sided barriers and a smaller inverse relationship with efficiency for Wall barriers.

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

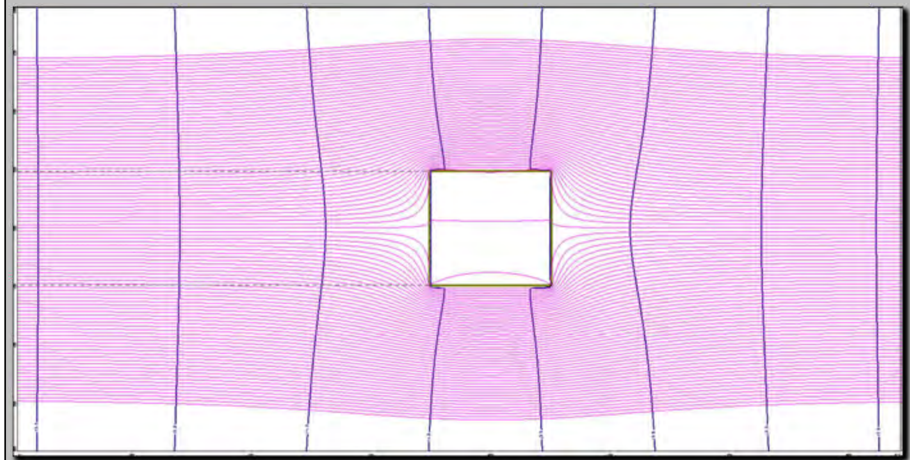
Start | Go | ***OR*** | G_Visual

Results - Effects of Barrier Thickness

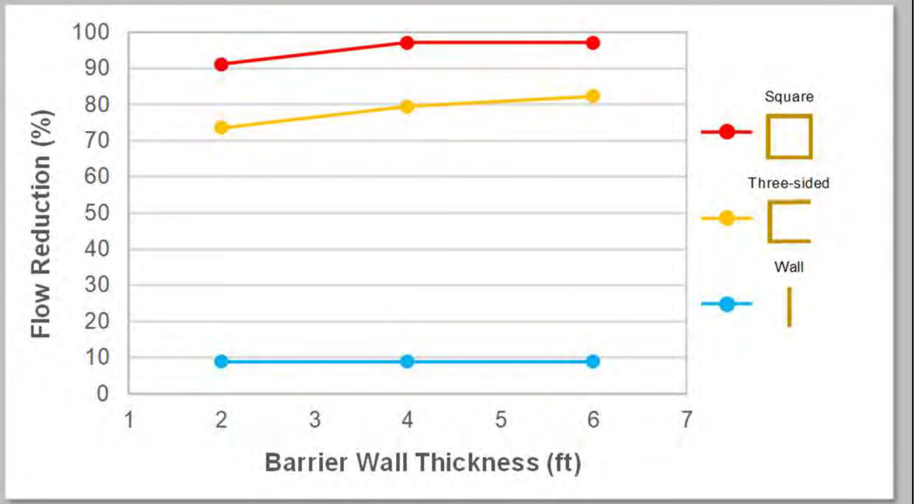
Groundwater streamlines from MODFLOW modeling runs with a barrier in place are shown below. A detailed description of the model is provided at the bottom.

Select option to see modeled flow lines: Square - 2 ft

(The barrier (thick black line), equipotential lines (blue), and streamlines (magenta) are shown below in plan view for the different barrier configurations. The flow reduction percentage was determined by evaluating the number of flowlines that were diverted away from the source zone by the barrier. Areas used for the evaluation of the flow reduction are shown by the dashed gray lines.)



Flow Reduction for Barrier Design 91 **(%)**



Key Point
Barrier wall thickness has a small effect on efficiency for Square and Three-Sided configurations and no effect on efficiency for a Wall configuration.

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

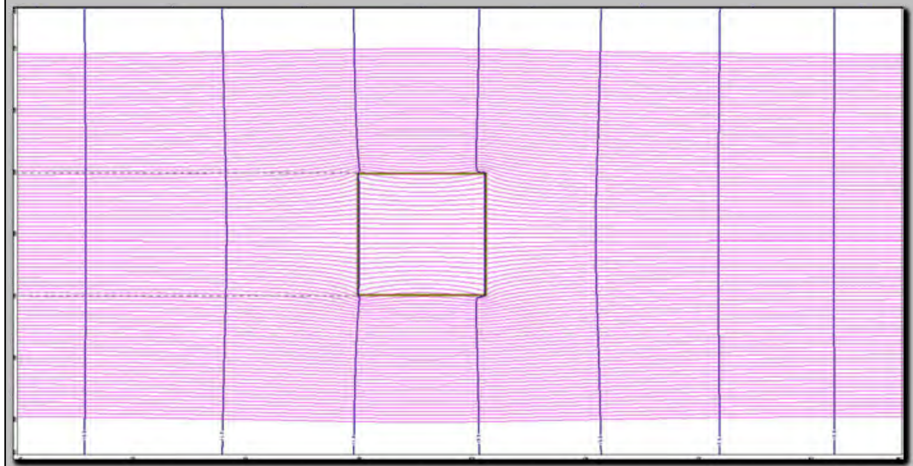
Start | Go | OR | G_Visual

Results - Effects of Hydraulic Conductivity Ratio

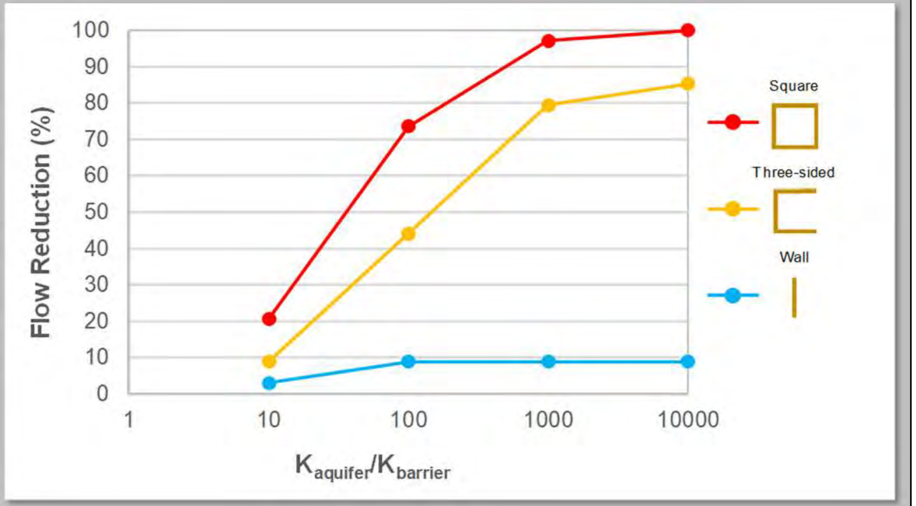
Groundwater streamlines from MODFLOW modeling runs with a barrier in place are shown below. A detailed description of the model is provided at the bottom.

Select option to see modeled flow lines: Square - K Ratio 10

(The barrier (thick black line), equipotential lines (blue), and streamlines (magenta) are shown below in plan view for the different barrier configurations. The flow reduction percentage was determined by evaluating the number of flowlines that were diverted away from the source zone by the barrier. Areas used for the evaluation of the flow reduction are shown by the dashed gray lines.)



Flow Reduction for Barrier Design 21 (%)



Key Point
The hydraulic conductivity ratio (site / within barrier) has a large effect on the reduction in flow for both the Square and Three-Sided configurations, but has a very small impact on the Wall configuration.

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

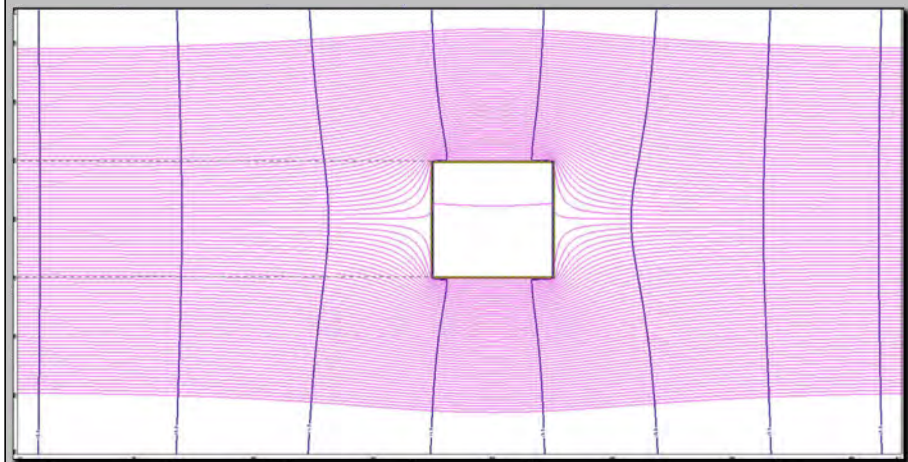
Start Go OR G_Visual

Results - Effects of Effective Porosity

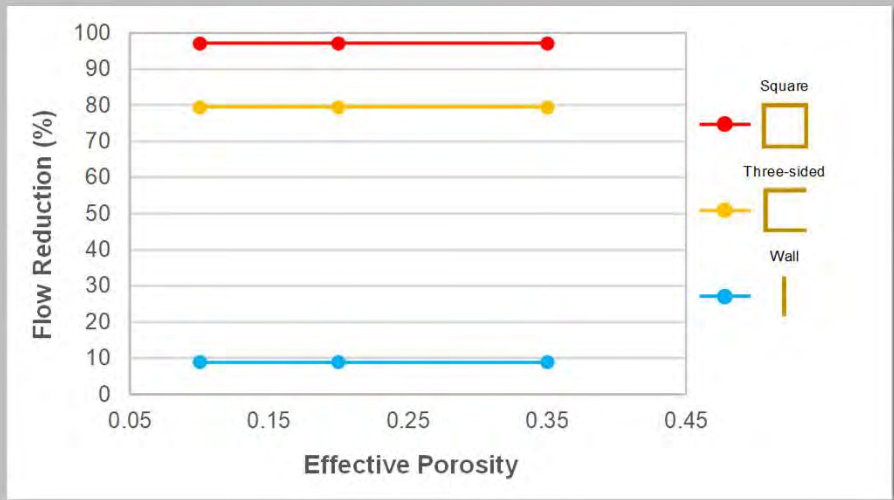
Groundwater streamlines from MODFLOW modeling runs with a barrier in place are shown below. A detailed description of the model is provided at the bottom.

Select option to see modeled flow lines: Square - Effective Porosity 0.1

(The barrier (thick black line), equipotential lines (blue), and streamlines (magenta) are shown below in plan view for the different barrier configurations. The flow reduction percentage was determined by evaluating the number of flowlines that were diverted away from the source zone by the barrier. Areas used for the evaluation of the flow reduction are shown by the dashed gray lines.)



Flow Reduction for Barrier Design 97 **(%)**



Key Point
Effective porosity of a site (initial conditions) has no effect on flow reduction for any barrier configuration.

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

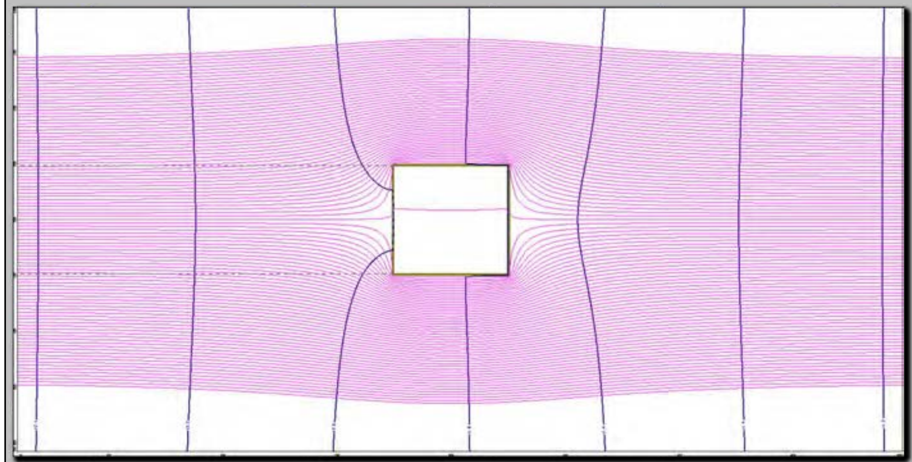
Start | Go | OR | G_Visual

Results - Effects of Hydraulic Gradient

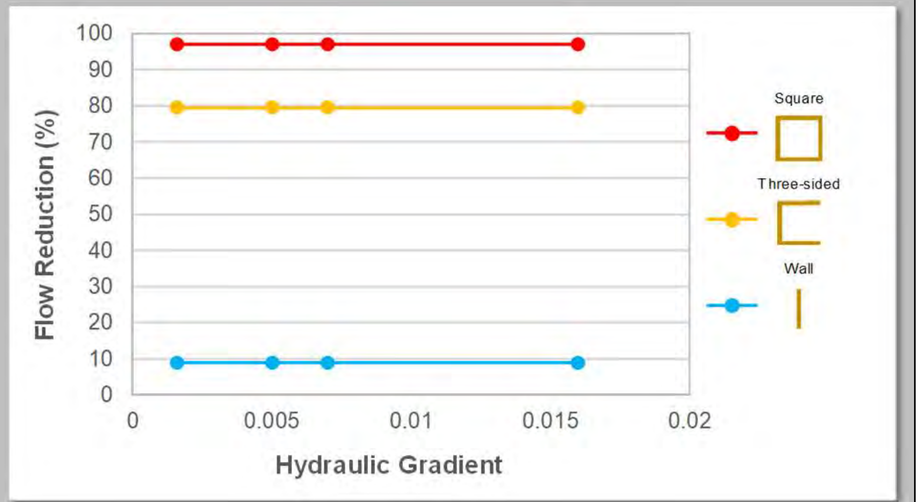
Groundwater streamlines from MODFLOW modeling runs with a barrier in place are shown below. A detailed description of the model is provided at the bottom.

Select option to see modeled flow lines: Square - Gradient 0.0016

(The barrier (thick black line), equipotential lines (blue), and streamlines (magenta) are shown below in plan view for the different barrier configurations. The flow reduction percentage was determined by evaluating the number of flowlines that were diverted away from the source zone by the barrier. Areas used for the evaluation of the flow reduction are shown by the dashed gray lines.)



Flow Reduction for Barrier Design 97 (%)



Key Point
Hydraulic gradient of a site (initial conditions) has no effect on efficiency for any barrier configuration.

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

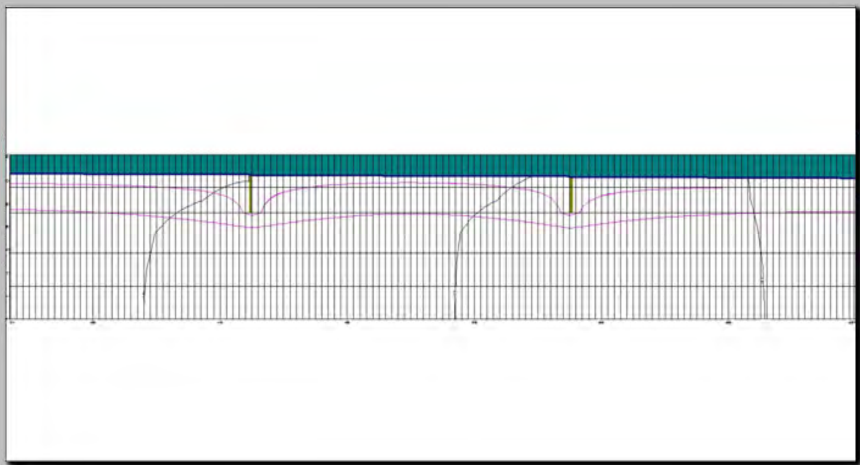
Start | Go | OR | G_Visual

Results - Effects of Hanging Barrier

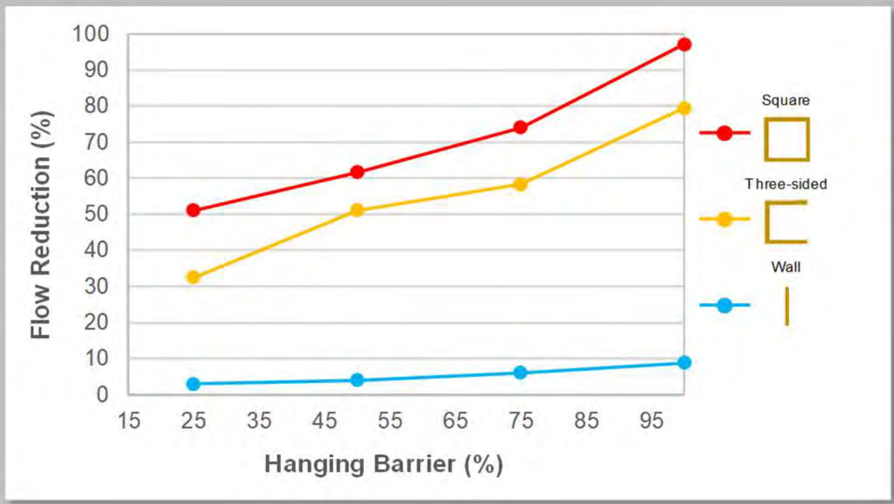
Groundwater streamlines from MODFLOW modeling runs with a barrier in place are shown below. A detailed description of the model is provided at the bottom.

Select option to see modeled flow lines: Square - Hanging 25%

(The barrier (thick tan bar), equipotential lines (blue), streamlines (magenta), and model cells (black) are shown below in cross-section view for the different barrier configurations. The flow reduction percentage was determined by evaluating the number of flowlines that were diverted away from the source zone by the barrier. Green areas represent the unsaturated zone.)



Flow Reduction for Barrier Design 51 **(%)**



Key Point
Barrier depth has a moderate relationship with efficiency for Square and Three-sided barriers and a smaller relationship with efficiency for Wall barriers.

