

GEOLOGY-FOCUSED CSM: BEST PRACTICE FOR PFAS REMEDIATION OPTIMIZATION

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RemPlex Summit November 2025



The Primary Challenge to Groundwater Remediation: Aquifer Heterogeneity

Application of Oil and Gas
Technology to Groundwater:
Sequence Stratigraphy and Facies
Models

Case Study

Challenges and Path Forward



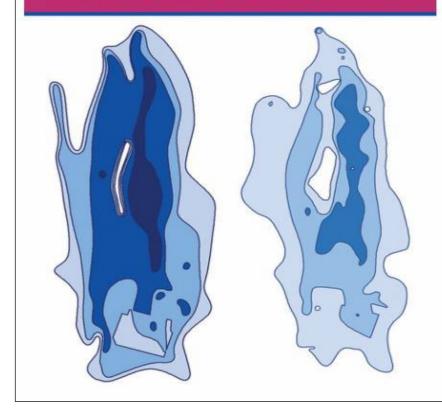
The Challenge: Geologic Heterogeneity in Aquifers

- Heterogeneity is the rule, not the exception
- More than 126,000 sites across the U.S. require remediation
- More than 12,000 of these sites are considered "complex"
- "...due to inherent geologic complexities, restoration within the next 50-100 years is likely not achievable."
- PFAS is more problematic than solvents... mobility, longevity...
- Will we repeat the mistakes of the past?

Alternatives for Managing the
Nation's Complex Contaminated
Groundwater Sites
National Academy of Sciences
Committee on Future Options for
Management in the Nation's Subsurface
Remediation Effort, 2013

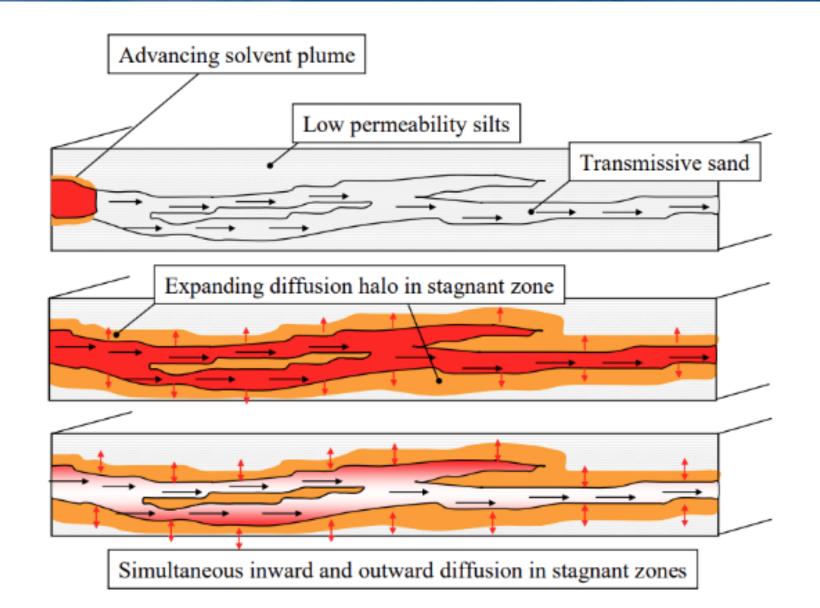
NATIONAL RESEARCH COUNCIL OF THE MATIONAL ACADEMIES

ALTERNATIVES FOR MANAGING THE NATION'S COMPLEX CONTAMINATED GROUNDWATER SITES





Example of the Challenges of Aquifer Heterogeneity





Leveraging the Geology

"Water Breakthrough" threatened the economics of oil and gas projects.

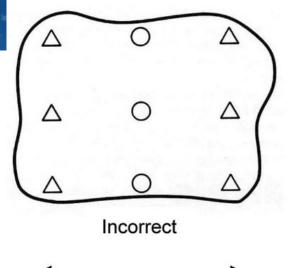
The petroleum industry learned to work with nature to effectively move fluids in the subsurface. There is a "correct way" and an "incorrect way".

