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GEOLOGY-FOCUSED CSM: BEST PRACTICE FOR PFAS REMEDIATION OPTIMIZATION

Mike Shultz, Ken O'Donnell, Colin Plank, Rick Cramer - Geosyntec Consultants

RemPlex Summit
November 2025

OUTLINE

The Primary Challenge to Groundwater Remediation: Aquifer Heterogeneity

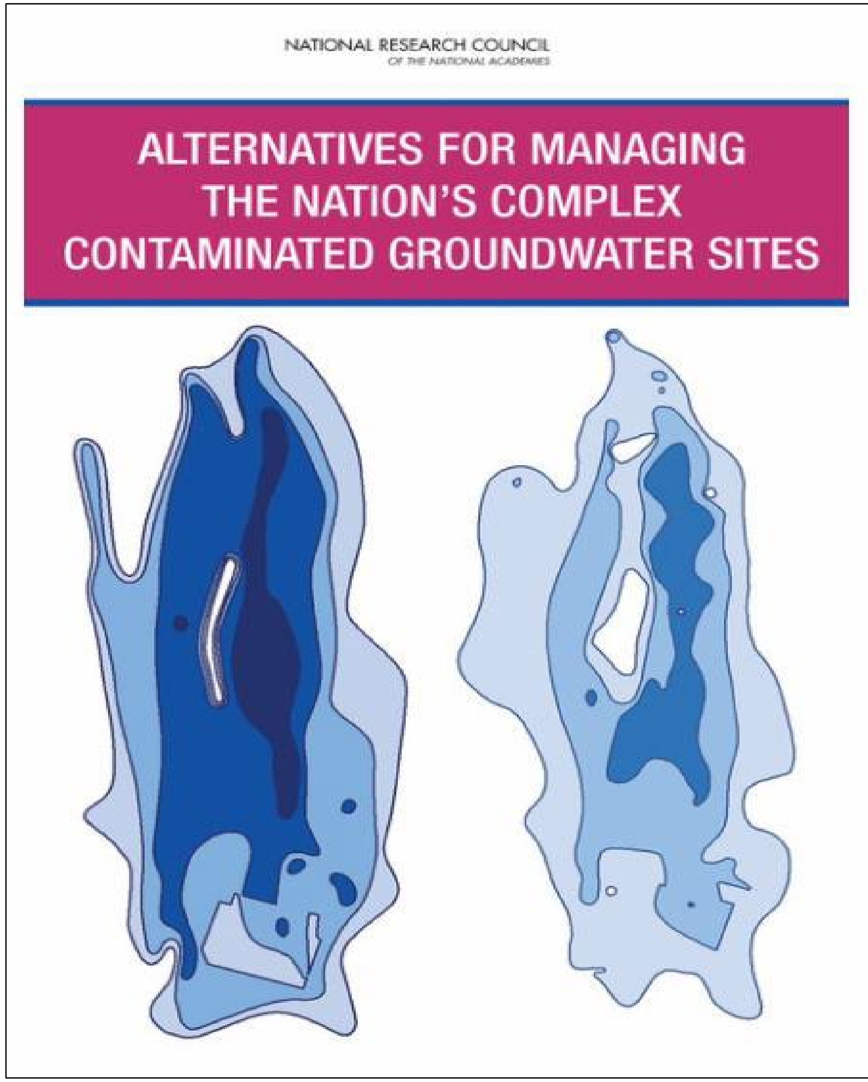
Application of Oil and Gas Technology to Groundwater: Sequence Stratigraphy and Facies Models

Case Study

Challenges and Path Forward

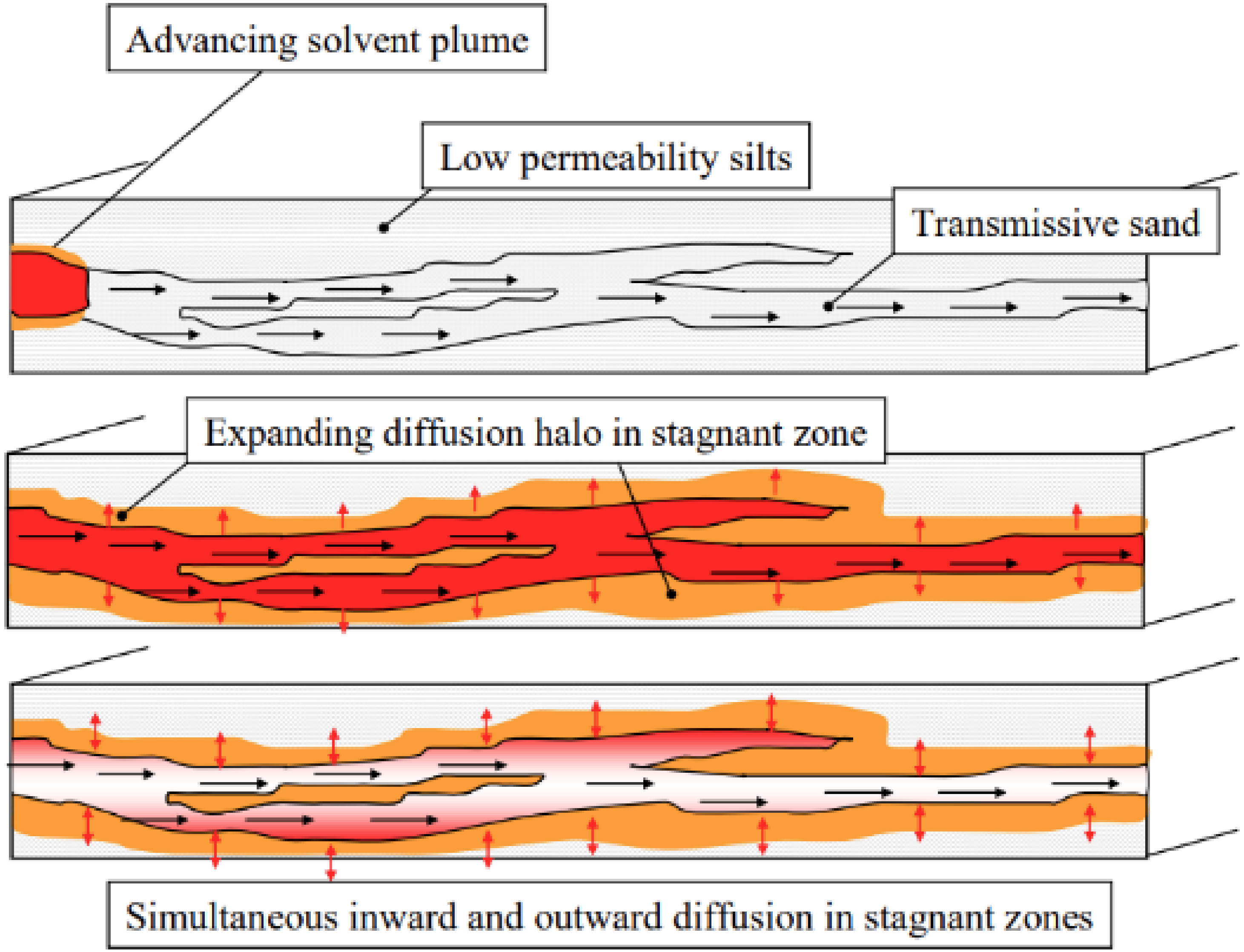
The Challenge: Geologic Heterogeneity in Aquifers