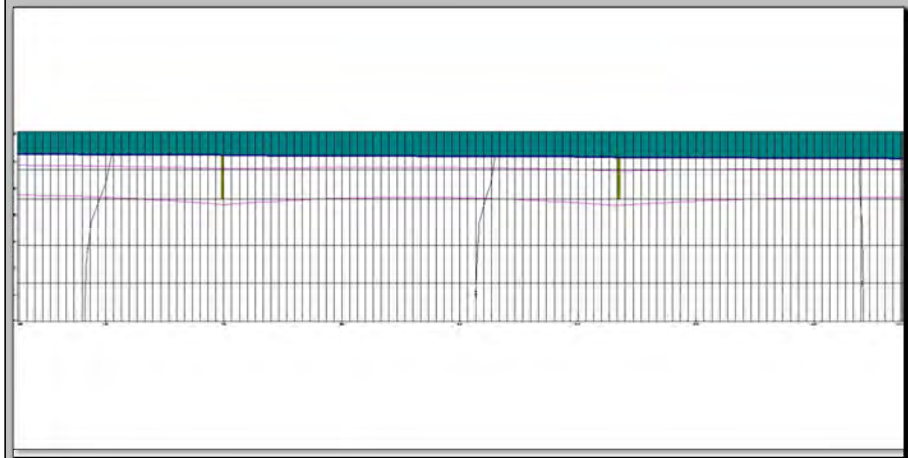
Navigation Panel
(select from dropdown option and press "Go" or press red arrow)
Start | Go | **OR** | G_Visual

Results - Effects of Conductivity Ratio on Hanging Barrier

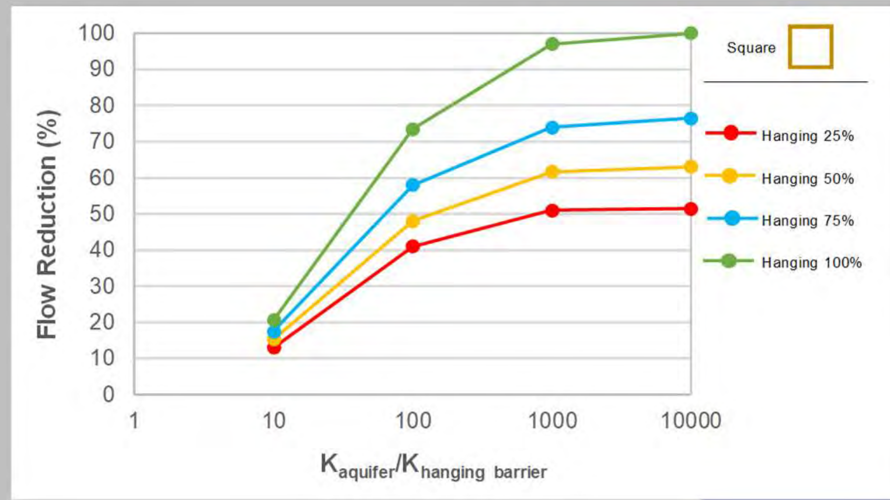
Groundwater streamlines from MODFLOW modeling runs with a barrier in place are shown below. A detailed description of the model is provided at the bottom.

Select option to see modeled flow lines: Square Hanging 25% - K Ratio 10

(The barrier (thick tan bar), equipotential lines (blue), streamlines (magenta), and model cells (black) are shown below in cross-section view for the different barrier configurations. The flow reduction percentage was determined by evaluating the number of flowlines that were diverted away from the source zone by the barrier. Green areas represent the unsaturated zone.)



Flow Reduction for Barrier Design 13 **(%)**



Key Point
For the Square configuration, the hydraulic conductivity ratio (site / within barrier) has a large effect on the reduction in flow that increases with depth of the barrier.

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

Start | Go | ***OR*** | G_Visual

SHEET H_RECHARGE:
Will Recharge (Infiltration) to GW Cause Problems?

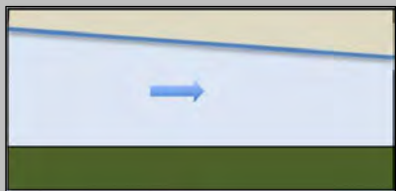
Will Recharge (Infiltration) from the Surface to Groundwater and Other Factors Cause Problems?

1. Will infiltration from the surface (recharge) entering the barrier cause the groundwater level in the barrier to increase and cause a problem if there is no pumping?

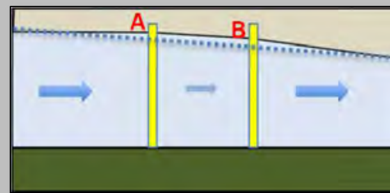
In the figure below, Point **B** is inside the ***barrier*** and shows an increase in groundwater level due to the extra head needed to force infiltrating water out of the barrier.
For a 100 foot wide by 100 foot long, non-sheet wall barrier, a groundwater model showed up to 2 inches per year of recharge did not increase the water levels significantly.
You can use the calcuator to the right to estimate the recharge at your site, based on annual rainfall and soil type, to see if you have more than 2 inch per year recharge.
(Note: A more detailed analysis of recharge impact is recommended as part of the detailed design of any unpumped barrier system, particularly for sheet wall systems.)

KEY: Data Input Instructions

##	*Enter value directly*
##	*Value calculated by model. Do not overwrite*



No Barrier



With Barrier

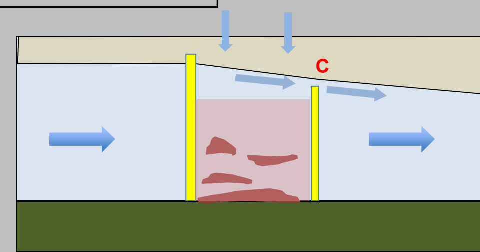
Select Limiting Vadose Zone Soil Type	Sand	
Annual Precipitation	30	in/yr
Recharge Rate through Vadose Zone	4.1	in/yr

Restore Black Cell

What types of engineered factors can be added to unpumped barriers to ensure recharge won't cause a problem?

Two types of engineered factors could be applied to the flux reduction barrier concept to reduce the potential for high groundwater levels:

1. Flux reduction barriers can be constructed with engineered “spillways” (Point **C** to the right) that would relieve any groundwater mounding within the barrier due to high recharge or extreme recharge events (hurricanes), broken water lines, etc.
2. Runoff from roofs of buildings within the barrier footprint and/or associated impervious surfaces could be redirected to areas where this runoff would not be converted to infiltration. Standard stormwater conveyance practices, such as redirecting building downspouts, lining grass swales, and other methods could reduce recharge into the flux reduction barrier.



Note: Spillway concepts may not be appropriate if recharge[0] encounters source materials before discharging.

2. Will groundwater pond up behind the barrier and cause a problem?

In the figure above, Point **A** is immediately upgradient of the ***barrier*** and shows an increase in groundwater level due to the extra head needed to force the groundwater around the barrier. A groundwater model showed a 0.5 foot increase in groundwater elevation at Point A upgradient of a 100 foot wide barrier.
See G_Visual for the streamlines and equipotential lines for aquifers with barriers.

H. Learn More About These Topics

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)

Start | Go | ***OR*** | Main

WILL RECHARGE (INFILTRATION) FROM THE SURFACE TO GROUNDWATER OR OTHER FACTORS CAUSE PROBLEMS FOR UNPUMPED BARRIERS?

Why Unpumped Barriers?

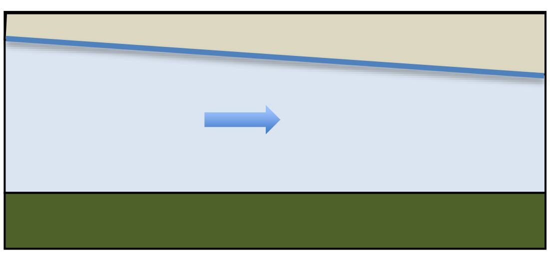
In theory, pumping to maintain an inward gradient reduces outflow to zero. In practice, this can be expensive and more difficult than expected. At many low-risk sites, we feel that unpumped barriers can provide significant benefits compared to source treatment projects that are faced with diminishing returns. At these sites, the reduction in mass flux leaving the source zone is enough for MNA to control the plume.

Potential Groundwater Level Increase from Unpumped Barriers

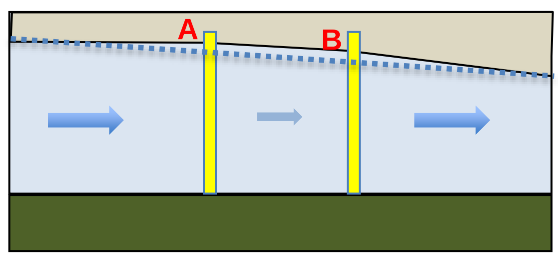
It is possible to construct unpumped barriers that do not increase the groundwater elevations significantly either upgradient (Point A below) or within the barrier (Point B) and do not cause problems such as leakage to surface water or increased vapor intrusion concerns.

Mounding upstream of the barrier is expected to occur only for very large barriers or for impermeable barriers. Barrier systems installed with slurry walls and/or permeation grouting are not completely impermeable. Therefore a slurry wall or permeation grouting barrier can transmit recharge flow through the barrier with only a modest increase in groundwater elevation within the barrier. However, sheet pile systems and other methods likely closer to impermeable conditions will require a more detailed water level increase study.

Our conceptual model is that groundwater flow alone will not cause the potentiometric surface to increase over the highest groundwater elevation in the vicinity of the barrier (i.e. within a short distance upgradient of the barrier):



No Barrier



With Barrier

Qualitative Assessment

Point A is the groundwater elevation a short distance upstream. As demonstrated in the MODFLOW modeling below, this distance upgradient is fairly short, tens or maybe hundreds of feet, but not miles. When this is applied to typical hydraulic gradients in shallow groundwater plumes (1 foot per hundred feet or less) the increase in water level at **Point A** above is limited.

Recharge into the containment zone will result in higher water levels inside the barrier, with the highest elevation increase at **Point B**. However, our experience is that at most contaminated source zones groundwater recharge is a relatively small percentage of the water balance at any site. The reason for this is the amount of recharge upgradient of the source zone that is carried by the groundwater flow in the aquifer is usually much greater than the recharge through the source area alone. A barrier can reduce the natural flow by 90% or more, but at many sites the remaining flow will still be greater than the recharge. The water level within the barrier will find the equilibrium level so that the inflow matches the outflow. Our conceptual model suggests this will be a relatively small increase in groundwater elevation.

MODFLOW Modeling

These qualitative factors describe the project team's understanding of the barrier system flow regime. To provide a quantitative estimate of the groundwater level increase at a hypothetical site, a six-layer system was modeled in MODFLOW. The top four layers represent a heterogeneous system with variable hydraulic conductivities of 10^{-2} cm/sec, 10^{-4} cm/sec, 10^{-2} cm/sec, 10^{-4} cm/sec, respectively, each 10-feet thick. The entire system is underlain by a 10^{-6} cm/sec clay which in turn is underlain by an uncontaminated sand unit.

Model Layer	K (cm/sec)	K_{wall} (cm/sec)	K/K_{wall} Ratio	Layer Type
Layer 1	10^{-2}	10^{-8}	10^{+6}	Convertible
Layer 2	10^{-4}	10^{-10}	10^{+6}	Confined
Layer 3	10^{-2}	10^{-8}	10^{+6}	Confined
Layer 4	10^{-4}	10^{-10}	10^{+6}	Confined
Layer 5	10^{-6}	1	1	Confined
Layer 6	10^{-2}	1	1	Confined

Note: All six layers were set at ten feet thick each.

A containment zone, 100 feet by 100 feet, with an extremely low permeability barrier wall (10^{-8} to 10^{-10} cm/sec) was assumed **(Note: Waterloo Barriers are reported to achieve bulk hydraulic conductivity in the 10^{-8} to 10^{-10} cm/sec range (ES&T, 1999) so this modeling study may not be representative of a sheet piling/Waterloo Barrier configuration).** While unrealistic, the goal of the modeling was to evaluate a very tight barrier that would exaggerate any potential groundwater elevation increase.

The median hydraulic gradient reported in the HGDB Database (0.006 ft/ft) (Hydrogeologic Database, Newell et al,. 1990) was applied to all four top units. Our goal was to model a typical site where recharge is more of a regional process that results in generally evenly spaced elevation contour lines. When high recharge is modeled on a site-specific basis for a low-moderate transmissivity aquifer like the one above, then a non-uniform water table is created: low hydraulic gradient upgradient and high hydraulic gradient downgradient. This flow pattern is only found in nature where almost all of the flow through a site is from recharge and not from upgradient inflow.

A recharge rate of **2 inches per year** was found to be the maximum recharge rate that could be entered in the model without significant distortion of the groundwater elevation contour lines. In other words, for the hydraulic conductivities and thicknesses in the table above, two inches of infiltration appeared to be an upper level amount of recharge that maintained a conventional-looking potentiometric surface map with generally evenly spaced contour lines.

With this model run under steady state conditions, the before-barrier (natural conditions) and after-barrier water levels were evaluated at two places in Layer 1: Points A and B. Groundwater elevation increases of only 0.5 feet and 1.1 feet were observed upgradient and inside the barrier, respectively.

Modeling Scenario	Groundwater Elevation at Point A (Upgradient) (feet)	Groundwater Elevation at Point B (Inside Barrier) (feet)
Natural Conditions	54.99	54.42
Flux Barrier	55.45	55.54
Increase in Groundwater Elevation Due to Flux Barrier	**0.46**	**1.12**

The model was also used to evaluate a **leaky upgradient wall**. For this purpose, the upgradient portion barrier hydraulic conductivities in each layer were reduced by a factor of 100. That is, to 10^{-6} cm/sec, 10^{-8}cm/sec, 10^{-6} cm/sec, 10^{-8} cm/sec, respectively for each layer. For the leaky upgradient wall scenario, groundwater elevation increases of 0.4 feet and 1.1 feet were observed upgradient and inside the barrier, respectively.

Modeling Scenario	Groundwater Elevation at Point A (Upgradient) (feet)	Groundwater Elevation at Point B (Inside) (feet)
Natural Conditions	54.99	54.42
Leaky Flux Barrier	55.44	55.56
Increase in Groundwater Elevation With Leaky Flux Barrier	**0.45**	**1.14**

Finally, the potential for “**upwelling**” was simulated by modeling the system with no wall in layer four (in the case of unexpected hydrogeologic changes). Groundwater elevation increases of 0.5 feet and 0.8 feet were observed upgradient and inside the barrier, respectively, for the upwelling system.

Modeling Scenario	Groundwater Elevation at Point A (Upgradient) (feet)	Groundwater Elevation at Point B (Inside) (feet)
Natural Conditions	54.99	54.42

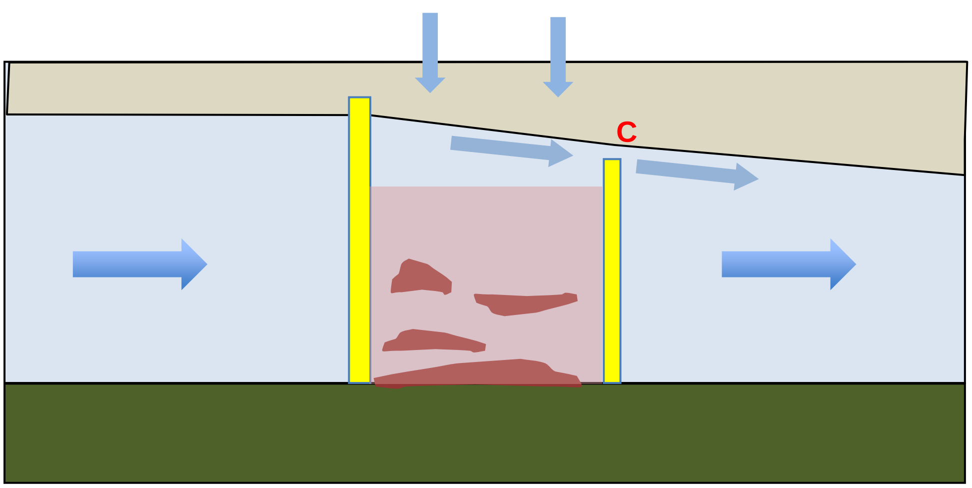
Flux Barrier “Upwelling”	55.45	55.23
Increase in Groundwater Elevation Due to Flux Barrier “Upwelling”	**0.46**	**0.81**

Despite the limited evidence for groundwater elevation increase, we recommend that a more detailed analysis of the hydraulics of an unpumped barrier be performed as part of the project’s detailed design. Additionally, we recommend groundwater monitoring both inside and outside of the barrier be performed to ensure that increasing groundwater levels are not a problem.

Engineered Factors

Two types of engineered factors could be applied to the flux reduction barrier concept to reduce the potential for high groundwater levels that could exacerbate vapor intrusion problems under active buildings and potentially cause other problems.

First, the flux reduction barriers can be constructed with engineered “**spillways**” that would relieve any groundwater mounding within the barrier due to high recharge sites or extreme recharge events (hurricanes), broken water lines, etc. A conceptual picture of the spillway concept is shown below, where the downgradient portion of the barrier is completed at the highest elevation desired by the building and facilities personnel at the site (**Point C** on the graphic below). In this graphic, most of the groundwater leaving the spillway would be considered clean water, as any recharge would have a limited ability to mix with deeper contaminants caused by DNAPL. Therefore, the recharge water would not contribute to increased mass discharge from the barrier. For sites with contamination in the unsaturated zone or shallow groundwater outflow from the spillway likely have some contamination, and therefore, an engineered spillway may not be appropriate or a small-scale permeable reactive barrier type spillway may be required.



Note: Spillway concept may not be appropriate if recharge encounters source material before discharging.

As a second engineered factor, any runoff from the building roof and/or associated parking lots could be **redirected** to prevent it from contributing to recharge into the barrier. Standard stormwater conveyance practices, such as redirecting building downspouts, lining grass swales, and other methods can be applied for recharge reduction.