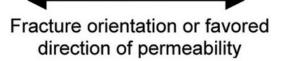
The groundwater restoration community is learning this 40 years later.

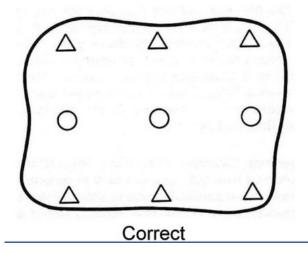
"Environmental Sequence Stratigraphy ("ESS") as a bridge...

Rose, S.C., Buckwalter, J.F., and Woodhall, R.J. 1989. *The Design Engineering Aspects of Waterflooding*, Vol. **11**. Richardson, Texas: Monograph Series, SPE.

For waterflood or steamflood, the success depends on the injectorproducer layout with respect to the geology of the reservoir ○ Production wells
 △ Injection wells









Innovating in the Groundwater Space: Environmental Sequence Stratigraphy

"ESS" is the application of the technologies to groundwater challenges



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Best Practices for Environmental Site Management:

A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models

Michael R. Shultz¹, Richard S. Cramer¹, Colin Plank¹, Herb Levine², Kenneth D. Ehman³



Team of trained stratigraphers

- 2017 USEPA Best Practices Guidance
- **Air Force ESS Application:** 2010-present
- 80+ Base-wide CSMs for **Groundwater (PFAS)**
- **ESS** is prerequisite for CSM updates portfolio-wide (TORNs, RFPs)



BACKGROUND

This issue paper was prepared at the request of the Environmental Protection Agency (EPA) Ground Water Forum. The Ground Water, Federal Facilities, and Engineering Forums were established by professionals from the United States Environmental Protection Agency (USEPA) in the ten Regional Offices. The Forums are committed to the identification and resolution of scientific, technical, and engineering issues impacting the remediation of Superfund and RCRA sites. The Forums are supported by and advise Office of Solid Waste and Emergency Response's (OSWER) Technical Support Project, which has established Technical Support Centers in laboratories operated by the Office of Research and Development (ORD), Office of Radiation Programs, and the Environmental Response Team. The Centers work closely with the Forums providing state-of-the-science technical assistance to USEPA project managers. A compilation of issue papers on other topics may be found here:

EPA/600/R-17/293

http://www.epa.gov/superfund/remedytech/tsp/issue.htm

The purpose of this issue paper is to provide a practical guide on the application of the geologic principles of sequence stratigraphy and facies models (see "Definitions" text box, page 2) to the characterization of stratigraphic heterogeneity at hazardous waste sites.

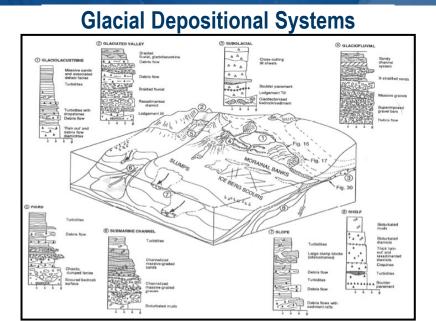
Application of the principles and methods presented in this issue paper will improve Conceptual Site Models (CSM) and provide a basis for understanding stratigraphic flux and associated contaminant transport. This is fundamental to designing monitoring programs as well as selecting and implementing remedies at contaminated groundwater sites. EPA recommends re-evaluating the CSM while completing the site characterization and whenever new data are collected. Updating the CSM can be a critical component of a 5 year review or a remedy optimization effort.