- 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***

Example of the Challenges of Aquifer Heterogeneity



Leveraging the Geology

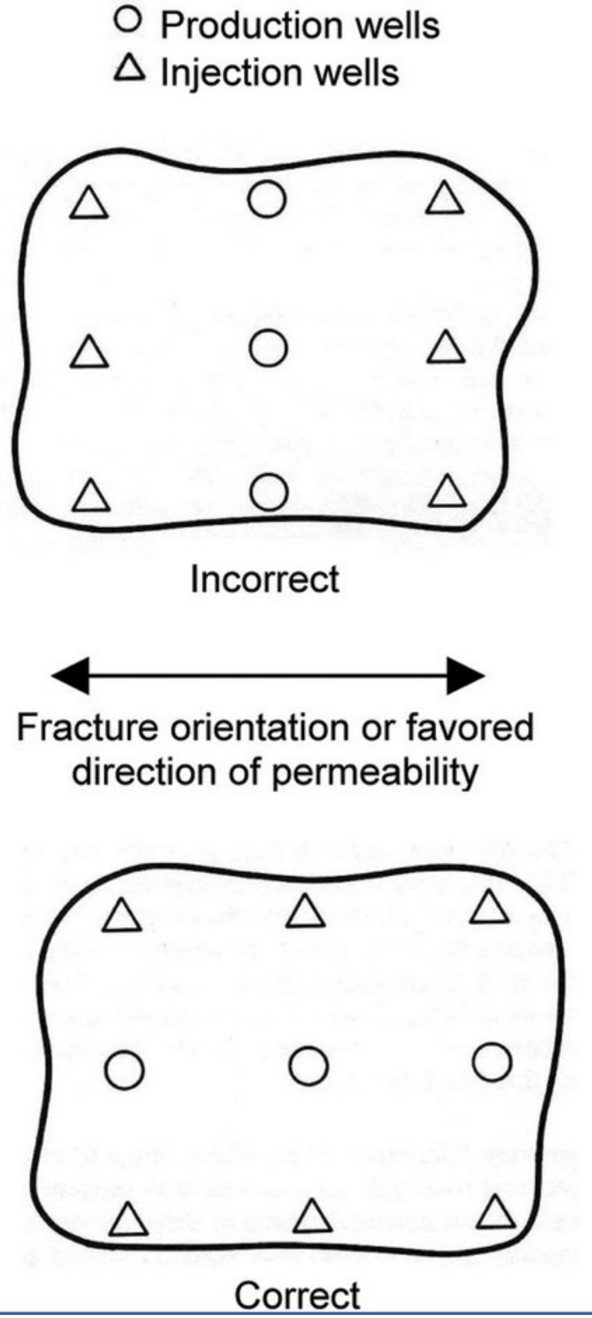
"Water Breakthrough" threatened the economics of oil and gas projects.

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…

For waterflood or steamflood, the success depends on the injector-producer layout with respect to the geology of the reservoir



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

Innovating in the Groundwater Space: *Environmental Sequence Stratigraphy*

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



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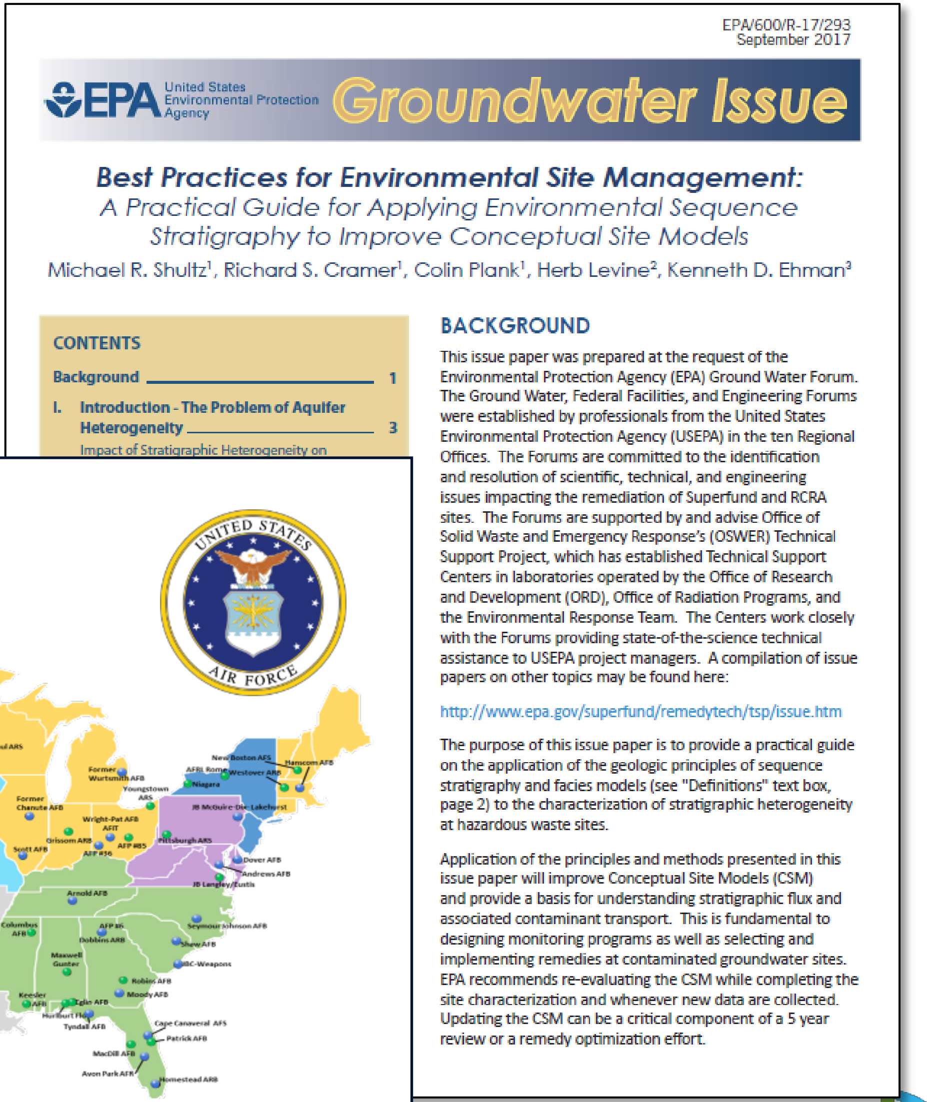
- **Team of trained stratigraphers**
- **2017 USEPA Best Practices Guidance**
- **Air Force ESS Application: 2010-present**
- **80+ Base-wide CSMs for Groundwater (PFAS)**
- **ESS is prerequisite for CSM updates portfolio-wide (TORNs, RFPs)**



EPA/600/R-17/293
September 2017

EPA United States Environmental Protection Agency **Groundwater Issue**

Best Practices for Environmental Site Management:
A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models

Michael R. Shultz[1], Richard S. Cramer[1], Colin Plank[1], Herb Levine[2], Kenneth D. Ehman[3]

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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:

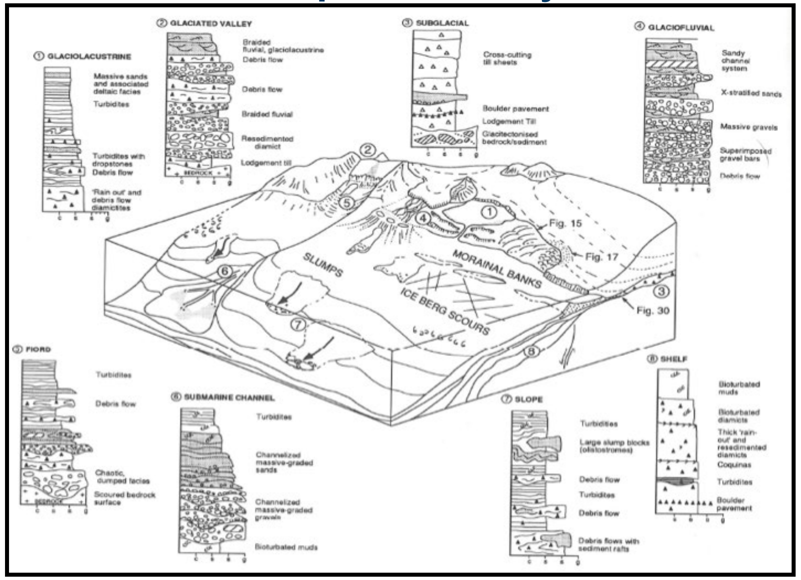
http://www.epa.gov/superfund/remedytech/tsp/issue.htm

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.