In the case where elevated groundwater conditions are observed after construction, these stormwater conveyance practices can also be implemented as a mitigation measure to reduce the influx of recharge into the barrier. For more information on stormwater management methods that can be used to better drain the site and reduce infiltration, see the local stormwater design manual from the county or city where the site is located.

As a third engineered factor, an engineered cap could be installed to reduce infiltration and recharge over the area contained by the barrier. Extensive guidance is available for the design and construction of caps (EPA, 2012; NJDEP, 2014).

We recommend detailed hydraulic studies be conducted before implementing any of these engineered factors for a barrier system.

REFERENCES

Environmental Science and Technology, 1999. Control of Contaminated Groundwater. March 1999.

EPA, 2012. A Citizen's Guide to Capping. Office of Solid Waste and Emergency Response.

Newell, C. J., L. P. Hopkins, and P. B. Bedient, 1990. "A Hydrogeologic Database for Groundwater Modeling", Ground Water, Vol. 28, No. 5.

NJDEP, 2014. "Technical Guidance on the Capping of Sites Undergoing Remediation", Site Remediation Program, Version 1.

Wiedemeier, T.H., Rifai, H.S., Newell, C.J., and Wilson, J.W., 1999. Natural Attenuation of Fuels and Chlorinated Solvents, John Wiley & Sons, New York. (equation 2.12)

INFILTRATION/RECHARGE ESTIMATES

Source: Wiedemeier et al. Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface. John Wiley & Sons, Inc. 1999. Chapter 2.

Once the concentration of contaminant in the leachate is estimated (using the partitioning relationships presented above), the volume of the leachate that is being generated each year must be calculated to estimate contaminant loadings to an aquifer. In the vadose-to-saturated-zone source scenario, leachate is generated from the net infiltration of precipitation through the surface soil column and then is diluted with fresh groundwater in the water-bearing unit. Net infiltration corresponds to total infiltration (precipitation minus runoff) minus the additional loss associated with evapotranspiration. The net infiltration term thereby represents the deep percolation flow through the contaminated vadose zone, which transports contaminants to the groundwater. Another term for net infiltration is recharge.

Because net infiltration is very rarely measured, it is a difficult value to estimate accurately. It can be derived from a variety of field and modeling techniques, including: soil/water balances, recharge estimated by steady-state yield, streamflow measurements, tracer (e.g., tritium or chloride) studies, water level fluctuations, soil models (including HELP), Richard's equation, direct measurement with lysimeters, and basin outflow.

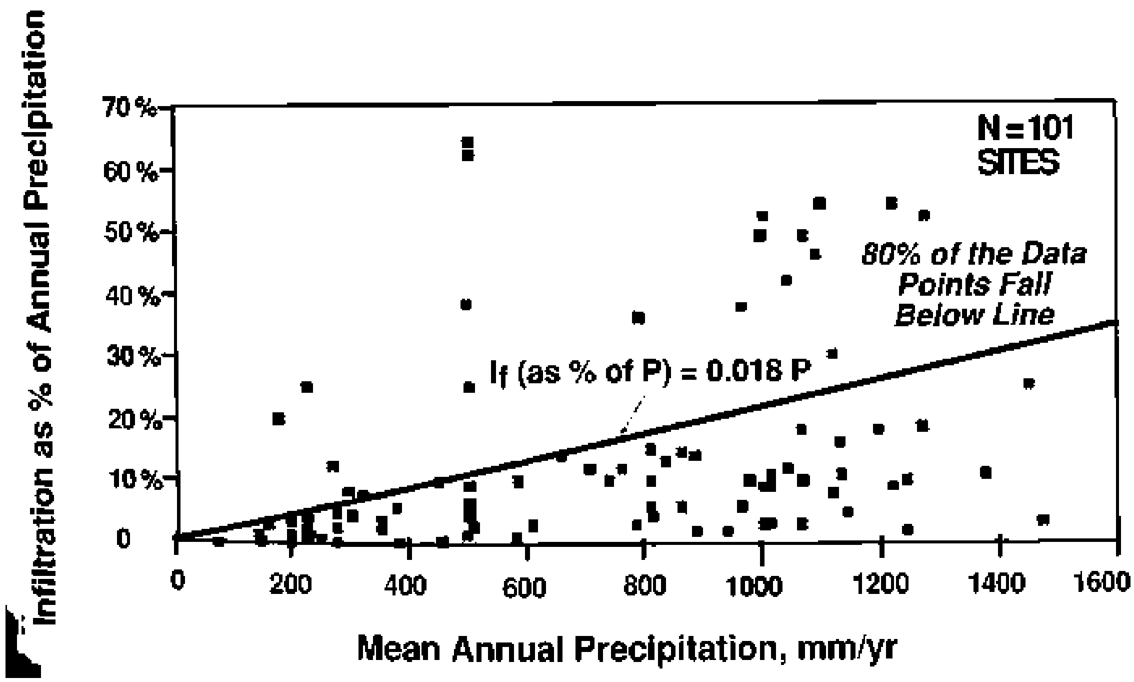


Figure 1. Annual infiltration as a percentage of annual precipitation as reported from 101 infiltration studies. The line represents an upper-range estimate for infiltration, as 80% of data points fall below the line. (From Wiedemeier et al., 1999; original data from American Petroleum Institute, 1996.)

One useful study (American Petroleum Institute [API], 1996) compiled data from more than 100 studies employing various methods to estimate infiltration (Figure 1). These data were used to develop simple, upper-bound estimates of net infiltration as a function of average rainfall and the predominant soil type (sand, silt, or clay), assuming a grass ground cover. Figure 1shows a curve that represents an 80% envelope line for rainfall infiltration data from more than 100 sandy-soil sites in 18 geographic regions in the U.S., as compiled in the API (1996) study. This curve provides a conservative (80%-upper-bound) estimate of net infiltration for sand or gravel soil sites reported in this database. Note that the y-axis represents the *percentage* of annual precipitation that becomes net infiltration, so that net infiltration in units of cm/yr becomes a function of annual precipitation squared:

For sandy soils: $I_f = 0.0018 \cdot (P)^2$ eq. 1

where:

I_f = Net infiltration per year (cm/yr)

P = Mean annual precipitation (cm/yr)

Curves for silty and clayey soils were then derived from the empirical sandy soil curve based on the relative percent infiltration described by Viessman et al. (1989) for the parameters of the Horton infiltration relationship. This relationship indicates that a silty soil will have 50% of the net infiltration through sandy soil during a theoretical storm event, and clayey soil will have only 10%. The following equations provide upper-bound estimates for net infiltration:

For Silty soils: $I_f = 0.0009 \cdot (P)^2$ eq. 2

For Clay soils $I_f = 0.00018 \cdot (P)^2$ eq. 3

Upper-bound net infiltration limit: $I_f \leq I_{f max} = K_{vs}$ eq. 4

For more detailed estimates of infiltration, the HELP model, a quasi-two-dimensional, deterministic, computer-based water budget model can be applied (Schroeder et al., 1994; https://www.nrc.gov/docs/ML1015/ML101590180.pdf).

REFERENCES

American Petroleum Institute (API), 1996, Estimation of Infiltration and Recharge for Environmental Site Assessment, Daniel B. Stephens & Associates, Inc., API Publication 4643, Washington, D.C.

Schroeder, P. R., Aziz, N. M., Lloyd, C. M. and Zappi, P. A. (1994). "The Hydrologic Evaluation of Landfill Performance (HELP) Model: User's Guide for Version 3," EPA/600/R-94/168a, September 1994, U.S. Environmental Protection Agency Office of Research and Development, Washington, DC.

Viessman, W., Lewis, G.L., and Knapp, J.W., 1989, Introduction to Hydrology, 3rd ed., Harper Collins Publishers, New York, New York.

Wiedemeier, T.H., Rifai, H.S., Newell, C.J., and Wilson, J.W., 1999. Natural Attenuation of Fuels and Chlorinated Solvents, John Wiley & Sons, New York.

SHEET I_SURVEYS and I2_EPA:
Survey of Sites with Installation of Barriers

This Project's Survey of Sites with Installation of Barriers

Site ID	Site Location	Barrier Type (year of installation)	Purpose of Barrier	Dimensions of Barrier in feet (year)	Pump-and-Treat System?	Cap?	Other Remediation Technologies Implemented
1	CA	Slurry wall (1993)	Direct groundwater flow to PRB	N/A	Yes	N/A	• Excavation • PRB • Pump-and-Treat
2	CO	Slurry wall (1998)	N/A	8,800 L	Yes	N/A	• Excavation • Extraction wells • GW collection trenches
3	CA	Slurry wall (1986) Slurry wall (1987)	N/A	40 D (1986) 100 D (1987)	Yes	N/A	• Excavation • Aeration • SVE • GAC
4	NY	Sheet pile (2001)	N/A	2,350 L × 20 D	Yes	Yes	• Excavation • Pump-and-Treat
5	CT	Steel sheet pile (1995)	Containment	700 L × 300 D	Yes	Yes	• OIS • Aquifer containment and treament system • Wetland • Excavation • In situ thermal treatment
6	GA	Soil-bentonite slurry wall (2009)	Containment	1,000 L × 480 D	Yes	Yes	N/A
7	NH	Slurry wall (1982)	N/A	4,000 L × 110 D	Yes	Yes	• Emergency GW system • Treatment plant • Drum removal
8	TX	Slurry wall (1997)	N/A	55 D	Yes	Yes	• On-site incineration • Excavation • GW/ DNAPL treatment system • Consolidation
9	CA	Slurry wall (1992)	Containment	410 L; 1 feet into clay layer	Yes	N/A	• UST removal • Excavation and treatment • Pump-and-Treat • Ozone • SVE
10	WA	Slurry wall (1988)	N/A	4,400 L × 40 D	Yes	Yes	• Excavation • Pump-and-Treat
11	CA	Slurry wall (2003) Slurry wall (2007)	Containment	1,900 L (2003) 1,500 L (2007)	Yes	Yes	• UST removal • Phytopumping system • GW extraction through slurry wall • PRB
12	CA	Slurry-bentonite wall (1989)	Containment of impoundments	1,315 L × 3 W × 35-45 D; 5 feet into aquitard	Yes	Yes	• Excavation • Pump-and-Treat

Notes: 1. L = Length
D = Depth
W = Width
2. N/A = Not available
3. PRB = Permeable Reactive Barrier
SVE = Soil Vapor Extraction
GAC = Granular Activated Carbon
OIS = On-site Interceptor System
UST = Underground Storage Tank
GW = Groundwater
DNAPL = Dense Non-Aqueous Phase Liquid

SUMMARY OF KEY CHARACTERISTICS

- Length: 410 to 8,800 ft; median = 1,700 ft.
- Depth: 20 to 480 ft; median = 50 ft.
- Purposes: Containment, also used as interim containment prior to the implementation of other technologies.
- Other technologies implemented: Pump-and-Treat system, Excavation, SVE, PRB, etc.

See See EPA Survey of Barrier Projects

Learn More

Navigation Panel
(select from dropdown option and press "Go" or press red arrow)
Start Go OR Main I2_EPA

Survey Results of Barriers at Waste Sites Performed by EPA (EPA, 1998)

Site	Barrier Type									Cap				Extraction System		
	Year Installed	SB	CB	SCB	Clay	Concrete	Sheet Pile	Plastic Concrete	Vibrating Beam	RCRA	Clay	Soil	Asphalt	Pumping Wells	Leachate Collection	Drains
1.	1989	•									•			•	•	
2.	1981	•									Under Construction		•			
3.	1987/89	•								•						
4.	1993	•								•					•	
5.	1991				•						•				•	
6.	1993	•								•				•		
7.	1990	•									•				•	
8.	1989/91						•								•?	
9.	1995	•													•	
10.	1988	•												•		
11.	1992	•		•						•				•	•	•
12.	1991								•			•				
13.	1984									•				•		•
14.	1987							•						•		
15.	1984/89	•										Proposed		•	•	
16.	1983		•				Existing					•				
17.	1991	•								•				•	•	•
18.	1994	•								•				•		
19.	1983	•								•				•	•	
20.	1996	•								Under Construction				Under Construction		
21.	1991	•								•						
22.	1991	•								•						
23.	1984															
24.	1996	•								•				•		
25.	1989	Hanging wall •														
26.	1977	•									•					
27.	1986	•								•				•		
28.	1986	•											•	•		
29.	1986	•								•				•		
30.	1991	• Primary							• Intermediate	•				• Intermittent		
31.	1986	•												•		•
32.	1989	•								•				•	•	
33.	1994		•	• Treatment Wall												
34.	1988	•														
35.	1994					•		•		•				•		
36.	1992									•					•	

Note: SB = Soil bentonite
CB = Cement bentonite
SCB = Soil cement bentonite
RCRA = Resource Conservation and Recovery Act Subtitle C

Sources of data

1. EPA, 1998. Evaluation of Subsurface Engineered Barriers at Waste Sites Volumes 1 & 2.
   https://www.epa.gov/remedytech/evaluation-subsurface-engineered-barriers-waste-sites-volumes-1-and-2
2. EPA Search Superfund Documents link: https://www.epa.gov/superfund/search-superfund-documents
3. California Water Resources Control Board database (Geotracker): https://geotracker.waterboards.ca.gov/

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GSI ENVIRONMENTAL

SURVEY OF KEY CHARACTERISTICS OF VERTICAL BARRIERS FOR CONTROLLING CONTAMINATED GROUNDWATER SOURCE ZONES

EXECUTIVE SUMMARY

- A search of waste sites in the U.S. with installations of barriers was performed
- Data sources included the GeoTracker database from California and EPA's publicly-available superfund site documents
- 96 sites were selected from the initial search
- 12 sites with available information were included in the final survey results

BACKGROUND

Subsurface vertical barriers around contaminated site source zones have been one of the most common technologies for reducing the risk and protecting the human health and the environment. The vertical barriers are implemented to limit and/or eliminate the movement of the contaminant from the source through the subsurface. They can be designed with minimal complexity, and are relatively inexpensive compared to the in-situ remediation cleanup technologies for large, complex sites. Commercially available subsurface barrier technologies and those in the development stage are designed for different hydrogeological settings, and many factors such as the dimension of the containment zone, the material for the barrier; soil type, and construction methods are considered before deciding on whether a barrier is appropriate and which containment system to choose.

The objective of this survey was to review available site documents in order to assess the characteristics of vertical barriers.

METHODOLOGY

Data Sources

An initial search of candidate barrier sites was performed using the California Water Board database, GeoTracker. A total of 83 sites were identified with some mention of "barrier" in the key word search performed on the database containing remediation technologies implemented and which had groundwater impacts of chlorinated solvents. Another 13 sites were included in the review stage based on the publicly-available Environmental Protection Agency (EPA) Superfund documents.

Review Process

From the subset of sites identified, site documents were reviewed in order to compile the following key information of historical barrier installations:

- site location;
- barrier construction details (types, year of installation, purpose and dimensions);
- other remedial technologies implemented at the site;

- primary Constituents of Concern (COCs).

Subsequently, a final dataset of 12 sites with the available information was included in the final survey results.

RESULTS

Table 1 below summarizes the results of the survey. The sites were geographically distributed in 8 states and represented a wide range of barrier age and barrier dimensions. Most of the barriers were slurry walls while two sites had utilized sheet-pile walls. More than one type of in-situ remedial technology was implemented at all sites (e.g., excavation, soil vapor extraction), with pump and treat systems being the most common.

GSI ENVIRONMENTAL

Table 1: Summary of Survey Results of Barrier Installations

Site ID	Barrier Type (year of installation)	Purpose of Barrier	Dimensions of Barrier in feet (year)	Pump-and-Treat System?	Cap Installed?	Other Remediation Technologies Implemented	Primary COCs
1	Slurry wall (1993)	To direct groundwater flow to PRB	N/A	Yes	N/A	▪ Excavation ▪ PRB ▪ Pump-and-Treat	TCE, PCE, VC
2	Slurry wall (1998)	N/A	8,800 L	Yes	N/A	▪ Excavation ▪ Extraction wells ▪ GW collection trenches	VOCs, Semi VOCs, PCBs, Metals, Pesticides, Methane and other gases
3	Slurry wall (1986) Slurry wall (1987)	N/A	40 D (1986) 100 D (1987)	Yes	N/A	▪ Excavation ▪ Aeration ▪ SVE ▪ GAC	TCE, PCE, 1,2-DCE, VC, Chloroform, 1,2-DCB, 1,1-DCA, 1,1-DCE, Freon 113, 1,1,1-TCA
4	Sheet pile barrier (2001)	N/A	2,350 L × 20 D	Yes	Yes	▪ Excavation ▪ Pump-and-Treat	N/A
5	Stelel sheet pile (1995)	Containment	700 L × 300 D	Yes	Yes	▪ OIS ▪ Aquifer containment and treament system ▪ Wetland ▪ Excavation ▪ In situ thermal treatment	VOCs, Semi VOCs, PCBs, Metals, Pesticides
6	Soil-bentonite slurry wall (2009)	Containment	1,000 L × 480 D	Yes	Yes	N/A	2,3,7,8-TCDD
7	Slurry wall (1982)	N/A	4,000 L × 110 D	Yes	Yes	▪ Emergency GW system ▪ Treatment plant ▪ Drum removal	Methylene Chloride, 1,2-DCA, TCE, Chloroform
8	Slurry wall (1997)	N/A	55 D	Yes	Yes	▪ On-site incineration ▪ Excavation ▪ Groundwater/ DNAPL treatment system ▪ Consolidation	1,1,2-TCA, 1,1-DCE, 1,2-DCA, Benzene, Vinyl Chloride, Bis(2-Chloroethyl)Ether, Naphthalene
9	Slurry wall (1992)	Containment	410 L; 1 feet into clay layer	Yes	N/A	▪ UST removal ▪ Excavation and treatment ▪ Pump-and-Treat ▪ Ozone sparging SVE	Gasoline
10	Slurry wall (1988)	N/A	4,400 L × 40 D	Yes	Yes	▪ Excavation ▪ Pump-and-Treat	TCE
11	Slurry wall (2003) Slurry wall (2007)	Containment	1,900 L (2003) 1,500 L (2007)	Yes	Yes	▪ UST removal ▪ Phytopumping system ▪ GW extraction through ▪ Slurry wall ▪ PRB	TCE, PCE, VC, Diesel
12	Slurry-bentonite wall (1989)	Containment of impoundments	1,315 L × 3 W × 35-45 D; 5 feet into aquitard	Yes	Yes	▪ Excavation ▪ Pump-and-Treat	Pentachlorophenol, Dioxins/furans, 1,2-DCA

Note: 1. L = Length
D = Depth
W = Width
2. N/A = Not available
3. PRB = Permeable Reactive Barrier
SVE = Soil Vapor Extraction
GAC = Granular Activated Carbon
OIS = On-site Interceptor System
UST = Underground Storage Tank
GW = Groundwater
DNAPL = Dense Non-Aqueous Phase Liquid
4. COCs = Chemicals of Concern
TCE = Trichroloethene
PCE = Tetrachloroethene
VC = Vinyl Chloride
PCBs = Polychlorobiph
1,2-DCE = 1,2-Dichloroethene
1,2-DCB = 1,2-Dichlorobenzene
1,2-DCA = 1,2-Dichloroethane
1,1-DCE = 1,1-Dichloroethene
Freon 113 = 1,1,2-Trichloro-1,2,2-trifluoroethane
1,1,1-TCA = 1,1,1-Trichloroethane
2,3,7,8-TCDD = 2,3,7,8-Tetrachlorodibenzodioxin
1,1,2-TCA = 1,1,2-Trichloroethane
VOCs = Volatile Organic Compounds

SHEET J_Q_vs_A:
Evaluation of Flow vs. Cross-Sectional Area at Sites

Evaluation of Flow vs. Cross-Sectional Area at Sites

Geologic heterogeneity is important, so what percent of an aquifer's cross-section carries how much groundwater flow?