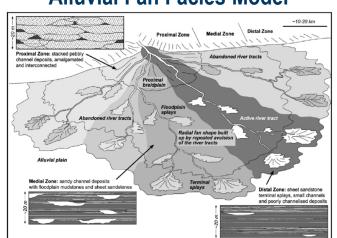
ESS is About Pattern Recognition



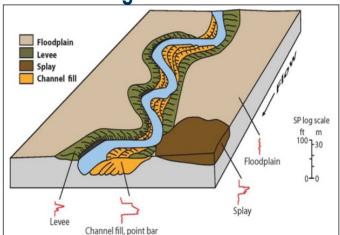




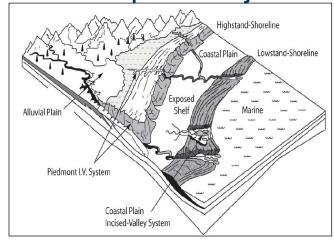
Alluvial Fan Facies Model



Meandering River Facies Model



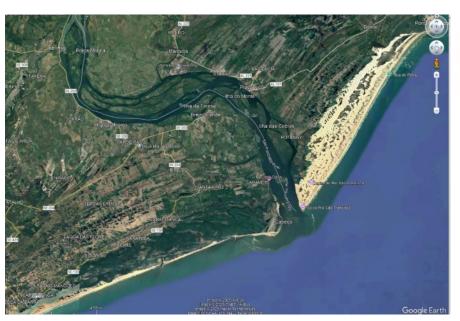
Coastal Depositional Systems

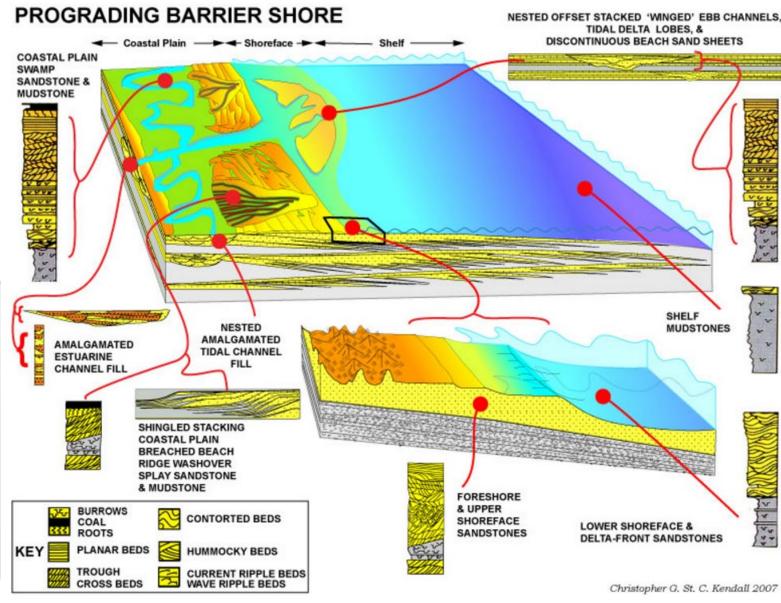




Facies Models Predict Between the Wells

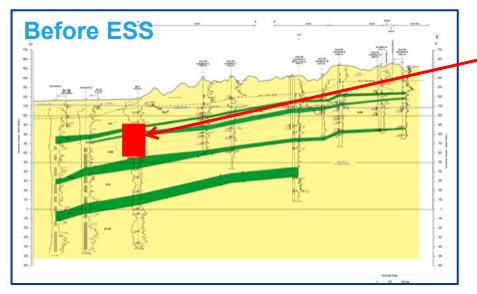
 Like completing the picture of the Mona Lisa with just a few key pieces, the stratigrapher can visualize the 3D volume with limited 2D data points (wells)





Case Study

Cost Savings and Sustainability: Optimize Plume Containment Remedy



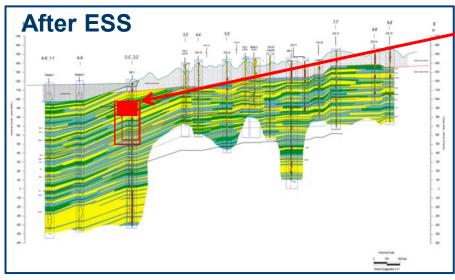
125' extraction interval

(includes nonimpacted strata)