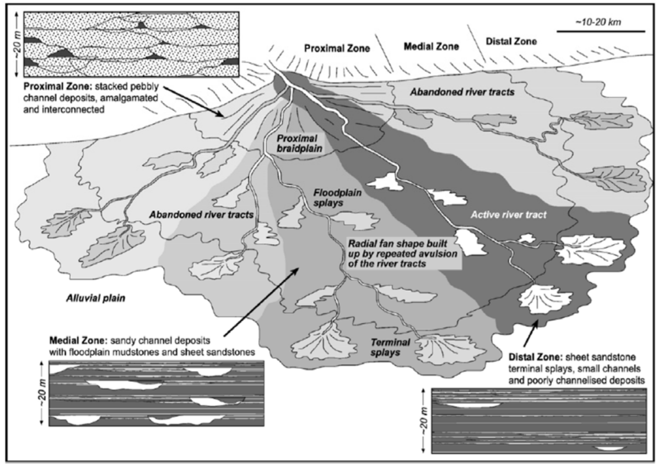
Application of the principles and methods presented in this issue paper will improve Conceptual Site Models (CSM) and provide a basis for understanding stratigraphic flux and associated contaminant transport. This is fundamental to designing monitoring programs as well as selecting and implementing remedies 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

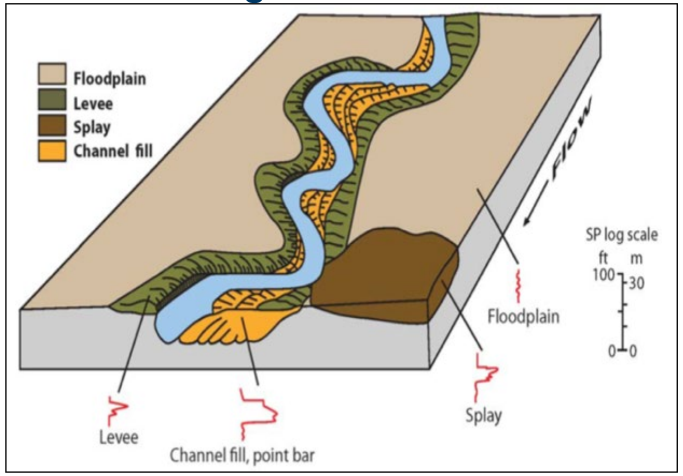
Glacial Depositional Systems



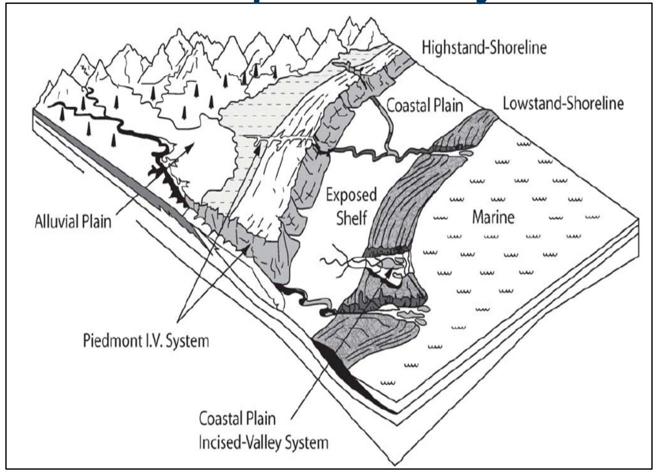
Alluvial Fan Facies Model



Meandering River Facies Model

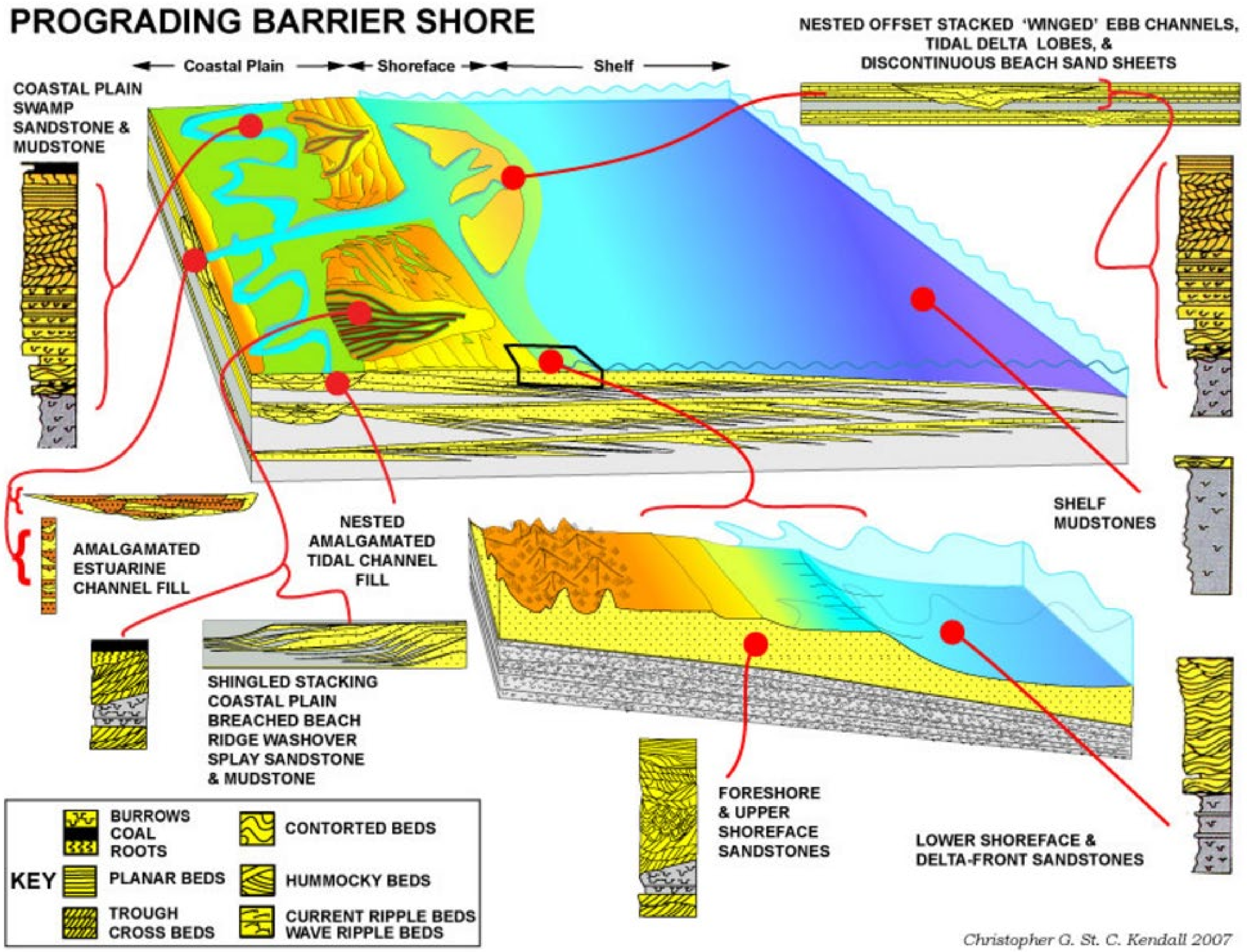


Coastal Depositional Systems



Facies Models Predict Between the Wells