The importance of geologic heterogeneity in the remediation field is now being emphasized by new concepts such as *"90% of the mass flux occurs in 10% of the cross-sectional area"* and that most of the flow occurs through the aquifer's *"mobile porosity"* which may be much lower than the commonly-used effective porosity (between 0.02 and 0.10 for mobile porosity vs. 0.25 for effective porosity).

A theoretical analysis by Payne et al. (2008) suggested that 90% of aquifer flow was transmitted in only 20% of the aquifer cross-section in "most natural aquifers". This question is also relevant to permeation grouting barriers where a grout is injected to fill in the transmissive portion of the aquifer. Therefore, as part of this ESTCP project, a data mining study was conducted to learn more about groundwater flow vs. aquifer cross-sectional area. GSI Environmental evaluated 141 boring logs from 43 sites to develop an empirical estimate of the groundwater flow vs. aquifer cross-sectional area. This ESTCP study indicated that at these 43 sites, **an average of 30% of the cross-sectional aquifer area carries 90% of the groundwater flow.**

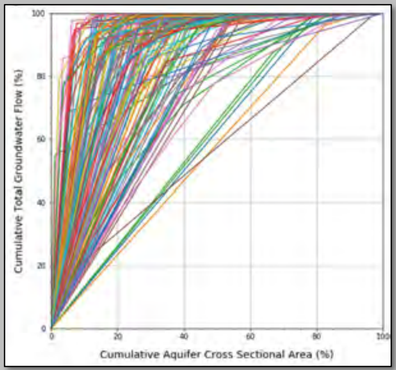

Figure 1: Cumulative Total Groundwater Flow vs. Cumulative Aquifer Cross-Section for 141 Boring Logs. The curves that are clustered to the top/left represent high heterogeneity settings with more low permeability material in the logs, while the few points near the diagonal line represent logs with more uniform settings.

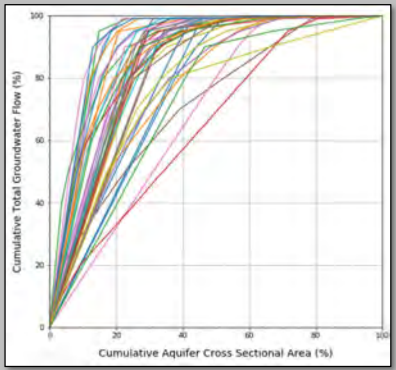

Figure 2: Average Cumulative Total Groundwater Flow vs. Cumulative Aquifer Cross-Section for Each of the 43 Sites.

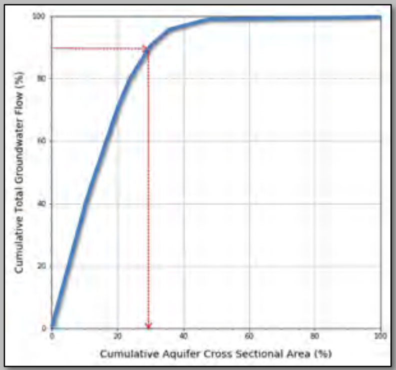

Figure 3: Average Cumulative Total Groundwater Flow vs. Cumulative Aquifer Cross-Section for all 43 sites and all 141 Boring Logs Analyzed as Part of this ESTCP Study. At these sites, approximately 90% of the groundwater flow was flowing through about 30% of the aquifer cross-section.

J. Learn More

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EVALUATION OF FLOW VS CROSS-SECTIONAL AREA AT SITES

EXECUTIVE SUMMARY

- The importance of geologic heterogeneity in the remediation field is now being emphasized by new rules of thumb such as *"90% of the mass flux occurs in 10% of the cross-sectional area"* and that most of the flow occurs through the aquifer's *"mobile porosity*" which is much lower than the commonly used effective porosity (between 0.02 and 0.10 for mobile porosity vs. 0.25 for effective porosity). A theoretical analysis by Payne et al. (2008) suggested that 90% of aquifer flow was transmitted in only 20% of the aquifer cross section in "most natural aquifers".

- The distribution of groundwater flow vs. an aquifer's cross-sectional area is an important concept for permeation grouting, one of the four different types of vertical barrier technologies.

- As part of ESTCP Project 201328, GSI Environmental evaluated 141 boring logs from 43 sites to develop an empirical estimate of the groundwater flow vs. aquifer cross-sectional area.

- This ESTCP study indicated that at these 43 sites, **an average of 30% of the cross-sectional area carried 90% of the groundwater flow.**

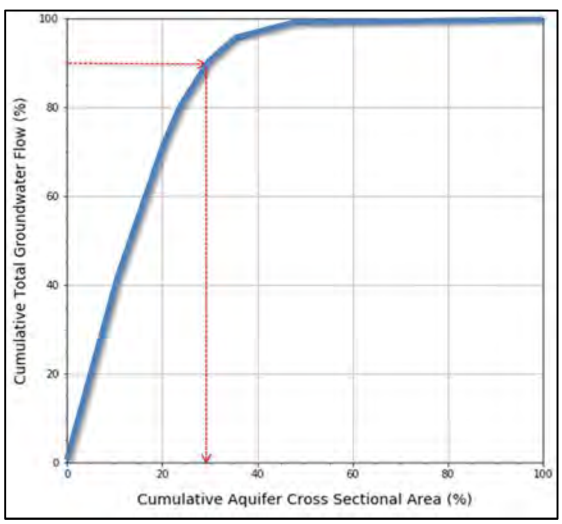


Figure E.1: Average Cumulative Total Groundwater Flow vs. Cumulative Aquifer Cross-Sectional Area for all 43 sites and all 141 Boring Logs Analyzed

- This flow-only result does not contradict the "90% of mass flux" rule of thumb because mass flux combines flow heterogeneity and concentration heterogeneity. Our flow-only analysis does provide moderate (but not confirmatory) support for the "mobile porosity" because 30% of the cross-sectional area multiplied by a typical value for effective porosity of 0.25 yields about 0.075 "mobile porosity" of an aquifer on a cross-sectional basis.

Background

In groundwater media, a traditional conceptual model of groundwater flow relies on the concept of an effective porosity. Effective porosity is generally defined as the portion of the soil through which groundwater moves or that portion of the media that contributes to flow. Effective porosity is also less than the total porosity because not all of the water-filled pores are interconnected or contribute to flow. Therefore, typical values of effective porosity used are 0.2 or 0.3 (e.g., see Newell et al., 1996).

Recently there has been an increasing focus on how geologic heterogeneity in aquifers makes remediation much more difficult due to effects such as matrix diffusion. In addition, there has been recognition that much of the groundwater flow and mass flux through the subsurface occurs in a relatively small fraction of an aquifer's cross section. For example, a recent training seminar by Cramer and Plank (2018) included the following slide that indicated that *"90% of the mass flux contaminant transport at Superfund sites has been shown to move through only 10% of aquifer material….controlled by geology" (*Figure 1).

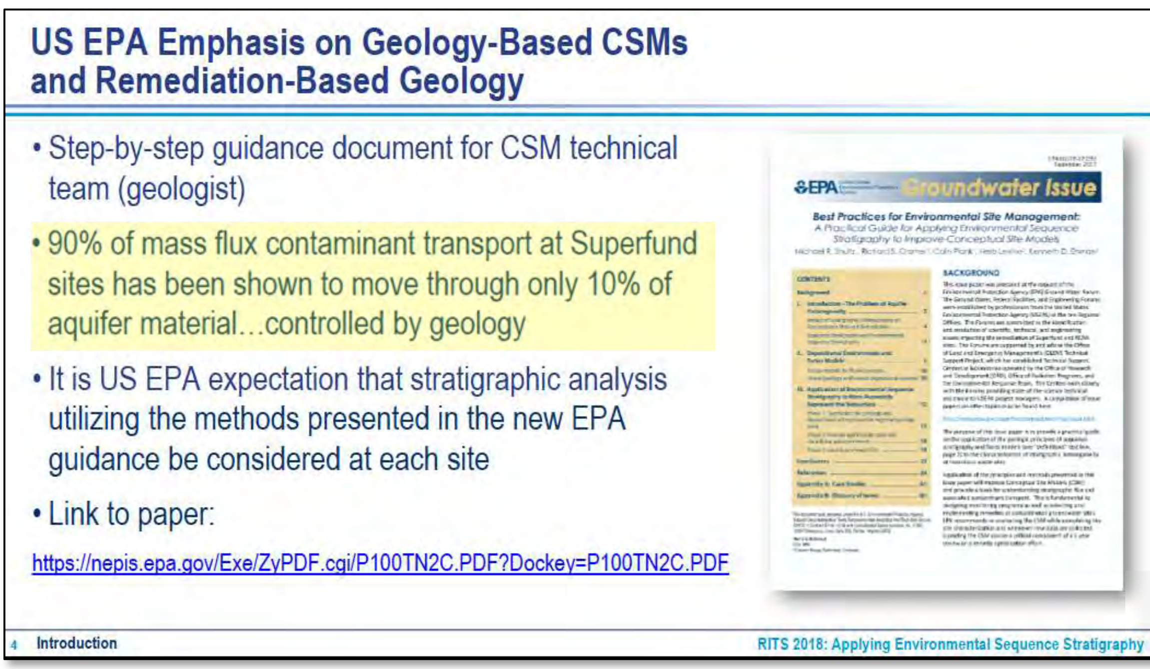


Figure 1: Slide from "Applying Environmental Sequence Stratigraphy to Unlock the Clues Beneath Your Site and Improve the Conceptual Site Model" (Cramer and Plank, 2018). Note the skewed distribution of mass flux is due to two processes: heterogeneity in groundwater flow (where a significant fraction of groundwater flow occurs through a small highly permeable portion of the aquifer cross section) and heterogeneity in the contaminant distribution (where there are small zones with very high concentrations and much larger areas with low or no concentration).

A related concept is described by the term **"mobile porosity"** which explains the preferential flow of fluid through "the segments of the aquifer with the highest permeability" (Payne et al., 2008). In subsurface plume migration, contaminants can more easily be traced and remediated by "recognizing that the flow is concentrated in the mobile porosity" (Payne et al., 2008). As seen in Figure 2 below, more homogenous soils can follow a path more similar to the dashed line, with very little variation in flow over the entire cross-section. Natural aquifers are more likely to follow a path like the solid line, where flow varies across the different soil layers. Here, 90% of the groundwater flow occurs through approximately 20% of the cross-sectional area at a site. In particular, Payne et al., 2008 notes that "for the purpose of assessing plume migration rates, assuming mobile porosities between 0.02 and 0.10 would be more appropriate than using the common 0.20 value".

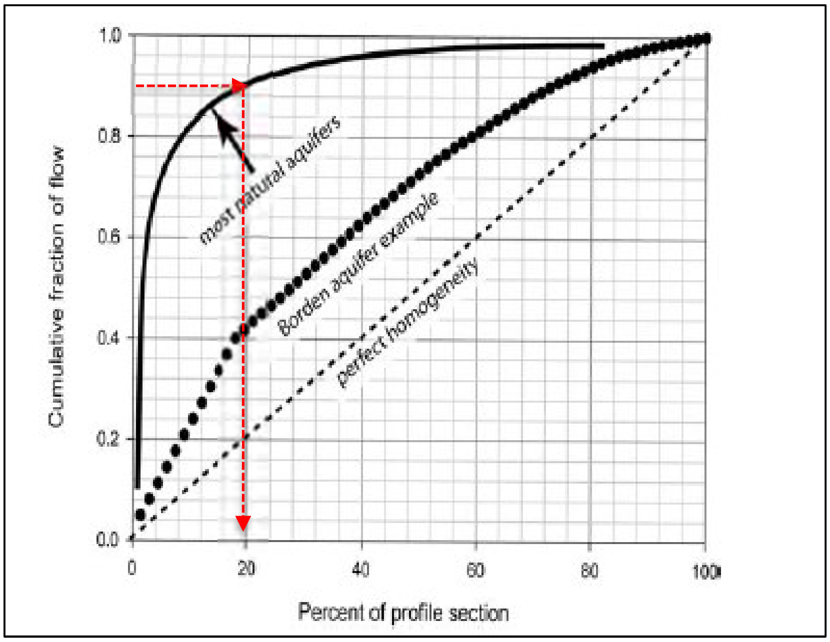


Figure 2: Distribution of Flow in Vertical Profiles. The dashed line represents the flow distribution for a perfectly homogenous media, black circles show the flow distribution for the Borden aquifer (one of the most geologically homogeneous sand aquifers in the world), and the solid line shows most natural aquifers where flow will be concentrated in a smaller fraction of the aquifer pore space. (Payne et al, 2008, Figure 8.2, Borden data from Rivett et al, 2001). The red arrows suggest that for "most natural aquifers" 90% of the flow occurs through about 20% of the aquifer cross-sectional area. Note the "most natural aquifers" line (solid black line) is conceptual, and not derived by data.

Therefore, mobile porosity represents the portion of total porosity that contributes to advective flow and transport in aquifers (Payne et al, 2008).

$$\Theta_t = \Theta_m + \Theta_i \quad (1)$$

Where: Θ_t = total porosity (%);
Θ_m = mobile porosity (%); and
Θ_i = immobile porosity (%).
Mobile porosity can be determined through tracer studies, as shown in Table 1. In different locations, likely with unique adjacent soil compositions, mobile porosity of

sandstone aquifers range from 0.08% to 5%, and from 1.7% to 9% in aquifers with gravel mixtures.

Table 1: Summary of Mobile Porosity Estimates Based on Tracer Studies (Payne et al, 2008 Table 3.2)

Location	Aquifer	Aquifer Material	Mobile Porosity	Notes
Quebec, Canada	---	Poorly Sorted Sand & Gravel	8.5%	6.4 m^3 injection in 7.25 hours
Central Valley, California	---	Poorly Sorted Sand & Gravel	4% to 7%	575 m^2 injection over 30 days; arrival monitored in 7 wells
Northern Texas	Ogallala	Poorly Sorted Sand & Gravel	9%	1460 m^3 injection over 28 days
New Jersey	Passaic Formation	Fractured Sandstone	0.1% to 0.7%	24.6 m^3 injection over 2 days
Los Angeles, California	Gaspur Aquifer	Alluvial Formation	10.2%	17 m^3 injection over 8 hours
Northern New Jersey	---	Glacial Outwash	14.5%	7.57 m^3 in 3 days
Northern Missouri	---	Weathered Mudstone Regolith	7% to 10%	4.54 m^3 in 9 days
Sao Paulo, Brazil	---	Alluvial Formation	7%	18.9 m^3 injection over 2.5 days
Phoenix, Arizona	---	Alluvial Formation	7%	2.27 m^3 in 8 hours
Savannah River Site, South Carolina	Atlantic Coastal Plain	Silty Sand	5%	Model Calibration
Kaiserslautern, Germany	Trifels Formation	Fractured Sandstone	0.08% to 0.1%	Multiple injections and volumes 0.1 m^3 to 5 m^3
West Texas	Rio Grande River Valley	Alluvium, Sand & Gravel	1.7%	18.9 m^3
Northern Texas	Ogallala	Alluvium, Poorly Sorted Sand & Gravel	0.3% to 1.7%	Dipole test, 61.3 m^3
Central Colorado	Cherry Creek	Alluvium, Sand & Gravel	11% to 18%	Two injection tests, 4.9 m^3 and 7.6 m^3
Central Colorado	Denver Formation	Siltstone, Sandstone, Mudstone	1% to 5%	Monipole – Tracer Injected in monitoring well / Pumping well

Vertical Barriers vs. Flow Distribution

The distribution of flow (and/or mass flux) vs. the cross-sectional area of the aquifer is related to one aspect of contaminant barriers. If the flow is limited to a relatively small portion of the aquifer cross section, then using permeation grouting technology to form partial barriers might prove to be an economical way to reduce the mass flux leaving hard-to-treat source zones. In theory, permeation grouting tends to fill the mobile porosity with the grout material but does not enter low permeability zones.

Because of this potential advantage of permeation grouting, and because of the general interest in rules of thumb such as 90% of the flux through 10% of the cross-sectional area**, a planning-level empirical study was performed to determine the distribution of flow vs. cross-sectional area by compiling actual site data.**

In this study, 287 boring logs from 56 sites were obtained from the California GeoTracker database and analyzed in order to determine the percent of cross-sectional area carrying the majority of groundwater flow.