Remediation System Design (Before ESS)

- 12 extraction wells
- •~200 gpm per well
- •1,261 million gallons per year

Total cost = \$82 million



35' extraction interval

(impacted strata only)



Estimated Remediation System Cost (After ESS)

- 13 extraction wells
- •46 gpm per well
- 314 million gallons per year

Total cost = \$26.5 million

Reduced cost of remediation (by >\$50 million)

Reduced quantity of extracted groundwater (by >70%)



How can we avoid the mistakes of the past and improve outcomes with PFAS?

Monitored Natural Attenuation?

- Commonly applied where degradation can be demonstrated (solvents, hydrocarbons, etc.)
- Limited precedent for application to non-degradable contaminants (e.g., metals, radionuclides)
- Requires retention (not exactly attenuation...)

Key issue for application of Monitored Retention of PFAS in Groundwater:

PFAS is highly mobile, not prone to migrate into aquifer zones where retention is likely

Potential Solution: Stratigraphic Sequestration

Monitored natural attenuation to manage PFAS impacts to groundwater: Potential guidelines

Charles J. Newell | David T. Adamson | Poonam R. Kulkarni | Blossom N. Nzeribe | John A. Connor | Jovan Popovic | Hans F. Stroe |

Monitoring&Remediation

Monitored Natural Attenuation to Manage PFAS Impacts to Groundwater: Scientific Basis

by Charles J. Newell O. David T. Adamson, Poonam R. Kulkarni, Blassom N. Nzeribe, John A. Connor, Joyan Popovic and Hans F. Stroo

Abstract

Sites impacted by per- and polyfluorallysf substances (PFAS) pose significant challenges to investigation and remediation, including very low champo dipictives, limited information on natural FAS dependation processes in the subsurface, and the papearent mobility and persistence of PFAS. Consequently, monitured natural attenuation (MNAI) may be considered less applicable to PFAS compared to biodegradable classes of chemicals such as petrolaren hydroctorons and chioriated solvents that can completely biodegradable to innocuous ord products. However, MNAI has proven effective for certain non-degrading metals, metalloids, and radionuclides (e.g., chromium, arranic, and uranium). To assess the applicability of MNAI to PFAS, this paper reviews the fate and transport properties of PFAS in conjunction with the various phylochemical factors that control the subsurface movement of chemicals. This analysis demonstrates that two important retention processes: (1) chemical retention in the from of PFAS precursor, and 2) goochemical retention in the from of sospitan and marist diffusion to militigate the movement and potential impacts of PFAS in groundwater that may form the scientific has is for applying MNA to PFAS contamination. This paper describes the scientific and regulatory basis for unity MNA to manage PFAS-impacted opmondator.

opportunity to manage such sites more efficiently while still

protecting potential receptors. MNA refers to "the reliance

on natural attenuation processes (within the context of a

to achieve site-specific remediation objectives within a tim-

nore active methods" (USEPA 1999). Despite past skepti

several remedial technologies that can be employed at con-

taminated sites, as long as the science behind natural attenu-

ation (NA) processes is well understood and MNA helps

manage the chemicals of concern (COCs) in groundwate

(Adamson and Newell 2014). There is an extensive col

lection of MNA protocols and guidance for implementing

MNA for a wide variety of COCs in groundwater (Wiedemeier et al. 1995; National Research Council 2000; Pone

et al. 2004; Ford et al. 2007a; ITRC 2010). Depending or site conditions. MNA can be applied in several different

ways: (1) to manage an entire plume with or without source remediation; (2) to manage a portion of the plume, based or horizontal/vertical location and contaminant type; (3) as a

polishing step after plume remediation. MNA is generally

utilized where NA processes manage a groundwater plum

whereas a related technology, Natural Source Zone Depletion (NSZD), is utilized where NA processes manage source

zones (typically LNAPL source zones) (Garg et al. 2017).