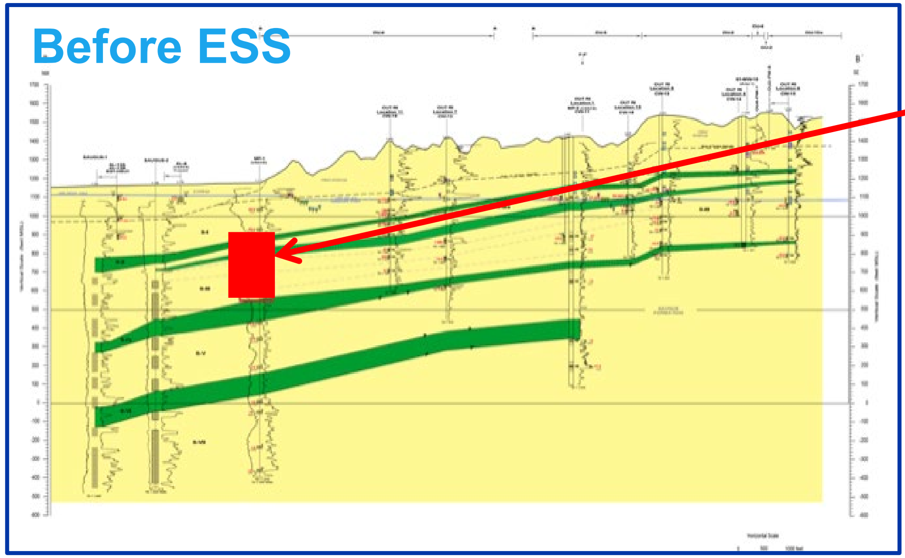
- Like completing the picture of the Mona Lisa with just a few key pieces, the stratigrapher can visualize the 3D volume with limited 2D data points (wells)



Case Study

Cost Savings and Sustainability: Optimize Plume Containment Remedy

Before ESS



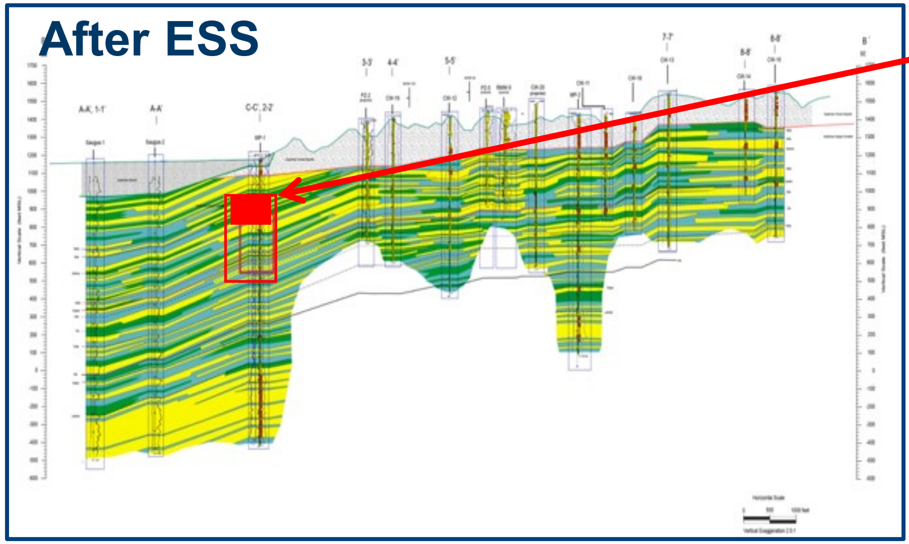
125’ extraction interval (includes non-impacted strata)

Remediation System Design (Before ESS)

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

Total cost = $82 million

After ESS



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?

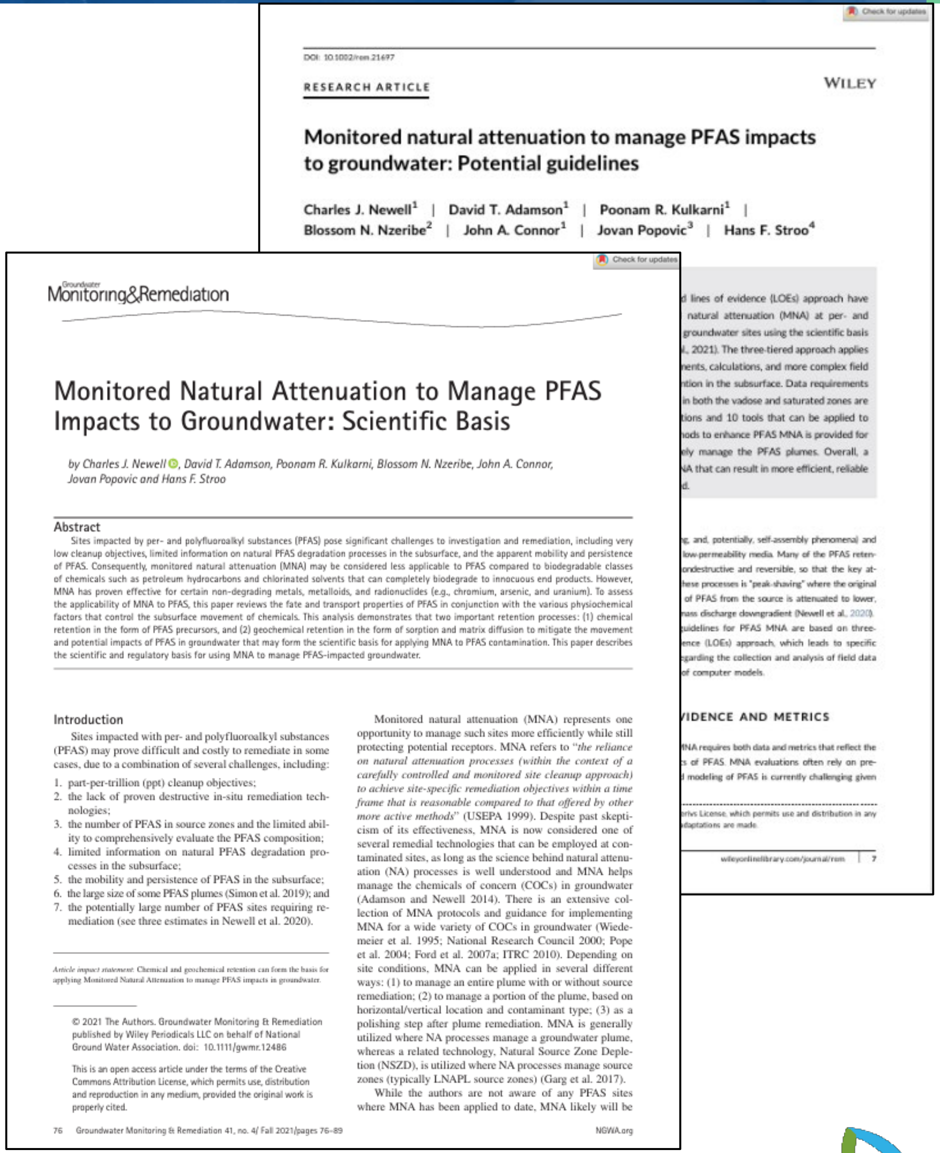
Monitored Natural Attenuation?