Methodology

Initial Dataset

The boring logs used in this study were obtained from the California State Water Resources Control Board GeoTracker database. At least five boring logs were downloaded and analyzed from various sites selected at random from the database, with all sites located in California. Before further selection criteria were applied, 287 boring logs from 56 sites were analyzed.

Additionally, the approximate depth to water in feet below ground surface was recorded for each boring log. From the initial dataset of 287 boring logs, 33 did not have specific depth to water information available. As such, for this subset, the depth to water was assumed to be 15 ft bgs based on the median value from various sites in the HGDB database (Newell et al., 1990). Additionally, only soil layers within the boring logs in the saturated zone at each site were retained for analysis.

Groundwater Flow and Cross-Sectional Area

From each soil section and soil type in a boring log, the Darcy velocity (ft/yr), cross-sectional flow area (ft^2), and finally the groundwater flow (gal/yr) were calculated. Literature values for hydraulic conductivity were used for each soil type recorded in boring logs (Table 2). In cases where two soil types were recorded in a single section, the average hydraulic conductivity of the combination was used.

Table 2: Hydraulic Conductivity Values used in Study

Soil Type Symbol	Classification	Hydraulic Conductivity (cm/s)	Data Source
GW/GM/GP/GC	Gravel	**3×10^{-1}**	Median D&S Table 3.2
SW	Sand, clean, well-graded	**5.5×10^{-2}**	Payne Fig. 3.9 for n = 0.35
SP	Sand, clean, poorly-graded	**5.5×10^{-3}**	
SM	Sand, silty	**1×10^{-3}**	
SC	Sand, clayey	**1.2×10^{-4}**	Geomean SM, SC
ML	Silt, sandy/Silt	**1.4×10^{-5}**	Payne Table 3.1
MH	Silt, clayey	**1.1×10^{-6}**	Geomean ML, CL
CL	Clay, sandy/silty, low plasticity	**1×10^{-7}**	Estimated
CH	Clay, high-plasticity	**2.1×10^{-8}**	Median D&S Table 3.2

D&S: Domenico and Schwartz, 1998
Payne: Payne et al., 2008

The next step was to partially randomize each hydraulic conductivity estimate to account for the natural variation in hydraulic conductivity in an individual boring. As discussed in Shultz et al., (2017), natural depositional environments almost always exhibit vertical heterogeneity in grain size and hydraulic conductivity, even within individual packets of sediments.

To account for the **variability within each soil type** above (e.g., variability within sands vs. silts vs. clays), the general range of estimated hydraulic conductivities for each row in Table 3.2 in Domenico and Schwartz (1998) was calculated, and showed that "coarse sand" had a potential range of x6700 between the low and high end estimates; "fine sand" had a range of x1000, and silt had a range of x20,000.

To evaluate the range due **to grain size and sorting in sands**, Figure 3.9 in Payne et al. (2008) was evaluated, and it showed that generally there was a factor of x1000 or more between fine and coarse sand; and a factor of x10 to x100 range between "very well sorted" and "very poor sorted."

To capture this variability in hydraulic conductivity, a x100 "random multiplier term" was added to the hydraulic conductivity for each soil type presented in Table 2 for each of the discrete soil types in each well log used for this analysis. For example, if a particular segment of a boring log indicated the presence of 5 feet of Silty Sand (SM), Table 2 indicated that a representative middle-range hydraulic conductivity was 1×10^{-3} cm/sec. The random multiplier term then increased or decreased this value in the range between 1×10^{-4} and 1×10^{-2} cm/sec. This random multiplier term, while constrained to a factor of x100, was different for each time SM was identified in a particular boring.

The hydraulic gradient was assumed to be constant at 0.007 and represented the median hydraulic gradient across sites from the HGDB database (Newell et al., 1990). As such, the Darcy velocity was calculated as follows:

$$v=ki \quad (2)$$

Where:

v = Darcy velocity or flux (ft/yr);
i= hydraulic gradient (ft/ft);
k= hydraulic conductivity (cm/s).

The cross-sectional width was also assumed to be constant (5 ft) and was used to determine the cross-sectional area (A) along with the thickness of each soil section in a log. The groundwater flow rate then was calculated using Equation 3.

$$Q=kiA \qquad (3)$$

Where:

Q= groundwater flow rate (gal/yr);
A= cross-sectional area of flow (ft^2)

Percent of Flow and Cross-Sectional Area

Within each boring log, the groundwater flow rate was calculated for each soil section, then the percent of total flow across the entire vertical length of the boring log was determined. Soil sections were sorted from highest to lowest percent of flow per foot to calculate cumulative percent of flow across the boring section.

$$Q_c = (Q/Q_t) \qquad (4)$$

Where

Q_c = cumulative flow across boring log (%);
Q_t = sum of flow across all soil sections in a boring log (gal/yr);
Q = flow across single soil section (gal/yr).

Cumulative flow area within each boring section was also calculated to find the percent of the total cross-sectional area that is receiving the majority of the flow.

$$A_c = (A)/A_t \qquad (5)$$

Where

A_c = cumulative flow area (%);
A_t = sum of cross-sectional areas of all soil sections in a boring log (ft^2);
A = cross-sectional area of a soil section (ft^2; thickness x cross-sectional width)

Figure 3 below depicts a single boring log used for this study and indicates: i) individual soil sections with soil types; and ii) layers that carry greater than 1% of the overall flow through the cross section (blue arrow and corresponding calculated percentage of flow). The image shows how Darcy's Law would describe the flow through the heterogeneous mixture of soils. Larger arrows indicate more flow. As previously discussed, the flow will be distributed among the layers, finding the path of least resistance based on thickness and soil type. In this example, about 16% of the cross-sectional area carries 90% of the cumulative flow (Figure 4).

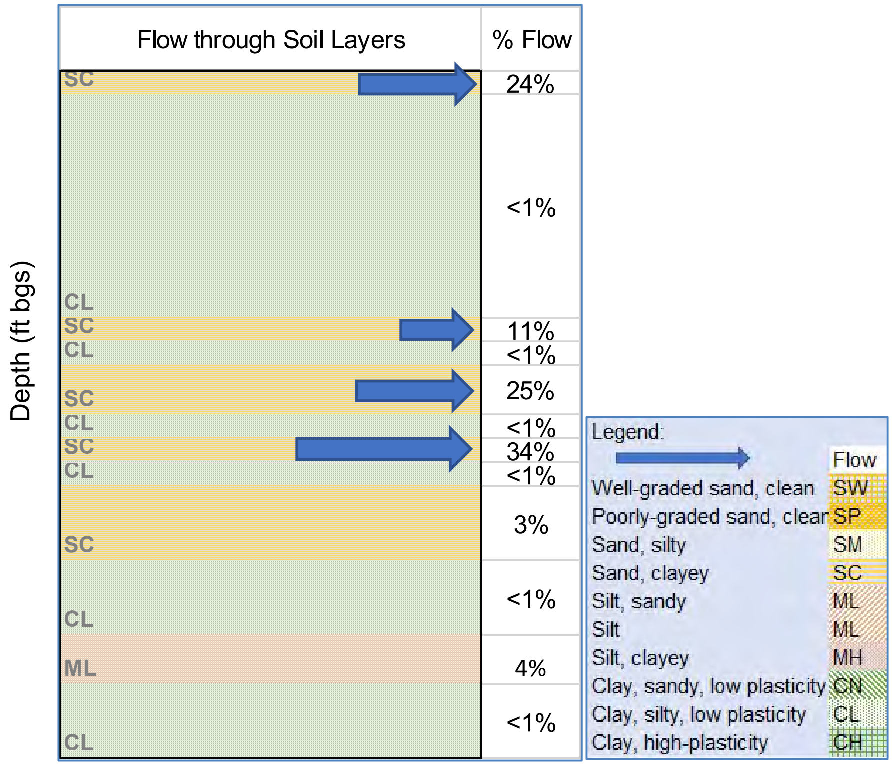


Figure 3: Data from Example Boring Log, Showing Soil Types over a Cross-Section.

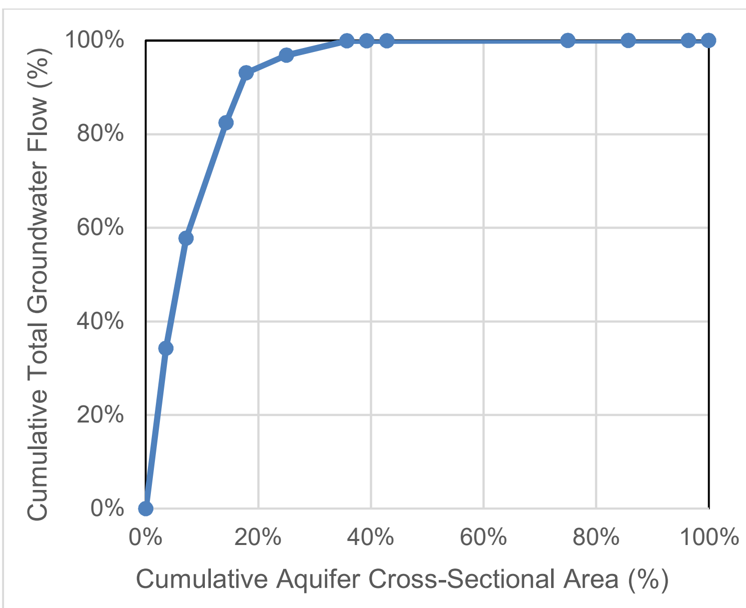


Figure 4: Example Cumulative Groundwater Total Flow vs. Cumulative Aquifer Cross-Sectional Area for Boring Log shown in Figure 3. In this single boring log, 90 percent of the flow is moving through about 16% of the aquifer cross-sectional area.

Final Dataset

Boring logs with three or more saturated soil sections were retained for further analysis. After employing this selection criteria, a total dataset of **43 sites and 141** boring logs were included in the study, with an average of approximately 3 boring logs per site. The median saturated zone thickness of the dataset evaluated was approximately 20 feet.

Results

The Cumulative Total Groundwater Flow vs. Cumulative Aquifer Cross-Sectional Area curves for all 141 boring logs are shown in Figure 5. This array of curves shows a wide distribution of geologic settings, from very heterogeneous ones as shown by lines to the left/top of the graph) to more uniform geologic settings that are closer to the 45 degree diagonal line.

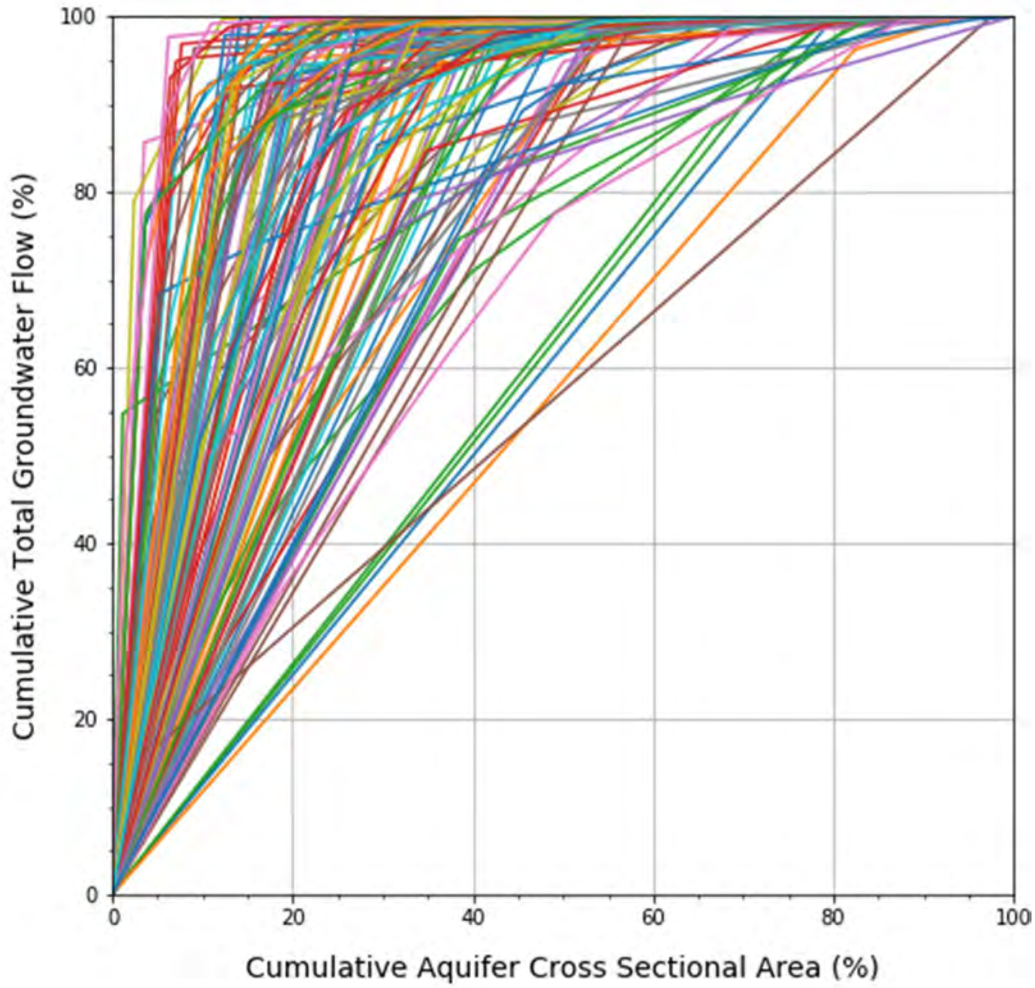


Figure 5: Cumulative Total Groundwater Flow vs. Cumulative Aquifer Cross-Sectional Area for 141 Boring Logs. The curves that are clustered to the top/left represent high heterogeneity settings with more low permeability material in the logs, while the few points near the diagonal line represent logs with more uniform settings.

After all the boring logs at each site were averaged, Groundwater Flow vs. Cross-Sectional Area curves were developed for each of the 43 sites as shown in Figure 6.

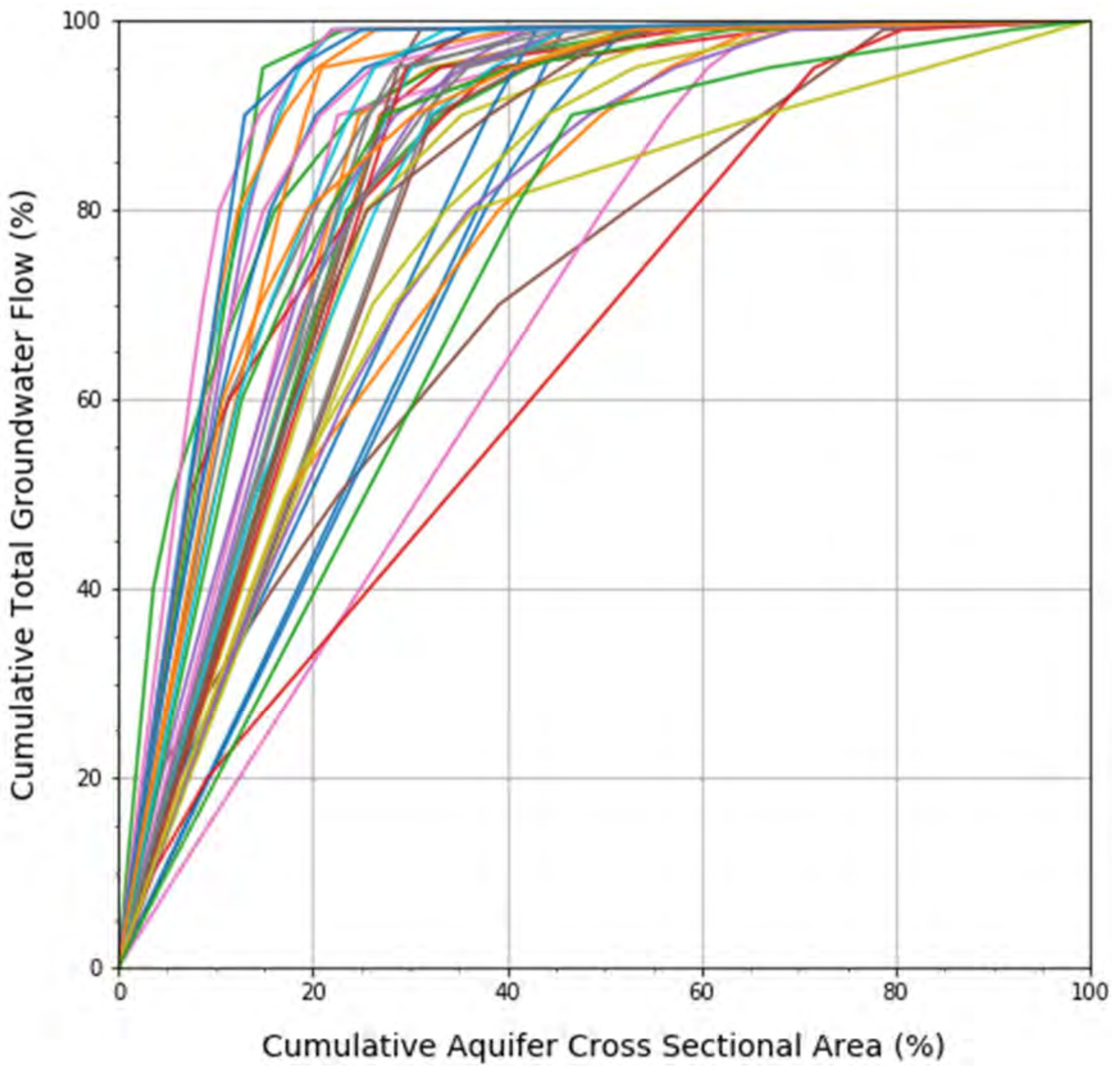


Figure 6: Average Cumulative Total Groundwater Flow vs. Cumulative Aquifer Cross-Sectional Area for Each of the 43 Sites.

Finally, the curves for each of the 43 sites were averaged to form a single curve representing all of the data in Figure 7.