While the authors are not aware of any PFAS sites

where MNA has been applied to date, MNA likely will be

frame that is reasonable compared to that offered by othe

cism of its effectiveness. MNA is now considered one of

ntroduction

Sites impacted with per- and polyfluoroalkyl substances (PFAS) may prove difficult and costly to remediate in some cases, due to a combination of several challenges, including:

- part-per-trillion (ppt) cleanup objectives;
 the lack of proven destructive in-situ remediation tech-
- nologies;
 3. the number of PFAS in source zones and the limited abil-
- ity to comprehensively evaluate the PFAS composition;
 4. limited information on natural PFAS degradation processes in the subsurface;
- the mobility and persistence of PFAS in the subsurface;
 the large size of some PFAS plumes (Simon et al. 2019); and
 the potentially large number of PFAS sites requiring re-
- mediation (see three estimates in Newell et al. 2020).

terforle empact realessees. Chemical and geochemical releasion can form the basis for applying Monitored Natural Attenuation to manage PFAS impacts in groundwater.

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suses in the subsurface, and the apparent mobility and persistence rered less applicable to PFAS compared to biolegograble classes an completely biodegrade to innecuous end products. However, radiouculdies (e.g., chromium, arsent), and uranium.) To assess operfiles of PFAS in conjunction with the various physiochemical nonnotrates: that thus important retention processes: (1) chemical form of sorption and matrix diffusion to mitigate the movement is for applying MNA to PFAS contamination. This paper describes roundwater.

Monitored natural attenuation (MNA) represents one
Monitored natural attenuation (MNA) represents one

> MNA requires both data and metrics that reflect the is of PFAS. MNA evaluations often rely on pre-I modeling of PFAS is currently challenging given

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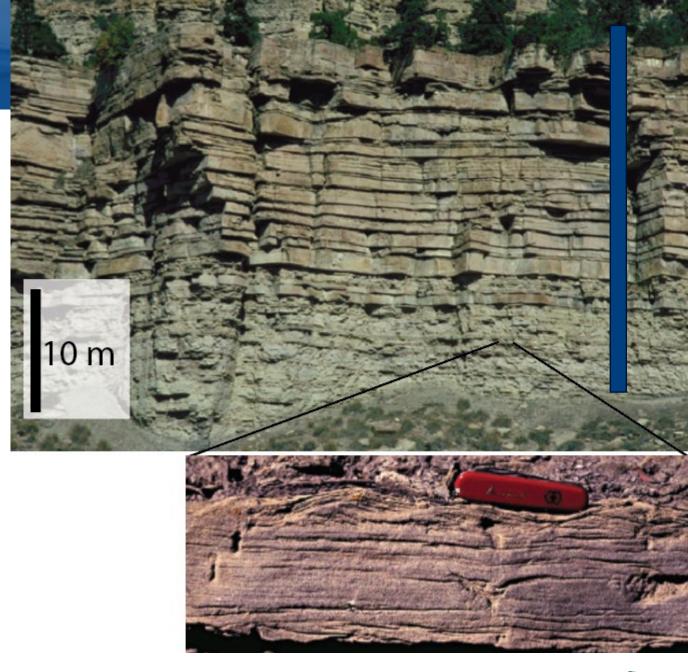
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Stratigraphic Sequestration

There is far more carbon substrate already present in the aquifer than required to immobilize all of the PFAS in groundwater. You just have to lead the PFAS to it.