- 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

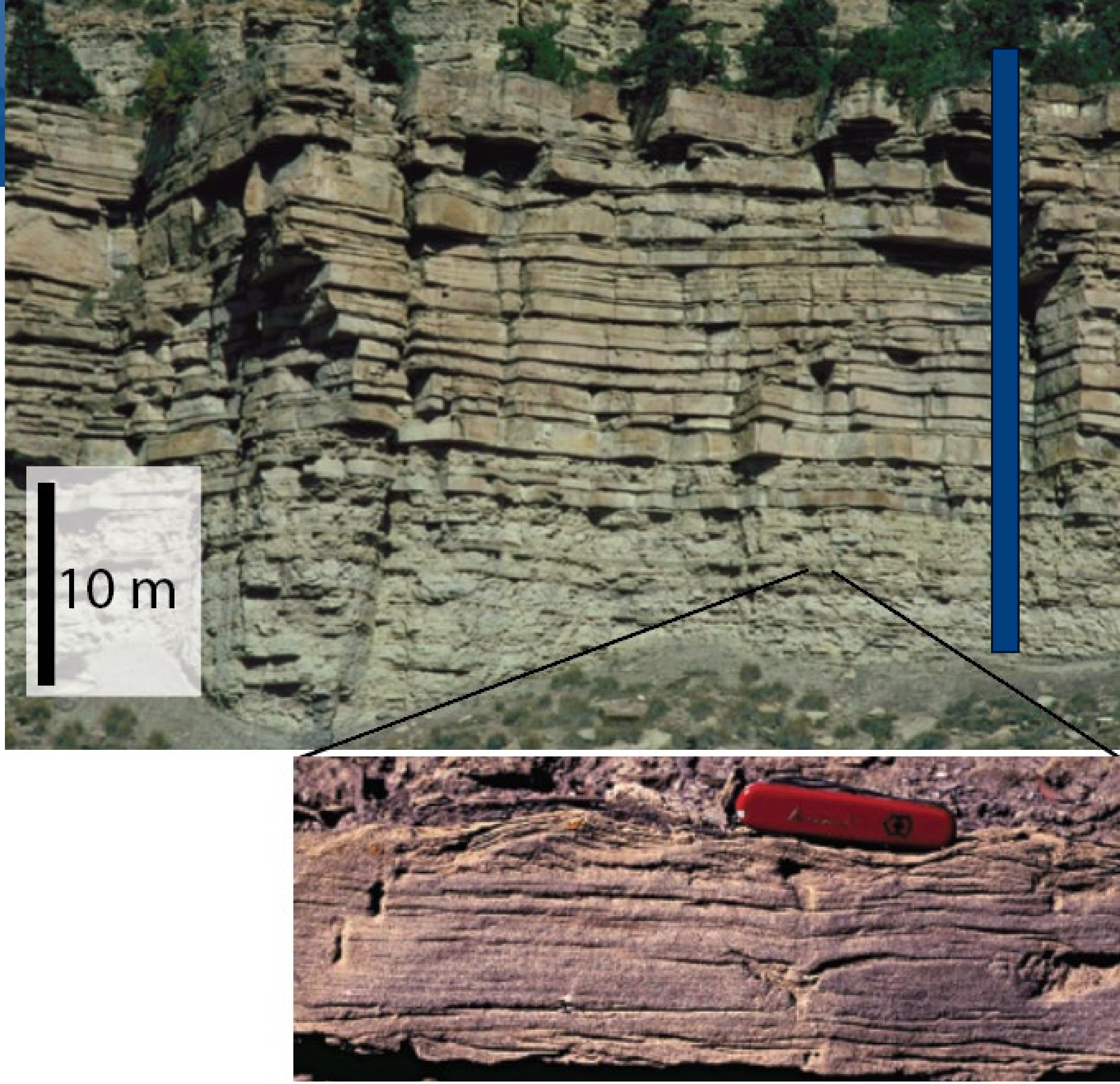
Potential Solution: Stratigraphic Sequestration



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



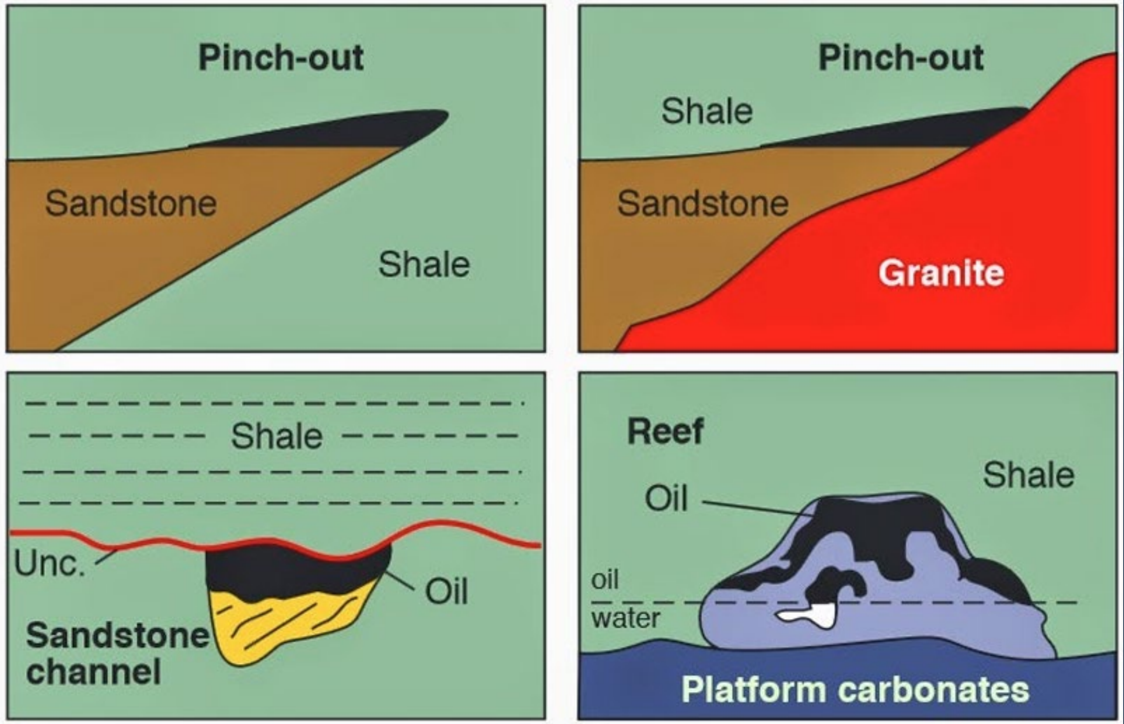
Stratigraphic Traps are Well Understood and They Work