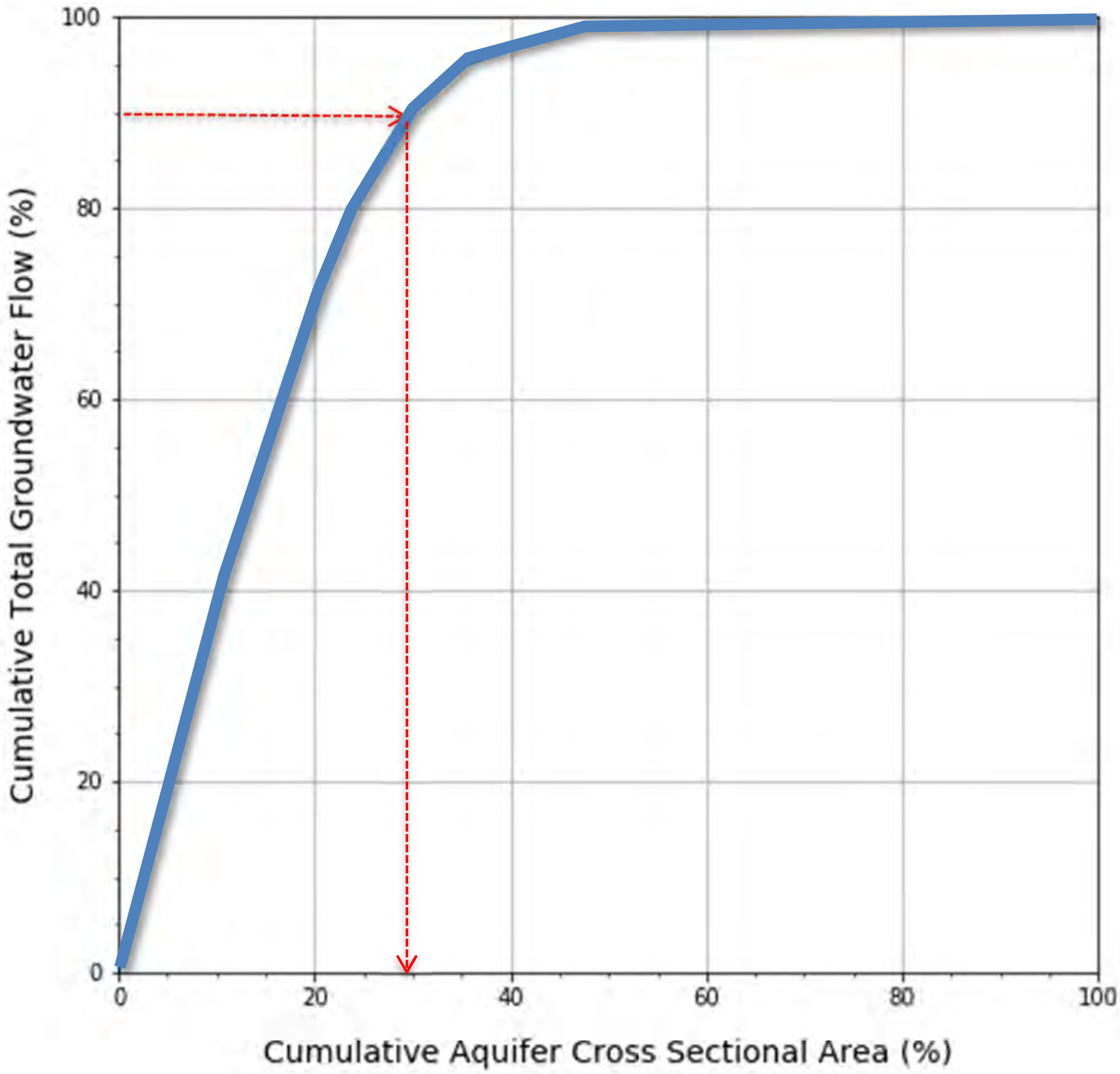


Figure 7: Average Cumulative Total Groundwater Flow vs. Cumulative Aquifer Cross Sectional Area for all 43 sites and all 141 Boring Logs Analyzed as Part of this ESTCP Study. At these sites, approximately 90% of the groundwater flow was flowing through about 30% of the aquifer cross section.

The empirical data from the 43 sites was then compared to Payne's theoretical curve for "most natural aquifers" as shown in Figure 8.

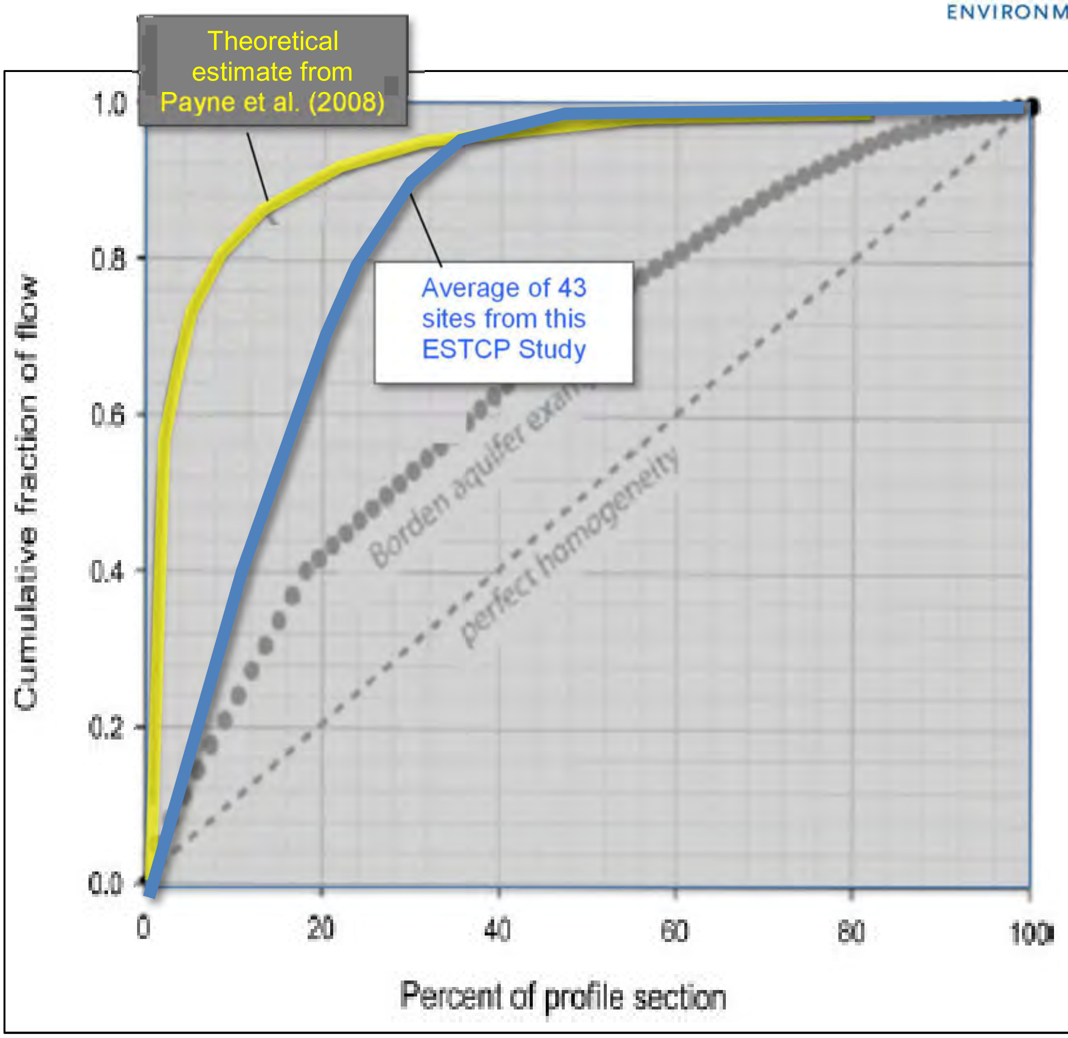


Figure 8: Total Groundwater Flow vs. Cumulative Aquifer Cross-Sectional Area from Payne et al. (2008) Theoretical Analysis (Yellow Line) Compared to the Empirical Analysis of 43 Sites and 141 Boring Logs from this ESTCP Study (Blue Line). The empirical data shows slightly less heterogeneity than Payne et al.'s theoretical analysis. Underlying graph from Payne et al., 2008 (see Figure 2).

CONCLUSIONS

There has been increasing interest in understanding the heterogeneity of groundwater flow through aquifer cross sections as indicated by the these developments:

- Payne et al., (2008), estimated that **90% of the flow** in "most natural aquifers" flowed through only **20% of the aquifer cross section**.
- A recent U.S. Navy training course indicated **that 90% of the mass flux** (which considers both heterogeneity in flow and concentration) moved through **only 10% of the aquifer material.**
- An alternative conceptual model for analyzing contaminant transport in groundwater suggested that the "effective porosity" (with a commonly used value

of 0.25) should be replaced with a much smaller "mobile porosity" **ranging from 0.02 to 0.10.**

This ESTCP performed a data mining study of 141 geologic boring logs at 43 randomly selected sites in California to develop actual empirical relationship between groundwater flow and aquifer cross-sectional area. The groundwater flow through each soil type segment in each geologic log (for example, well sorted sands (SW) and silts (ML)) was estimated using representative hydraulic conductivities for each soil type. The cumulative flow was then plotted vs. the cumulative aquifer cross section.

This analysis suggested that on average at these 43 sites **90% of the groundwater flow was carried by only 30% of the aquifer cross section.** About half the flow was conducted by the most permeable 15% of the aquifer cross-section. Overall, these data support the conclusion that groundwater flow in aquifers is extremely heterogeneous with most of the flow (and most of the mass flux) going through a small, highly permeable portion of the aquifer.

REFERENCES

Cramer, R. and C. Plank, 2018. "Applying Environmental Sequence Stratigraphy to Unlock the Clues Beneath Your Site and Improve the Conceptual Site Model." NAVFAC, 2018.

Domenico, P. and F. Schwartz, 1997. Physical and Chemical Hydrogeology, 1997.

Newell, Charles, 2017. "Advection and Groundwater Flow". EnviroWiki. < http://www.environmentalrestoration.wiki/index.php?title=Advection_and_Groundwater_Flow>

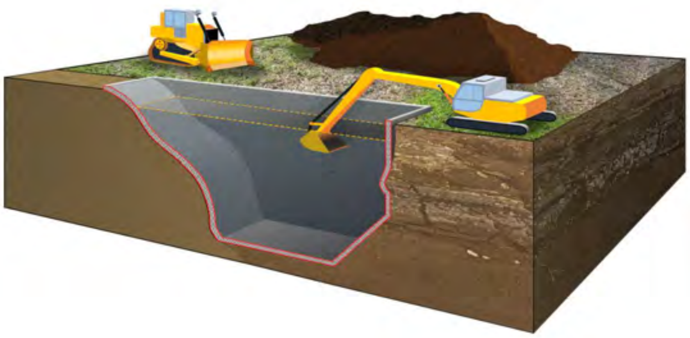
Payne, F., J. Quinnan, S. Potter, 2008. Remediation Hydraulics, 2008.

Raymond, Jimmy, 2015 via Michael D. LaGrega, Phillip L. Buckingham and Jeffery C. Evan. 1994. Hazardous Waste Management. McGraw Hill, Inc. <https://www.ajdesigner.com/phpdarcyslaw/darcys_law_equation_flow_rate.php>

Wiedemeier TH, Rifai HS, Newell CJ, Wilson JT. Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface, 1999.

SHEET K_SLURRY and K2_COST:
Slurry Wall and Cost Evaluation

Slurry Wall

	A Slurry Wall creates a homogeneous vertical barrier a few feet thick extending from the surface into groundwater with low hydraulic conductivity to reduce mass flux of contaminants. The most common type of slurry used for groundwater remediation purposes is to use native soil from the excavation mixed with bentonite. A long-armed excavator is used to dig the trench around the source zone to be isolated; the slurry is added to keep the trench from collapsing. The resulting soil/bentonite mix has a very low hydraulic conductivity typically in the 10^{-7} cm/sec range, thereby greatly reducing flow in and out of the isolated area. The most inexpensive way to install slurry walls (with excavator) can reach depths of up to 70 feet bgs.

SLURRY WALLS

OVERVIEW

A slurry wall is a subsurface containment vertical barrier which prevents the migration of groundwater and hazardous contaminants. Slurry walls typically extend through the vadose zone and into the saturated zone by excavating a trench with a long reach backhoe or clamshell (Falta and Looney, 2000; Evans, 2002). While there are predominately three types of slurry walls, the most commonly-used type for groundwater remediation is the soil-bentonite slurry wall.

SLURRY WALL CONSTRUCTION

In the U.S., soil-bentonite slurry walls are constructed using a two-phase method of construction (EPA, 1998). In the first phase, a trench of the desired depth is excavated which encompasses the contaminated zone that is to be isolated. During the excavation, soil walls, and therefore trench stability, are maintained by a slurry comprising of 4%-6% sodium bentonite and 94%-96% water (by weight). Hydrostatic pressures from the slurry press against the filter cake which maintain the stability of the trench walls (Falta and Looney, 2000). After the trench is excavated, the slurry is displaced by a soil-bentonite backfill which is composed of a mixture of soil, sodium bentonite and water (EPA, 1998; Falta and Looney, 2000). In most cases, soil excavated from the trench is mixed on site if there is enough space adjacent to the trench. Figure 1 shows the excavation, backfill mixing and backfill placement associated with slurry wall construction. For costing see Sheet “K2_Cost”.

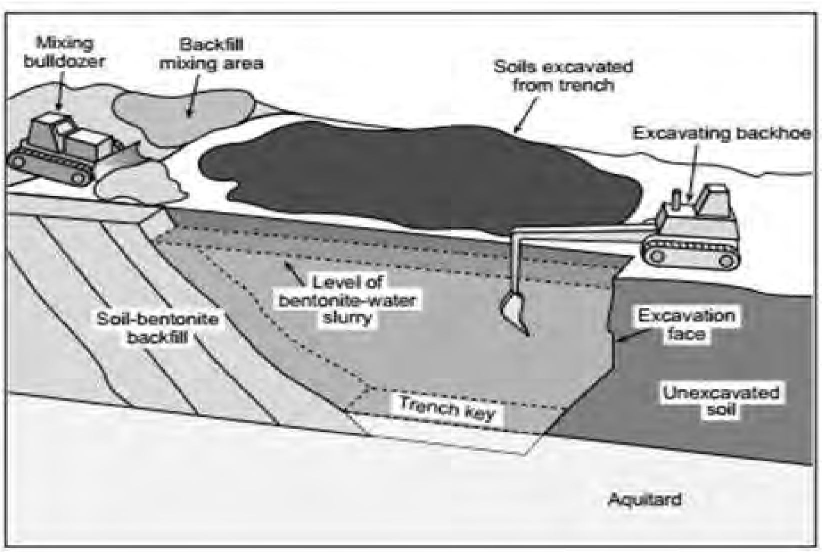


Figure 1: Soil-Bentonite Slurry Wall Operation (Rumer and Ryan, 1995 as presented by Evans, 1995)

The success of a slurry wall relies on the soil-bentonite backfill mixture. Koeling (1997) describes a soil-bentonite barrier for which the following backfill properties were specified: 15%-20% soil fines content, unit weight of at least 2.36 kN/m^3 greater than the unit weight of the trench slurry, slump of 76 to 178 mm, hydraulic conductivity of ≤ $1x10^{-7}$ cm/s . ASTM 5084 is usually used to determine hydraulic conductivity of backfill.

In limited cases, some specific contaminants may degrade the slurry wall, reducing the long-term effectiveness (Table 1). However, this is relatively uncommon.

Table 1: Soil-Bentonite Permeability Increase due to Interaction with Various Pollutants (Source: Spooner et al., 1995)

Pollutant	Backfill[0]
Ca^{++} or Mg^{++} @ 1000 PPM	N
Ca^{++} or Mg^{++} @ 10,000 PPM	M
NH_4NO_3 @ 10,000 PPM	M
Acid (pH>1)	N
Strong Acid (pH<1)	M/H*
Base (pH<11)	N/M
Strong Base (pH>11)	M/H*
HCL (1%)	N
H_2SO_4 (1%)	N
HCL (5%)	M/H*
NaOH (1%)	M
CaOH (1%)	M
NaOH (5%)	M/H*
Benzene	N
Phenol Solution	N
Sea Water	N/M
Brine (SG=1.2)	M
Acid Mine Drainage ($FeSO_4$ pH ~3)	N
Lignin (in Ca^{++} solution)	N
Organic residues from pesticide manufacture	N
Alcohol	M/H

N - No significant effect; permeability increase by about a factor of 2 or less at steady state.

M - Moderate effect; permeability increase by factor of 2 to 5 at steady state.

H - Permeability increase by factor of 5 to 10.

* - Significant dissolution likely.

0 - Silty or clayey sand, 30 to 40% fines.

SLURRY WALL PERFORMANCE

Slurry walls typically exhibit hydraulic conductivities of 10^{-7} cm/sec, but can be constructed with values as low as 5 x 10^{-8} cm/sec (Pearlman, 1999).

ADVANTAGES

- Relatively inexpensive to construct barrier around a large source zone compared to in-situ treatment of entire source zone (see Sheet "K2_Cost"). Typical costs are $10 to $20 per vertical square foot of barrier.
- Can extend to 70 feet deep or more.
- Well established construction technique.
- Results in barriers with very low hydraulic conductivity (typically ≤ 1×10^{-7} cm/s).
- Provides long term effective barrier to contain contaminants in the isolated zone.

DISADVANTAGES

- Construction can be disruptive and requires significant working area around barrier.
- Most efficient construction occurs with long straight construction lines; more expensive to construct with irregular trench alignments.

REFERENCES

Evans, J. C., 2002. Slurry Walls for the Rehabilitation of Land Disposal Sites. Retrieved from https://www.witpress.com/elibrary/wit-transactions-on-ecology-and-the-environment/56/1075

Falta, R. W., and B.B. Looney, 2000. *Vadose Zone Science and Technology Solutions.* Battelle Press, 2000.