- Outcrop of "sequestration zone" strata
- "Thin-bedded", laterally continuous for hundreds to thousands of meters
- Sand beds permit groundwater flow
- Organic- and clay-rich "interbeds" between sand beds provide ample surface area for sorption of PFAS





Stratigraphic Traps are Well Understood and They Work

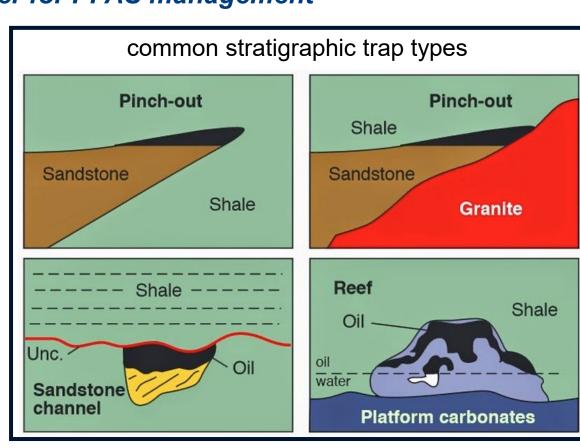
Stratigraphic Sequestration adapts tried and true petroleum industry concepts of stratigraphic trap to groundwater for PFAS management

Stratigraphic Traps

- Pinch out or lateral facies changes
- Common trap type
- Pressure data demonstrates isolation.

Benefits of Stratigraphic Sequestration vs Traditional Remedies:

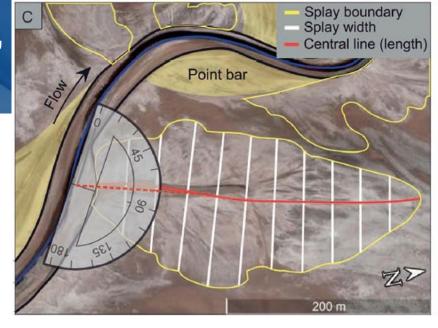
- Reduce PFAS mass flux, protective of receptors
- Extracting CLEAN groundwater, eliminates need for surface handling of PFAS
- Eliminates need for treatment or Destruction of PFAS
- Reduces cradle-to-grave liability for PFAS
- Accelerates potential application of MNA

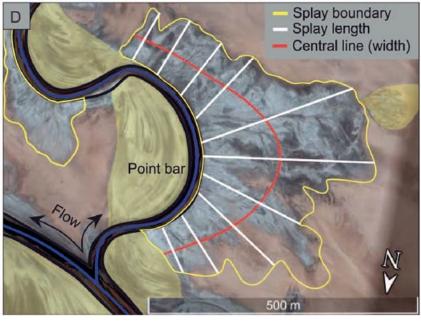


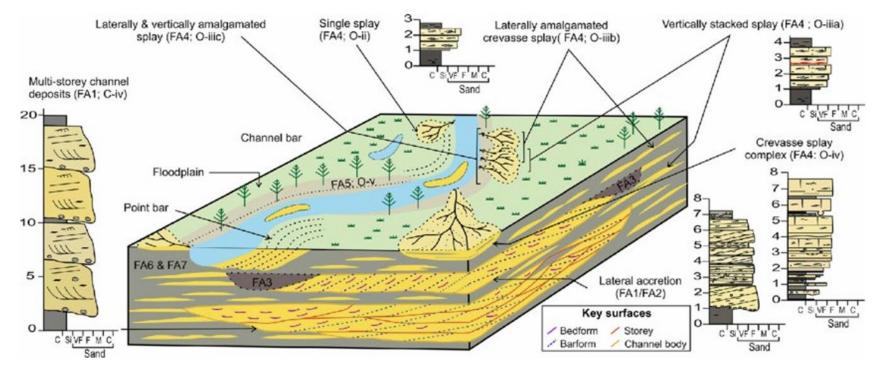


"Crevasse Splays"

- Splays form where rivers overtop banks in flood stage
- Limited aerial extent
- Encased in floodplain clays (hydrogeologic "dead ends")
- Ubiquitous in river valley systems
- Excellent potential sequestration targets