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

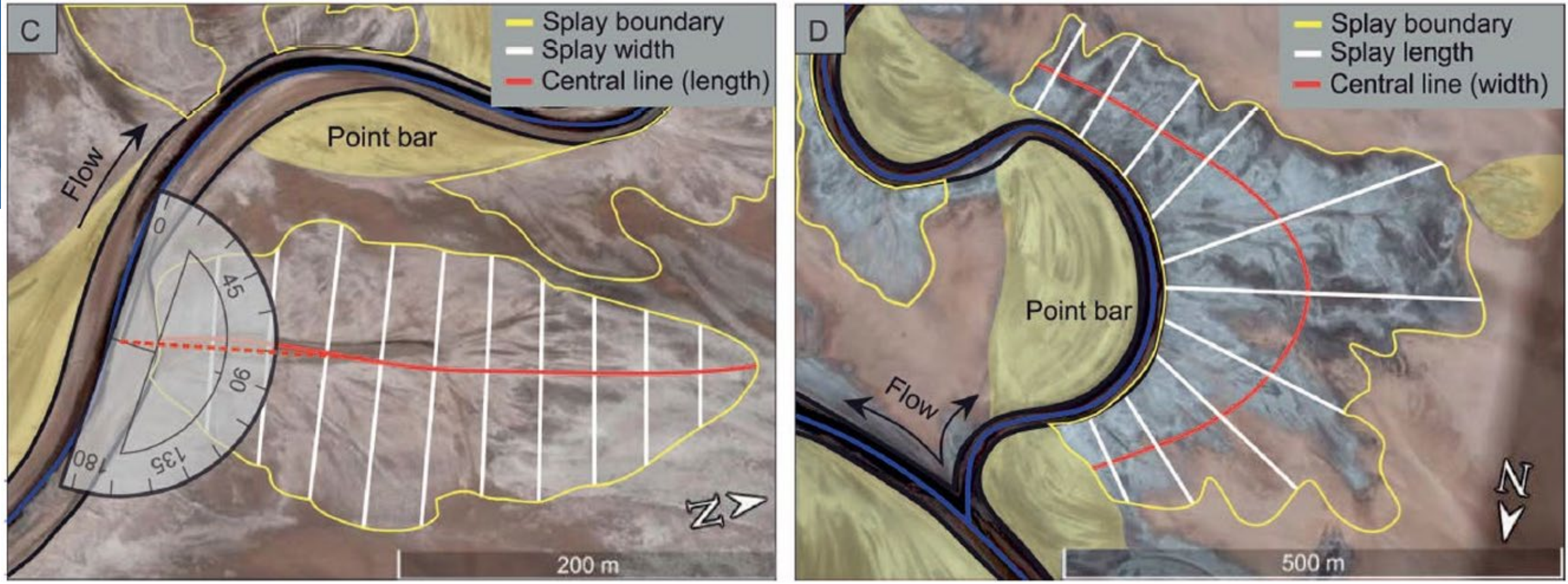
Benefits of Stratigraphic Sequestration vs Traditional Remedies:
- ***Reduce PFAS mass flux, protective of receptors***
- ***Extracting CLEAN groundwater, eliminates need for surface handling of PFAS***
- ***Eliminates need for treatment or Destruction of PFAS***
- ***Reduces cradle-to-grave liability for PFAS***
- ***Accelerates potential application of MNA***