Koeling, M.A., 1997. *Case History: Vertical Barrier Wall System for Superfund Site*. Washington, DC. USDOE.

Pearlman, C., 1999. Subsurface Containment and Monitoring Systems: Barriers and Beyond. U.S. EPA, 1999.

Rumer, R.R, and Ryan, M.E., 1995. Barrier Containment Technologies for Environmental Remediation Applications. Wiley, New York.

Spooner, P., Wetzel, R., Spooner, C., Furman, C., Tokarski, E., Hunt, G., Hodge, V., and Robinson, T., 1985. Slurry trench construction for pollution migration control. Noyes Publications, Park Ridge, NJ.

U.S. EPA, 1998. *Evaluation of subsurface engineered barriers at waste sites*. Washington, D.C.: U.S. Environmental Protection Agency.

Planning-Level Cost Evaluation: Slurry Walls

KEY: Data Input Instructions

##	*Enter value directly*
##	*Previously entered or intermediate calculation. OK to overwrite*
##	*Value calculated by model. Do not overwrite*

Variable	*Value*	*Units*
Treatment Zone		
Total Length	300	ft
Slurry Wall Depth	50	ft
Capital Costs		
Slurry Wall Capital Cost	$177,220	$

Cost Assumptions and Limitations

COST SUMMARY

Total Costs	*Value*	*Units*
Total Cost (Most Likely)	**$177,220**	$
Total Cost (Low Range)	**$132,915**	$
Total Cost (High Range)	**$265,830**	$

*Disclaimer: This is a planning-level tool only, and does not include a detailed design of this technology. Costs are approximate and a site-specific evaluation should be conducted prior to implementation.

Navigation Panel

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SHEET L_PILES AND L2_COST:
Sheet Pile Walls and Cost Evaluation

Sheet Piling

	Sheet Piling consists of placing interlocked steel sheets installed by vibratory hammers, impact hammers, or hydraulic pushing as determined by soil type and surrounding area. Typical maximum depth is about 90 feet, although deeper depths are possible. For most groundwater control applications, the joints are then sealed to greatly reduce any groundwater flow through the barrier; for example, Waterloo Barriers have a special seal that can achieve bulk wall hydraulic conductivities of 10^{-8} to 10^{-10} cm/sec. The steel pilings are not vulnerable to desiccation, freeze thawing, or plant roots. Construction is fast and requires relatively small working area but is noisy.

SHEET PILING

OVERVIEW

Sheet piling is a physical barrier constructed by placing steel sheets with interlocking edges into the ground. Sheets are prefabricated and either hot roll or cold formed depending on the manufacturers' preference. Sealants are used to fill gaps in the interlock, increasing the water tightness of the wall and helping to create a positive seal. Typical sealants include clay-based grouts, such as bentonite and attapulgite; cement-based grouts; epoxy polymers, and urethane polymers (Looney et al., 2000). One vendor, Waterloo Barriers, provides a sheet piling/sealant technology that has been used extensively for isolating contaminant source zones (Figure 1).

Figure 1: Waterloo Barrier with sealant grout (Waterloo Barriers.com)

INSTALLATION

Depending on the soil type and surrounding area, sheets can be installed by vibratory hammers, impact hammers or hydraulically pushed. They are typically driven into the ground until they contact an impermeable stratum beneath the contaminated zone (Bedient et al., 1994). This particular containment method is particularly suited to the vadose zone as the sheet piles are not vulnerable to desiccation, freeze thawing or plant roots (Looney et.al., 2000). Problems with sheet piling may arise, however, if the soil is coarse, dense and contains numerous boulders (Bedient et al., 1994). For costing see Sheet "L2_Cost".

SHEET PILE PERFORMANCE

Waterloo Barriers, a specialized sheet pile technology designed for groundwater isolation projects, have installed barriers with hydraulic conductivities in the 10^{-8} to 10^{-10} cm/sec range (Jowett et. al., 1999).

ADVANTAGES

- Rapid and clean construction (i.e. no soil excavation required, and piles can be driven or vibrated straight into the ground).
- Relatively small construction footprint with minimal site disturbance.

- Irregular barrier alignments (curves, corners, etc.) are easier to construct with sheet piling vs. slurry walls.
- Typical construction techniques can be used for barriers installed to depths of 90 feet.
- Temporary or permanent: piles can be left in place at site or removed.
- Reusable: removed piles can be reused at different sites.

DISADVANTAGES

- Sheet piles can be ruptured during installation when encountering dense soils or rocks/cobbles.
- Noisy installation processes.
- More expensive than slurry walls.

REFERENCES

Bedient, Philip B., et al. 1999. *Ground Water Contamination: Transport and Remediation*. Prentice Hall PTR, 1999.

Evans Piling, 2012. *Product Range Sheet Pile Sections*. HOESCH Spundwant Und Profil, 2012, www.evanspiling.co.uk/pdf/hoesch_brochure.pdf.

Falta, R. W., & Looney, B.B. *Vadose Zone Science and Technology Solutions.* Batelle Press, 2000.

Jowett, R.J., D. Smyth, D. Lee, and C. Creber, 1999. Control of Contaminated Groundwater, ES&T, March 1999.

Waterloo Barrier Inc., 2018. http://www.waterloo-barrier.com.

Planning-Level Cost Evaluation: Sheet Pile Walls

KEY: Data Input Instructions

##	*Enter value directly*
##	*Previously entered or intermediate calculation. OK to overwrite*
##	*Value calculated by model. Do not overwrite*

Variable	*Value*	*Units*
Treatment Area		
Total Length	500	ft
Total Depth	80	ft
Vertical Area	40,000	ft^2
Labor Costs		
Sheets Installed	100	ft/day
Approx. Days Required	7	day
Assume 2 Field Personnel Onsite	2,300	$/day
Other Expenses	170	$/day
Labor Costs	$17,290	$
Capital Costs		
Mobilization	42,500	$
Sheet Pile Cost per Vertical Area	68	$/ft^2$
Vertical Area	40,000	ft^2
Installation Cost	$2,720,000	$

COST SUMMARY

Variable	*Value*	*Units*
Total Cost (Most Likely)	**$2,779,790**	$
Total Cost (Low Range)	**$2,084,850**	$
Total Cost (High Range)	**$4,169,690**	$

*Disclaimer: This is a planning-level tool only, and does not include a detailed design of this technology. Costs are approximate and a site-specific evaluation should be conducted prior to implementation.

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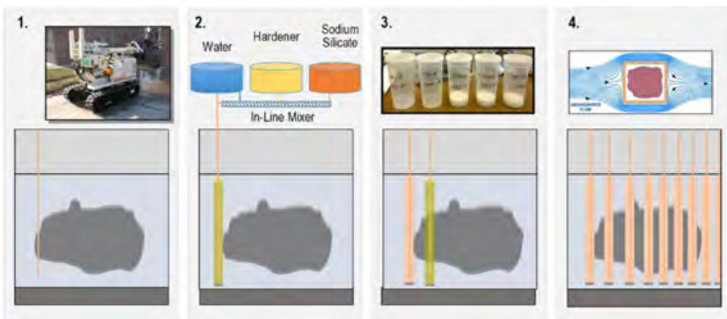
SHEET M_PERM, M2_FLOWCHART AND M3_COST:
Permeation Grouting, Decision Logic for Degradation at Sites, and Cost Evaluation

Permeation Grouting



Permeation Grouting reduces the permeability of soils surrounding a contaminant plume through an in-situ system of closely-spaced injection wells. The wells are injected with a chemical-based grout, typically silica gel, that changes from liquid to gel state in a few hours, filling the available pore space in the soil. Permeation grouting requires closely spaced injection points on the order of 2 to 4 feet apart. In general, permeation grouting with silica gel needs 1) a transmissive zone comprised of sand (not silt or gravel or fractured rock) with K between $5x10^{-4}$ to 10^{-2} cm/sec; and 2) a low permeability unit at the bottom of the transmissive zone; and 3) the site needs to be accessible by direct push rig to make the process economical. Note that non-silica gel grouts and other barrier technologies can be used at sites that don't meet these criteria.

PERMEATION GROUTING

OVERVIEW

Permeation Grouting is a vertical barrier technology where an injectable grout is used to construct vertical walls surrounding a contaminant source zone. A series of closely spaced (typically 2 to 4 feet spacing) injection points are used to inject a chemical grout such as silica gel, cement, or acrylate to form a vertical barrier. The grout is injected in a liquid form, enters the flowing pore space (also called mobile porosity) in the clean soils surrounding the source zone, and then chemically changes to either an impermeable gel (as in the case of silica gel) or hardens (as in the case of cement) to form a barrier to groundwater flow.

The injection points are positioned close enough so that the radius of influence of each grout injection will overlap slightly (0.8-2 m apart depending on the soil characteristics) to create a near continuous boundary around the zone to be isolated.

Key references are Kulkarni et. al (2017); Powers et. al (2017); and Karol (2003).

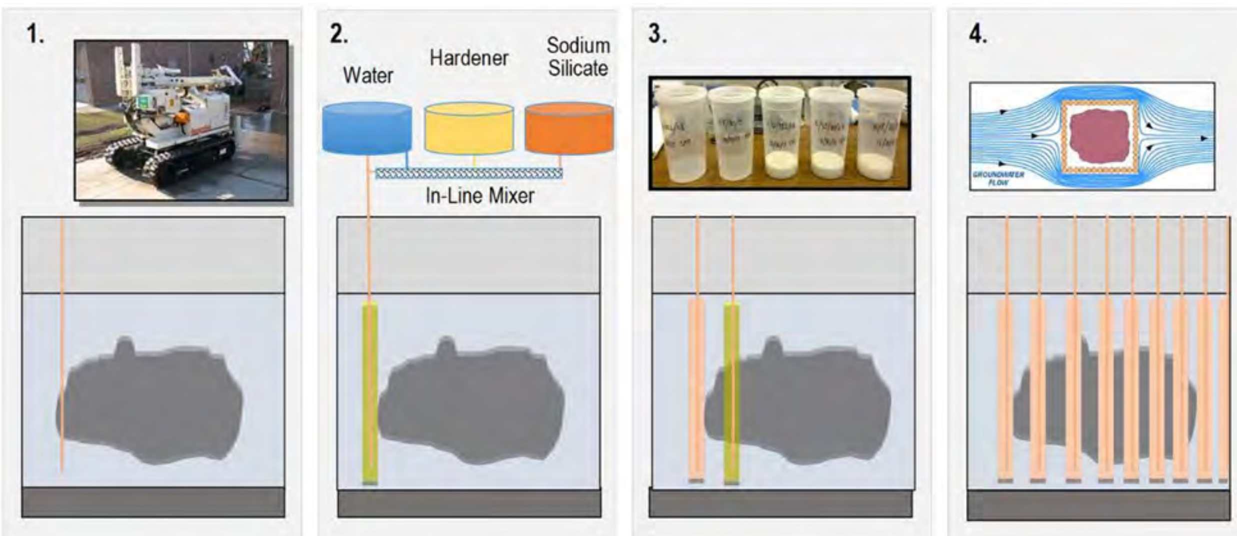


Figure 1: Permeation Grouting Process (the overlapping radius of influence of each injection point is not shown in this figure)

DIFFERENT GROUTS FOR DIFFERENT SOIL TYPES

The effectiveness of permeation grouting is impacted by the hydraulic conductivity of the subsurface. The type of grout used should be chosen based on the hydraulic conductivity of the subsurface to increase the groutability, ability of the soil to receive grout, of a site.

Table 1. Usable Grouts for a Given Range of Hydraulic Conductivities

Hydraulic Conductivity of Soil (cm/sec)	Groutability via Permeation Grouting Technology
≤ 10^{-6}	Cannot be grouted
Between 10^{-5} -10^{-6}	Groutable, with difficulty, by grouts with viscosity < 5 centipoise (i.e. not acrylate grouts)
Between 10^{-3} - 10^{-5}	Groutable with low viscosity grouts, avoid grouts with a viscosity > 10 centipoise (i.e. silica gel grout)
Between 10^{-1} -10^{-3}	Groutable with all commonly used chemical grouts (i.e. cement grouts)
≥ 10^{-1}	Groutable with suspension grouts or chemical grouts with a filler material

TWO CONSTRUCTION APPROACHES

Geotechnical contractors are available to apply permeation grouting for groundwater control. Their experience may be largely groundwater control for geotechnical purposes such as foundation construction.

As part of ESTCP Project ER-201328, design guidelines and technical resources were developed to help environmental contractors who are experienced with subsurface injection (such as injecting bioremediation amendments or chemical oxidation compounds) to inject silica gel type grout (Kulkarni et al., 2017). The following flowchart was developed (Figure 2) to provide a decision logic on applying permeation grouting for isolating chlorinated solvent source zones.

The ESTCP demonstration project (Kulkarni et al., 2017) was able to use existing remediation technology (direct push rigs and injection skids) to build four small barriers. The mixing process is generally more complex than standard injection-based remediation projects because the injection skid (Figure 3) needs to mix three fluids, delivery multiple locations simultaneously, let operators see pressure, flowrate, and have contingency for grout set-up in the injection manifolds. Because of the unexpectedly low permeability in the test zone for the ESTCP project, only a 60% reduction in flow was achieved compared to the performance goal of a 90% reduction.

PERMEATION GROUTING PERFORMANCE

A general rule of thumb is that permeation grouting with silica gel can reduce the hydraulic conductivity of sandy soils by one or two orders of magnitude (i.e., 90% to 99%) where the lowest practically achievable hydraulic conductivity is about 1 x 10^{-5} cm/sec (Powers et. al., 2007).

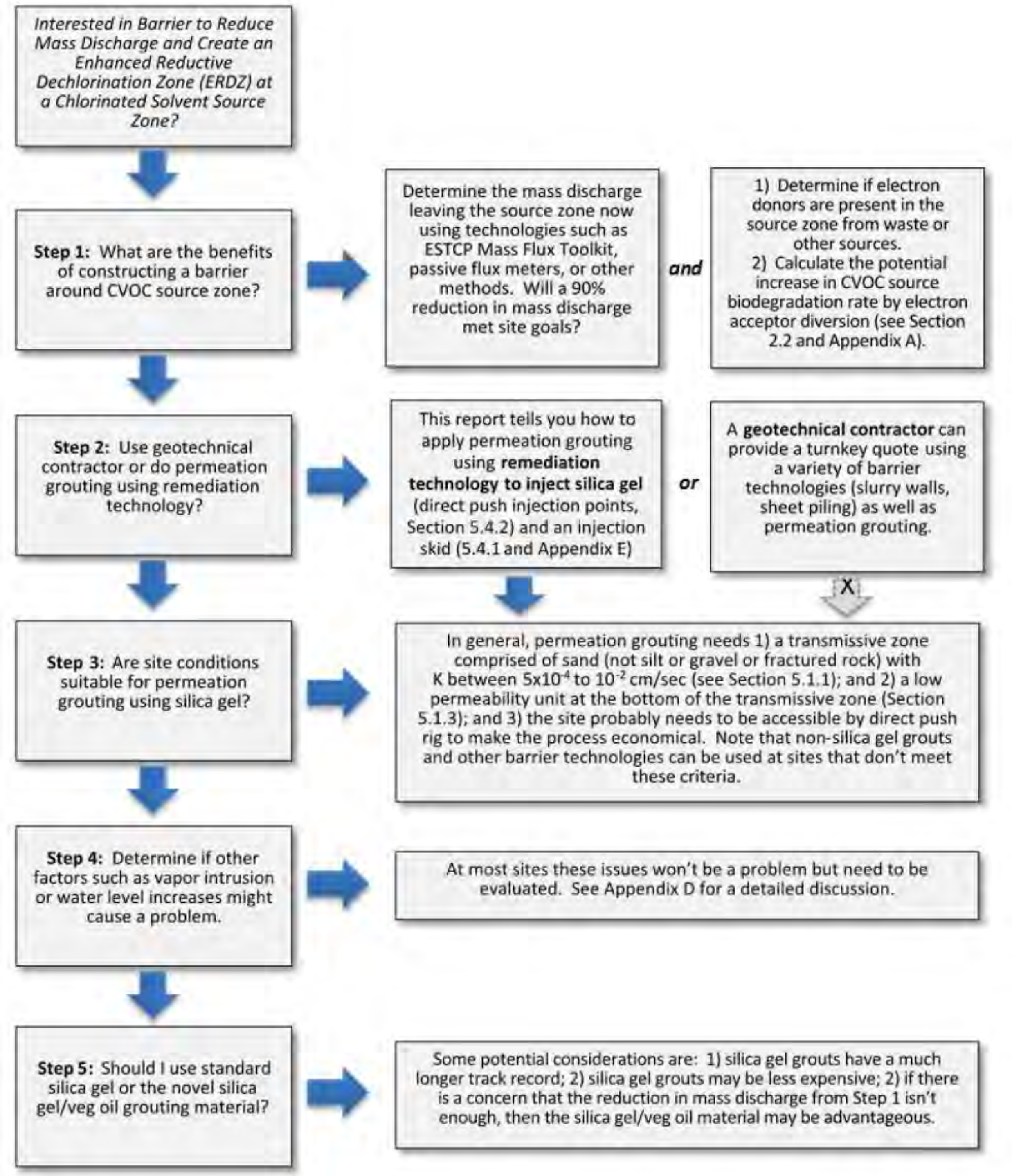


Figure 2: Decision Logic for Applying Permeation Grouting Technology to Chlorinated Solvent Sites (Kulkarni et al., 2017).

Figure 3: ESTCP Project Permeation Grouting Injection Skid for Injection of Silica Gel Grout

ADVANTAGES

- Small construction footprint: Unlike slurry walls where large amounts of excavation are needed to install the barrier, only a small working area enough for a small skid and a direct push rig is required to install the barrier.
- Permeation grouting has many of the same elements as in-situ injection technologies (i.e., bioremediation, chemical oxidation), so there is a potential for environmental contractors and consultants to use of existing injection equipment and injection experience.