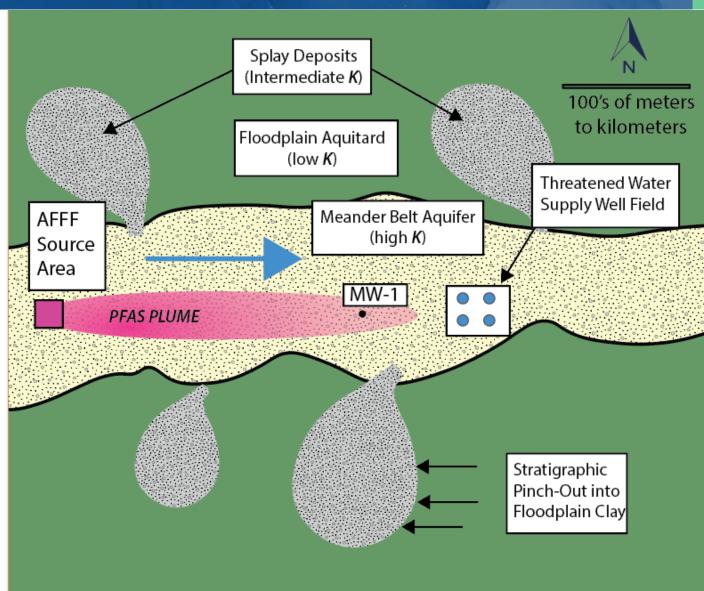


Conceptual Stratigraphic Sequestration Remedy Implementation

Phase 1: PFAS plume delineation

- PFAS detected in groundwater in high-quality meander belt sand and gravel aquifer
- Threatening water supply well field

Traditional approach would be to extract contaminated water within the plume to remove mass from the aquifer and slow or stop migration to the receptor

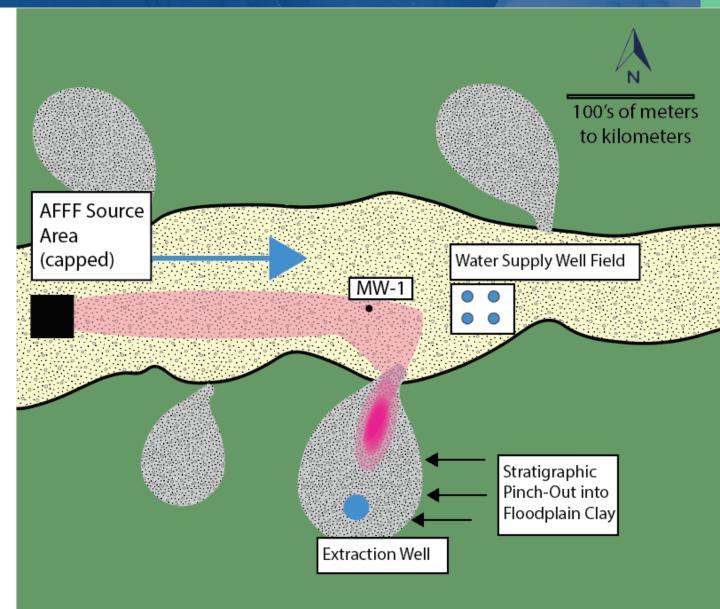


Conceptual Stratigraphic Sequestration Remedy Implementation

Phase 2: PFAS mass relocation to sequestration zone

- Sequestration zone identified
- Source zone capped
- Extraction well installed in sequestration zone

Stratigraphic Sequestration approach extracts clean groundwater PFAS mass relocated, sequestered by natural filter