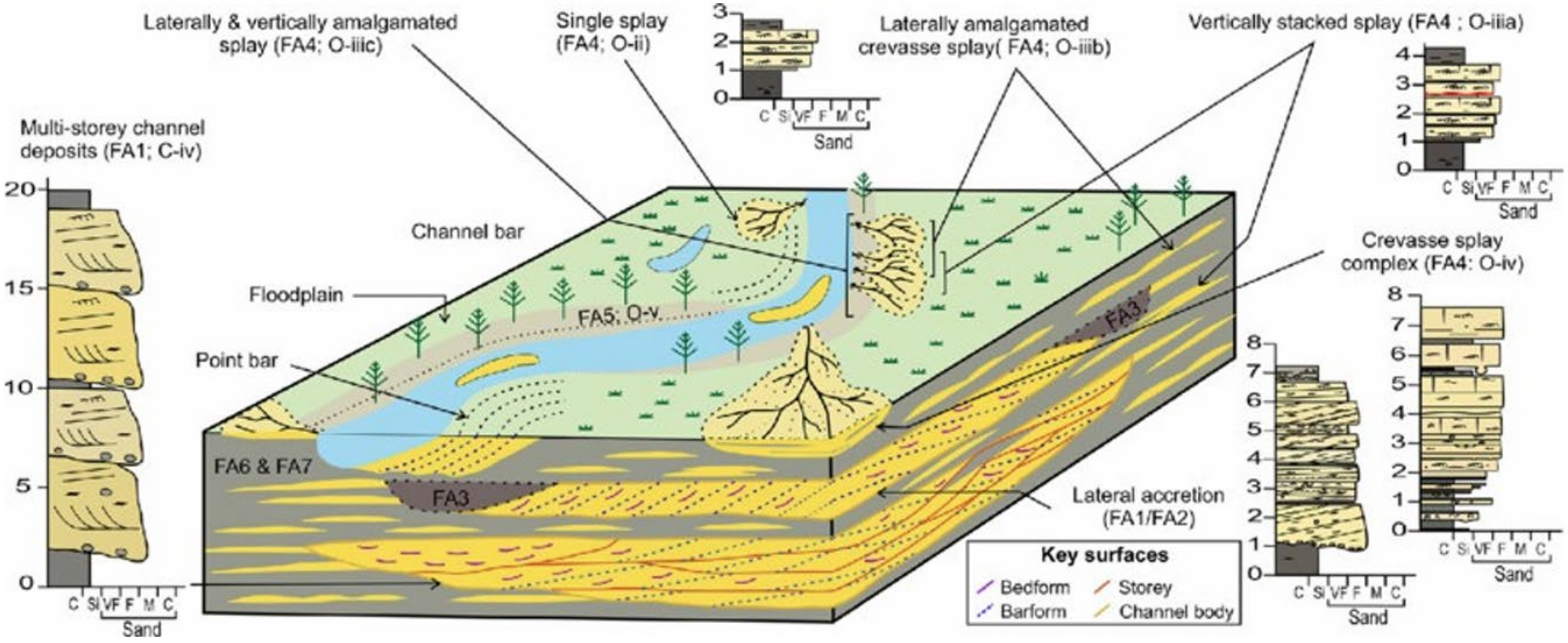
common stratigraphic trap types



"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



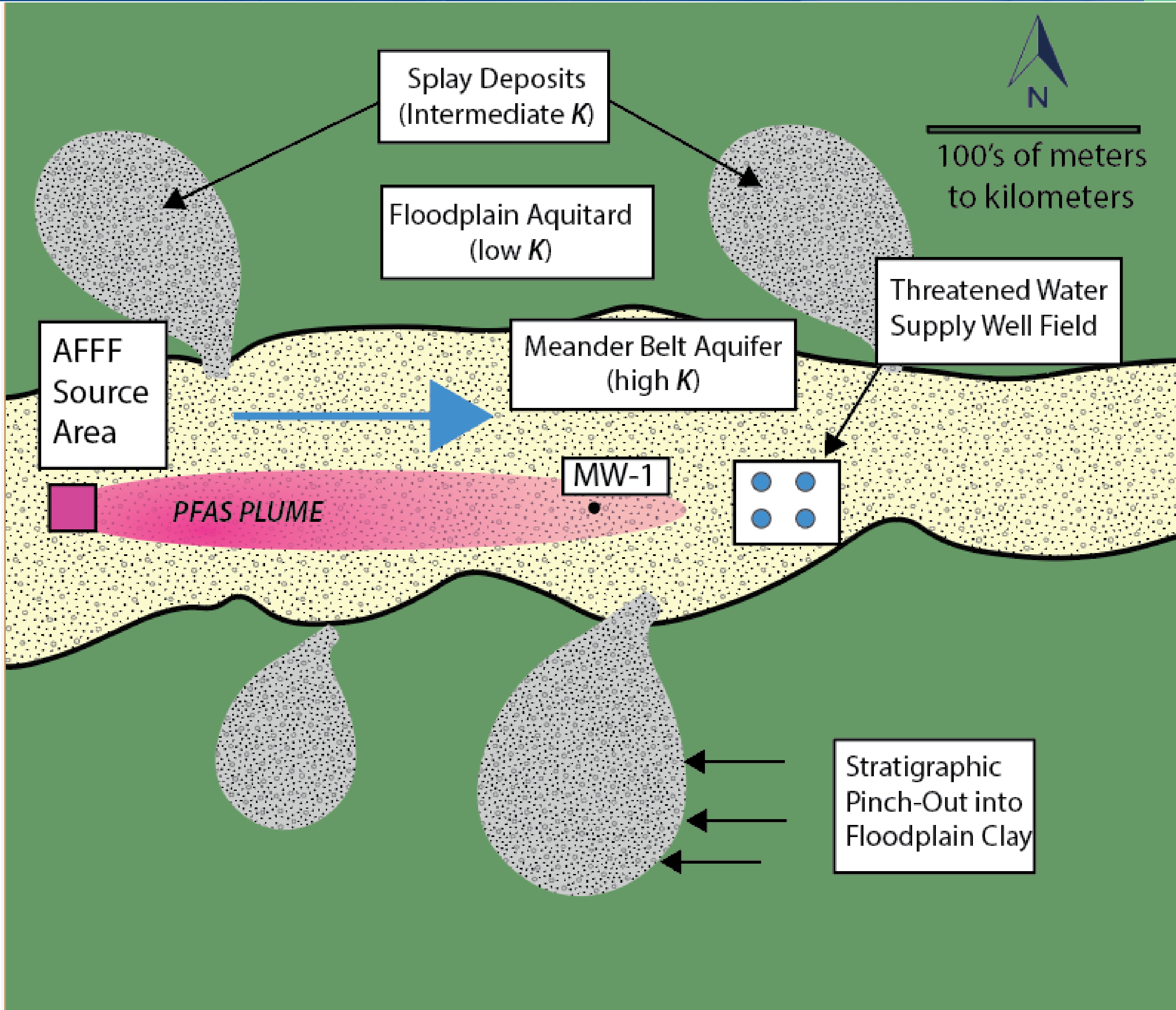


Conceptual Stratigraphic Sequestration Remedy Implementation

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

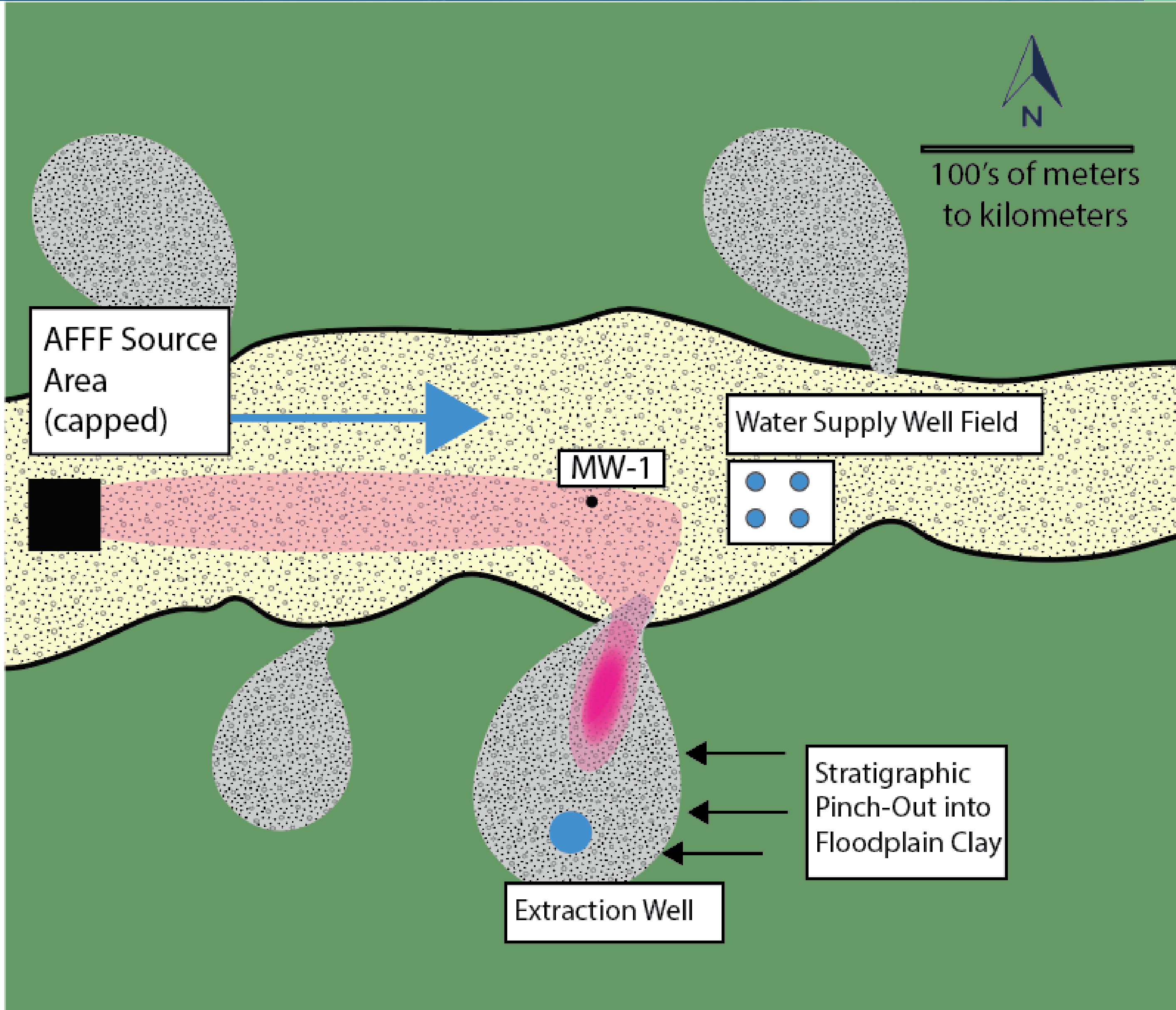


Conceptual Stratigraphic Sequestration Remedy Implementation

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



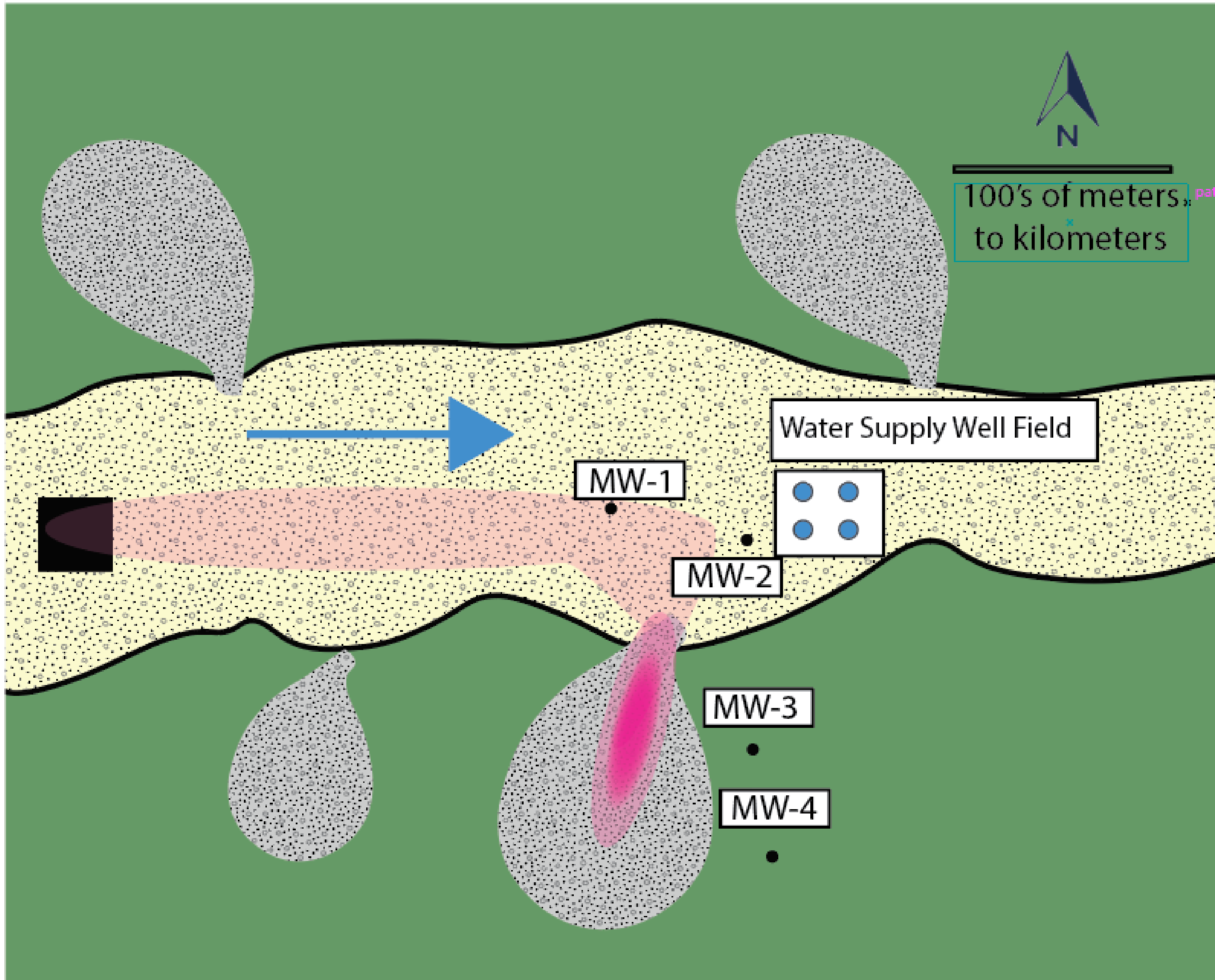
Conceptual Stratigraphic Sequestration Remedy Implementation

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	**Solutions**