DISADVANTAGES

- Difficult to predict grout radius of influence. Depending on the permeability of the soils around the injection well, the grout may move in uncertain directions. This leads to a difficulty in understanding how far the grout will permeate once injected into the subsurface.
- Hard to ensure complete barrier continuity. It can be difficult to determine if the barrier will be uniform as each injection well may not uniformly permeate in each direction. This is the reasoning for "overlapping" the radius of influence from each injection well.
- More difficult to apply in moderate to low permeability formations.
- This technology can be more expensive than other barrier technologies. Costs can rise quickly with mobilization costs, high cost per unit of grout, and a slow process for both installing deep wells and injecting grout. For costing see Sheet "M3_Cost".

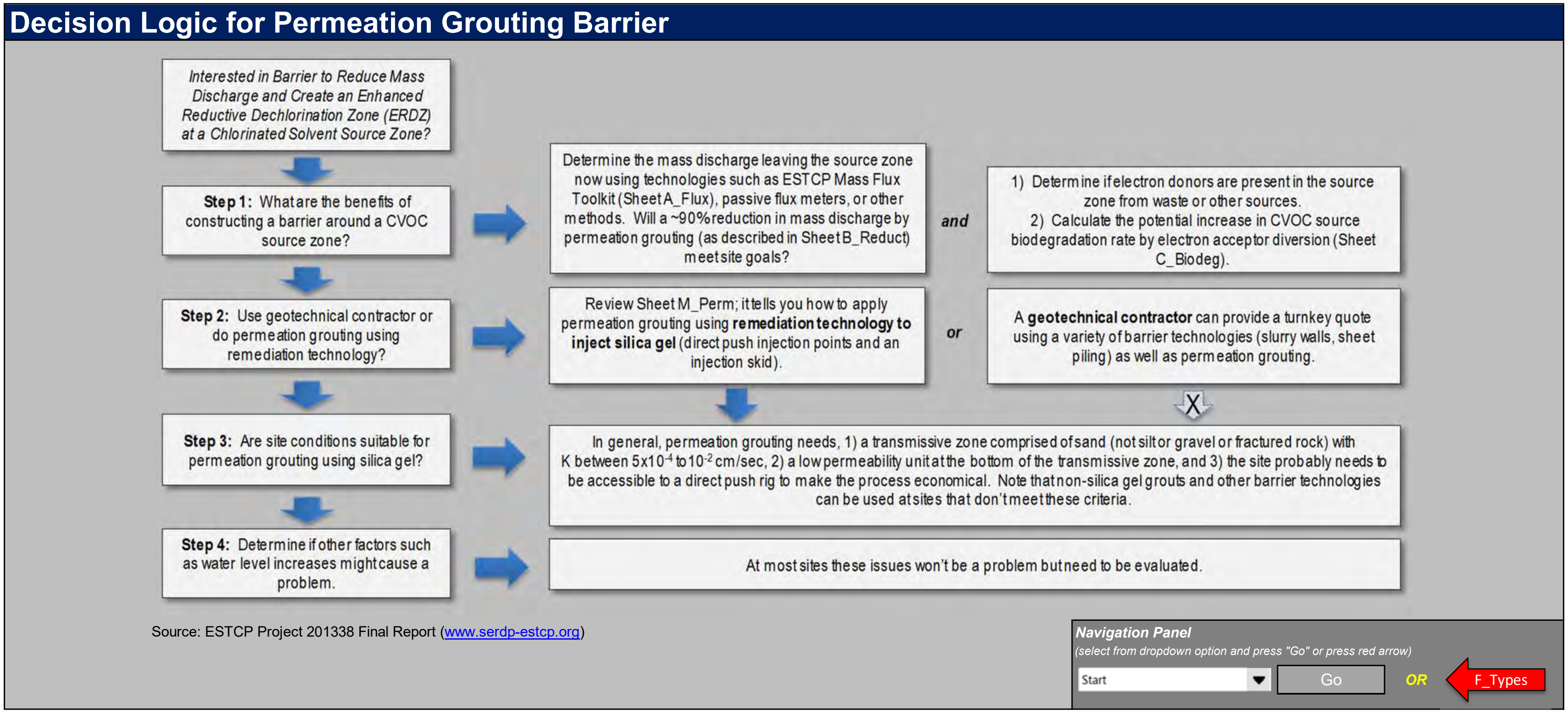
REFERENCES

Karol, R.H., 2003. Chemical Grouting and Soil Stabilization, 3rd Edition. Marcel Dekker Inc.

Kulkarni, P.R., Higgins, E.A., Strasters, B.A., Newell, C.J., 2017. Final Report: Contaminant Flux Reduction Barriers for Managing Difficult-to-Treat Source Zones in Unconsolidated Media. ESTCP Project ER-201328. Environmental Security and Technology Certification Program, Arlington, Virginia.

Falta, R. W., & Looney, B.B. *Vadose Zone Science and Technology Solutions.* Battelle Press, 2000.

Powers, P.T., A.B. Corwin, P.C. Schmall, and W.G. Kaeck, 2017. Construction Dewatering and Groundwater Control: New Methods and Applications, 3rd Edition, John Wiley and Sons, Inc. (Chapter 22).


Decision Logic for Permeation Grouting Barrier
Interested in Barrier to Reduce Mass Discharge and Create an Enhanced Reductive Dechlorination Zone (ERDZ) at a Chlorinated Solvent Source Zone?
Step 1: What are the benefits of constructing a barrier around a CVOC source zone?
Determine the mass discharge leaving the source zone now using technologies such as ESTCP Mass Flux Toolkit (Sheet A_Flux), passive flux meters, or other methods. Will a ~90% reduction in mass discharge by permeation grouting (as described in Sheet B_Reduct) meet site goals?
and
1) Determine if electron donors are present in the source zone from waste or other sources. 2) Calculate the potential increase in CVOC source biodegradation rate by electron acceptor diversion (Sheet C_Biodeg).
Step 2: Use geotechnical contractor or do permeation grouting using remediation technology?
Review Sheet M_Perm; it tells you how to apply permeation grouting using remediation technology to inject silica gel (direct push injection points and an injection skid).
or
A geotechnical contractor can provide a turnkey quote using a variety of barrier technologies (slurry walls, sheet piling) as well as permeation grouting.
X
Step 3: Are site conditions suitable for permeation grouting using silica gel?
In general, permeation grouting needs, 1) a transmissive zone comprised of sand (not silt or gravel or fractured rock) with K between 5x10-4 to 10-2 cm/sec, 2) a low permeability unit at the bottom of the transmissive zone, and 3) the site probably needs to be accessible to a direct push rig to make the process economical. Note that non-silica gel grouts and other barrier technologies can be used at sites that don't meet these criteria.
Step 4: Determine if other factors such as water level increases might cause a problem.
At most sites these issues won't be a problem but need to be evaluated.
Source: ESTCP Project 201338 Final Report (www.serdp-estcp.org)
Navigation Panel
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OR
F_Types

Planning-Level Cost Evaluation: Permeation Grouting

Variable	Value	Units
Treatment Zone		
Total Length	500	ft
Total Depth	50	ft
Depth to Water	15	ft
Total Porosity	0.3	
Injection Grout Materials		
Radius of Influence of Injection Point	2	ft
Percent Influence Overlap	20%	%
Well Spacing	4.0	ft
Perimeter	500	ft
Number of Injection Points	126	
Total Volume of Injection Grout	149,239	gal
Cost of Sodium Silicate Tote	2,000	$
Cost of Dibasic Ester Drum	1,003	$
Cost of Water and Tank Rental	0.40	$/gal
Cost of Injection Grout	2	$/gal
Injection Skid		
Capital Cost of Skid + Start-Up	50,000	$

Variable	Value	Units
Injection Time		
Hours per Injection Point (4 Depths)	4	hrs/point
Simultaneous Injections	3	points/time
Total Injection Time	17	days
Installation and Start-Up		
Drilling Hours per Injection Point	4	hrs
Number of Rigs	2	
Number of Work Days for Drilling	24	days
Total Number of Days	32	days
Mobilization	1,500	$
Addt'l Costs per Injection Point	500	$/point
Cost per Day	2,000	$/day/rig
Utility Clearance	5,000	$
Other Equipment Rental		
Generator Rental	1,300	$/month
Forklift Rental	1,050	$/week
Car Rentals, Consumables	100	$/day
Labor and Other Expenses		
Assume 2 Field Personnel Onsite	2,300	$/day
Other Expenses (Meals/Lodging)	170	$/day
Decomissioning		
Waste Disposal & Characterization	3,800	$
Transportation of Skid	4,800	$

KEY: Data Input Instructions

##	*Enter value directly*
##	*Previously entered or intermediate calculation. OK to overwrite*
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COST SUMMARY

Variable	Value	Units
Total Cost of Grout Materials	$295,360	$
Total Cost of Injection Skid	$50,000	$
Total Drilling Subcontractors	$167,000	$
Total Labor and Rentals	$60,640	$
Decomissioning Total	$8,600	$
Total Cost (Most Likely)	**$587,840**	$
Total Cost (Low Range)	**$440,880**	$
Total Cost (High Range)	**$881,760**	$

*Disclaimer: This is a planning-level tool only, and does not include a detailed design of this technology. Costs are approximate and a site-specific evaluation should be conducted prior to implementation.

Navigation Panel

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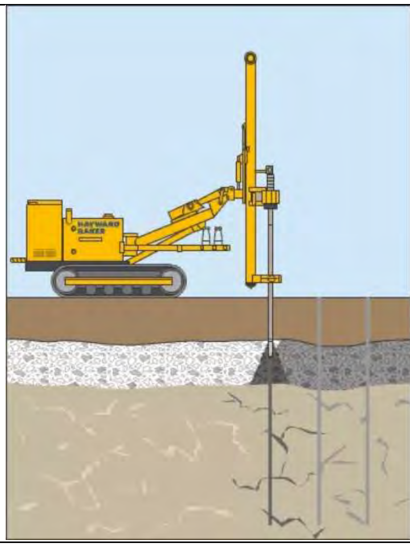
SHEET N_GROUT:
Grout Bomber (Experimental)

Grout Bomber

	The Grout Bomber is a direct-push based technology which inserts columns of various amendments (grout) into the subsurface via single stroke placement using a tall mast (mandrel). The geotechnical industry typically leverages this technology for compacting and stabilizing soils and fill materials. **Applications for isolating hazardous waste site source zones is still in the experimental stage, however.** For barrier construction, seven concentric “rings” of low permeability columns may be placed surrounding the contaminant source zone.

GROUT BOMBER TECHNOLOGY

OVERVIEW

The Grout Bomber is a direct-push drilling technology developed by Haywood Baker which drives columns of various amendments (grout) into the subsurface via single stroke placement as shown in Figure 1.

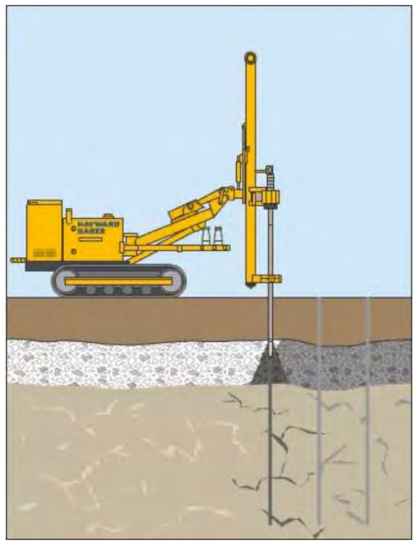


Figure 1: Grout Bomber Rig (HB, 2011).

The geotechnical industry typically leverages this technology for compacting and stabilizing soils and fill materials. Depending on the subsurface conditions, Portland cement, microfine cement, or specialty grout is injected under pressure at strategic locations through single port or multiple port pipes. The grouted mass has an increased strength, stiffness, and reduced permeability.

GROUT TYPES

Hayward Baker states: *“The grout mixture must have specific characteristics: a very low mobility (low slump) mixture that is ‘pumpable’ but, upon installation, exhibits an internal friction enabling it to remain intact and displace the surrounding soil without fracturing it”* (HB Brochure, 2011). The grout mixture can be altered on site to meet site specific geologic conditions as well as project goals as shown in Figure 2. For instance, a high mobility grout (HMG) can be used in soils with less than 15% fines, and it will infiltrate the pore space surrounding the injection point to create a solid mass (ASCE, 2010). Thus, HMG can create the most effective groundwater flow barriers, provided soil conditions are within acceptable limits. Due to its specialized properties and additional volumes required, HMG can be cost prohibitive (typically ~540 $/CY). Low mobility grout (LMG) will minimally, if at all (depending on site conditions), infiltrate pore space; however, due to its lower cost (typically ~265 $/CY), and the Grout Bomber rig’s ability to quickly install many, closely spaced columns, LMG may prove to be an attractively economic material for installing groundwater flow barriers. In addition, various specialty grouts (i.e., ZVI amendments) can be used with the Grout Bomber’s batch mixer and pumping equipment as needed.

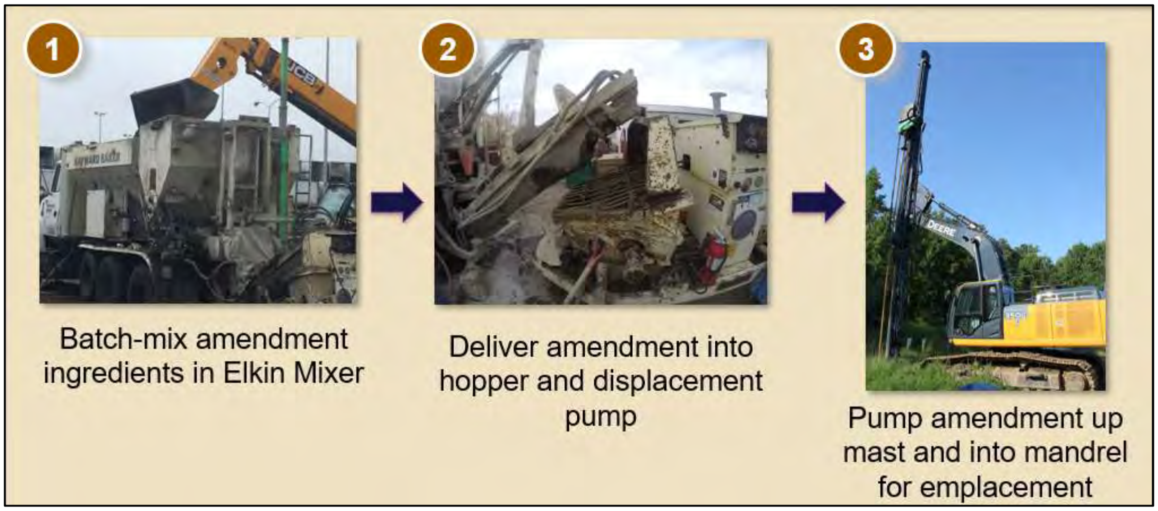


Figure 2: Grout Bomber Process Flow: How It Works.

BARRIER CONSTRUCTION (Note this is an experimental technology for barriers)

The Grout Bomber can be used to construct a barrier surrounding a groundwater contaminant source zone by installing two concentric "rings" of closely spaced, low permeability columns, on offset 2-foot spacing (see Figure 3). An assumed grout column diameter of 3 inches and a minimum column spacing of 2 feet reduces the risk that soil collapse will occur, which would threaten the integrity of the barrier (HB, 2018). While highly dependent on site conditions, geotechnical contractors have recommended the use of a low cost LMG for this application of the Grout Bomber. Should specialized grout properties be desired (i.e., low permeability reactive barrier), additional costs and testing may be required.

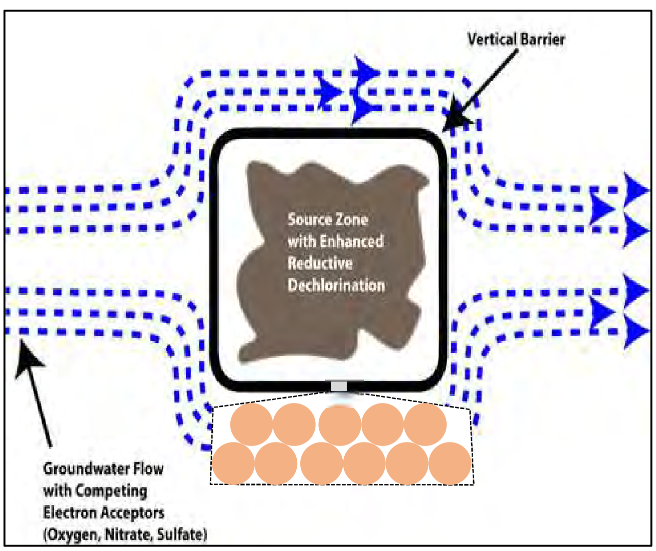


Figure 3: Conceptual Model - Groundwater Flow Barrier (Vertical Barrier) Constructed by the Grout Bomber. Inset shows the barrier constructed using seven concentric "rings" of grout columns spaced about two feet apart.

GROUT BOMBER PERFORMANCE

Due to this technology's experimental status for creating source barriers at environmental sites, the performance has not been verified. It is likely to have similar performance as permeation grouting, i.e., reduction of sandy soil hydraulic conductivity of 1 to 2 orders of magnitude (see Sheet "M_Perm").

ADVANTAGES

- High speed of installation (~100 columns per day).
- No waste spoil disposal (direct push).
- Able to reach depths unattainable by some other methods.
- Able to modify grout material properties on site in real time to meet desired goals.

DISADVANTAGES

- High mobilization cost (~$50,000).
- Experimental with regards to installing barriers at hazardous waste sites.

REFERENCES

American Society of Civil Engineers, 2010. *Compaction Grouting Consensus Guide*. American Society of Civil Engineers, 2010.

Hayward Baker, Inc., 2011. *Compaction Grouting Brochure.* 2011, www.HaywardBaker.com.

Hayward Baker, Inc., 2018. Personal Communication with Hayward Baker Field Engineer. July 2018.