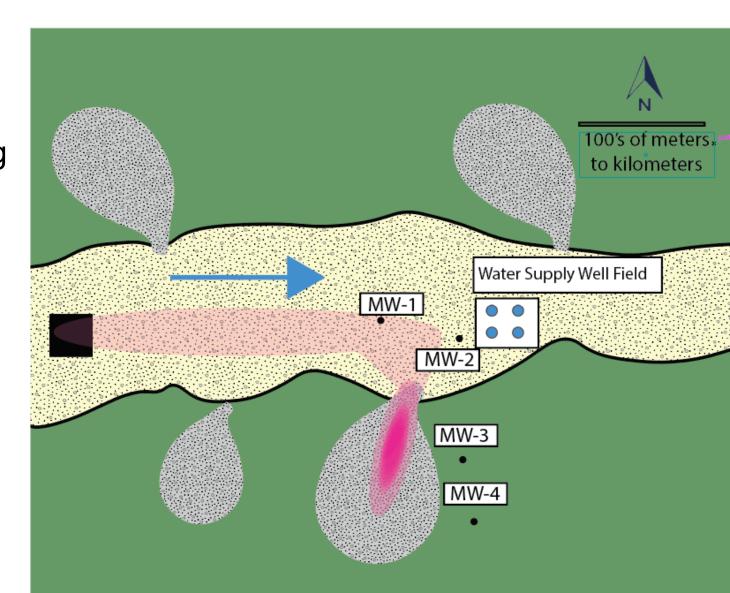


Conceptual Stratigraphic Sequestration Remedy Implementation

Phase 3: Cessation of pumping, inception of long-term monitoring

- Majority of mass sequestered
- Installation of additional monitoring wells

Stratigraphic Sequestration complete, low concentration residual plume If contaminants arrive at water supply wells, more affordable treatment due to low concentration, "peak shaving"



Conceptual Stratigraphic Sequestration: Regulatory Challenges and Solutions

Challenges

 EPA May consider target aquifer a drinking water source

Solutions

 Communicate with EPA Office of Superfund Remediation (OSR) early and often

- Permitting the Approach
- Developing and following the appropriate process with the regulatory community to review storage target adequacy
- Finding and Characterizing Target Storage Zones
 - Loss of Containment

 Detailed, refined stratigraphic modeling using ESS and multiple lines of evidence for hydrogeologic suitability

Conclusions

- 1. Geologic heterogeneity poses a significant challenge for groundwater restoration
- 2. Sequence Stratigraphy and Facies Models (ESS) can reduce uncertainty and improve project outcomes
- 3. Restoration of PFAS plumes to UU/UE may not be possible with traditional remediation approaches
- 4. Stratigraphic Sequestration of PFAS should be considered during assessment of remedy alternatives
 - Stratigraphic traps for hydrocarbons are well-understood and capable of stopping fluid flow in the subsurface
 - Technical and regulatory challenges exist but may not be insurmountable

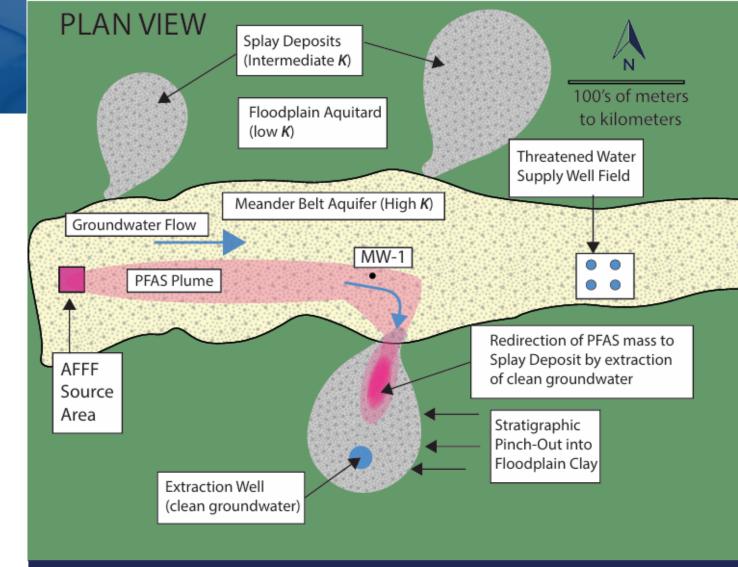


Figure 1. Map view showing conceptual stratigraphic immobilization remedy. Through temporary extraction of unimpacted groundwater, a hydraulic gradient is induced which draws a PFAS plume core from a high-K aquifer into an isolated natural immobilization zone, reducing or eliminating mass flux to a human or ecological receptor.



Thank You!

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