• EPA May consider target aquifer a drinking water source	• 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

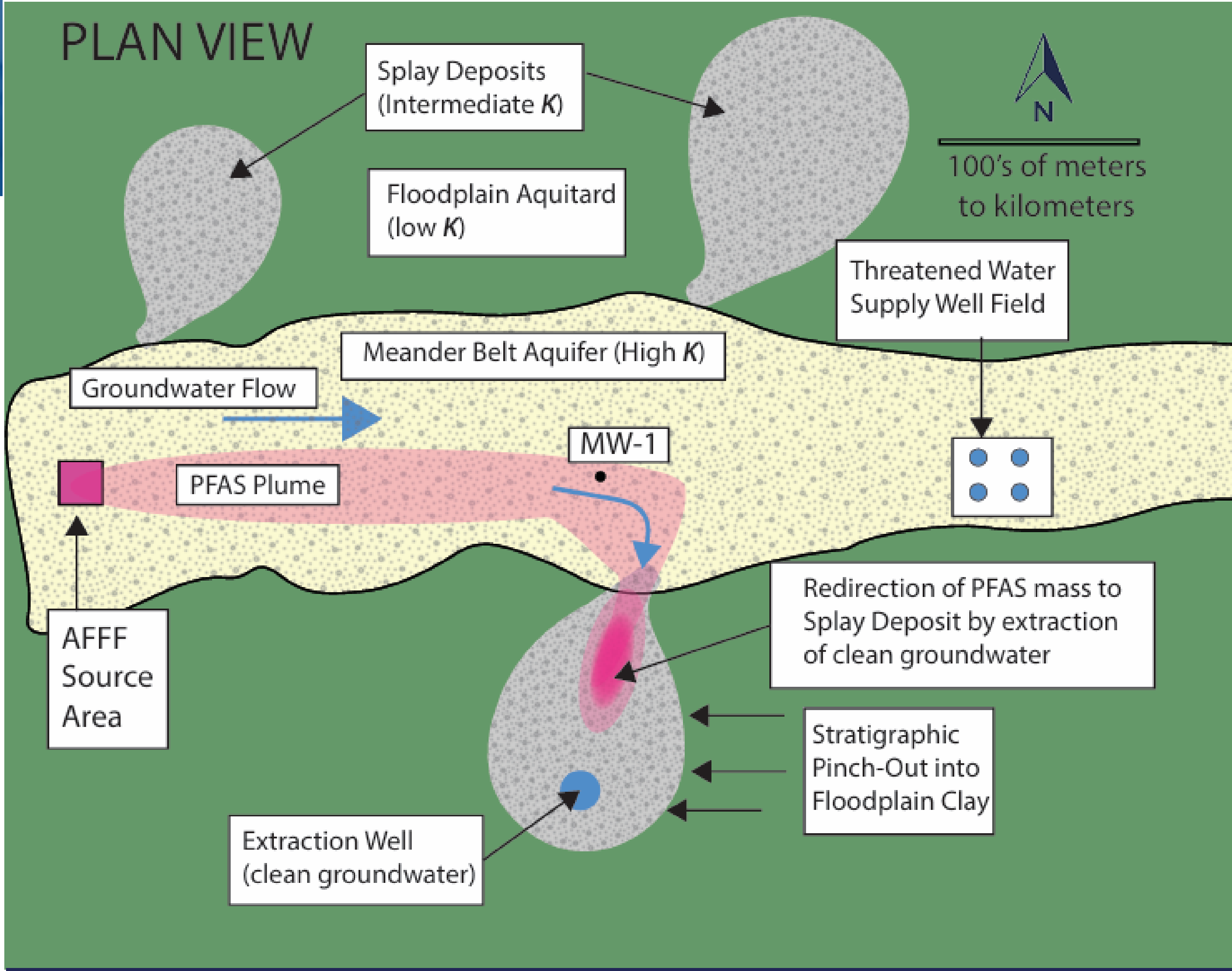


Figure 1. Map view showing conceptual stratigraphic immobilization remedy. Through temporary extraction of unimpacted groundwater, a hydraulic gradient is induced which draws a PFAS plume core from a high-K aquifer into an isolated natural immobilization zone, reducing or eliminating mass flux to a human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

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Thank You!

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